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Analysis of two nonfatal lightning accidents in Colombia

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ABSTRACT

Several lightning accidents involving human fatalities and injuries are reported every year in Colombia. This work presents and discusses two non-fatal lightning accidents, where the victims survived without evident permanent disabling traumas. In both cases, it was observed that metallic objects such as necklaces or buckle belts worn by the victims were intercepted by the lightning current. These metallic objects could possibly be a pathway to keep the lightning current on the victim's skin surface. To understand the interaction of these metallic objects and the indirect lightning currents, both the visual consequences of the indirect lightning current on the victim's skin and a comprehensive description of the cases scenarios are presented.

1. Introduction

Some geographical areas in the world are particularly more prone to lightning activity than others. Local geographical and meteorological conditions play important roles in the lightning activity, such as topography, proximity to waterbodies, seasonality, seasonal variation, time of the year, mesoscale convective systems (MCS) or the interannual El Niño/Southern Oscillation (ENSO) among others [1–6].

Colombia, due to some of the mentioned factors, is one of the countries with critical zones of high flash density [2,4,7]. To this lightning activity contributes its complex Andean mountain ranges and its geographical position between the Pacific and Atlantic oceans in the northwestern of South America. Due its location in the middle of the equatorial zone that drives thunderstorms, Colombia is subjected to the ENSO phenomenon and MCS variations.

The large lightning activity linked to Colombia could explain many of the accidents with fatal and nonfatal consequences, as reported for 2012 and 2013 [8,2]. Sadly, between 2003 and 2012 almost one out of two lightning accidents reported by the Direction of Integrity Preservation and Security of the Colombian Army (DIPSE) left a dead soldier hit by lightning [8]. An analysis is required to determine the circumstances in which these events occur and to propose lightning protection measures to reduce accidents.

In this paper, two scenarios previously reported in Ref. [3], are described, in which two lightning accidents caused by indirect lightning currents occurred in backcountry areas of Colombia. Both cases, located in the maps shown in Fig. 1, relate scenarios where two soldiers were injured by lightning currents. These accidents did not produce evident disabling conditions but palpable burn marks in the victims' skins.

2. Geographical information

The accidents of the two soldiers that were struck by lightning during military activities were initially reported in Ref. [3] and are complemented here with more precise geographical and lightning data. These traumatic events occurred in mountainous zones of the northern part of Colombia, as it is explain as follows.

Case A occurred in a foothill extension of *Cordillera Central* (Colombian central mountain range) known as "*Serranía de San Lucas*" – on the Santa Rosa del Sur municipality, Department of Bolivar – placed at 1900 m above mean sea level, during a rainy night. The *Serranía de San Lucas* is an isolated long mountain range with forested mountain massif being thus the northernmost part of *Cordillera Central* in northern Colombia. It makes part of the Magdalena-Urabá forests moist ecoregion. As it is shown in Fig. 1(c), according to Köppen-Geiger climate classification, *Serranía San Lucas* corresponds to a transition area between the tropical monsoon climate to the tropical rainforest (equatorial climate). The

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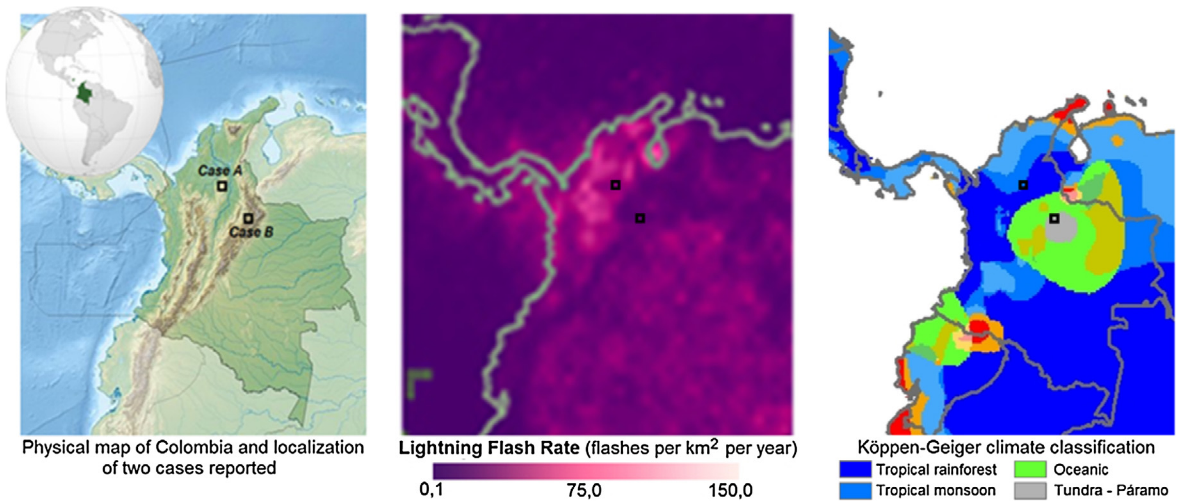

Fig. 1. Approximate location of the two nonfatal lightning accidents in a physical (a), lightning activity (b) and Köppen-Geiger climate classification (c) maps [3] (source: (a) adapted from wikimedia commons, (b) [9] and (c) [10]).

latter goes inside the Andean mountain range with local annual average temperatures driven by relief elevations.

Case B took place in the western side of the *Cordillera Oriental* (Colombian eastern mountain range) in the high altitude area known as "*Páramo de La Rusia*", on the border shared by Encino and Charalá municipalities, Department of Santander. Köppen-Geiger climate classification for this area corresponds to a transition between Tundra Climate and Oceanic Climate with strong altitude variations. The "*Guantiva-La Rusia*" Páramo complex has heights varying from 3100 m above sea level up to 4300 m above sea level. Due to the elevation, temperatures in the *páramo* can reach 0 °C and below, with low relative humidity.

According to lightning maps (Fig. 1(b)), it can be seen that the average atmospheric lightning activity is larger for the Case A than for the Case B. For the former case, the lightning flash rate is about 35 flashes per square kilometer per year while for the latter is around 15 flashes per square kilometer per year [9]. It is worth noting that the elevation in Case B is nearly 225% higher than in Case A.

3. Description of two accident scenarios

Lightning hazard increases during outdoor activities in open areas [2,11–14], such as leisure or recreational hiking, trekking, soccer, golf, farming, shepherding, but also military and security operations. In the case of Colombia, soldiers are continuously exposed to risk of lightning strikes in the accomplishment of their obligatory line of duty. The two case scenarios are presented below.

3.1. Case A: dug-out type shelter

For resting or protecting people from weather or from enemy attacks in military operations, trenches-like shelters are dug or semi-dug in the ground. Case A occurred at 19:15 h local time, placed on a top mountain of 1900 m above sea level with a temperate rainforest weather type, in a heavy rainy night. The victim was a 29-year-old sergeant of Colombian Army force resting in this type of excavated shelter. To isolate the shelter interior space from the ground moisture, the ground walls were covered with an outer layer of polyethylene film and terminated with wooden boards [3]. At the moment of the accident, the soldier was wearing an ornamental metallic necklace of gold alloy and had on his chest a portable communication unit. Fig. 2 presents the schematic of the scenario.

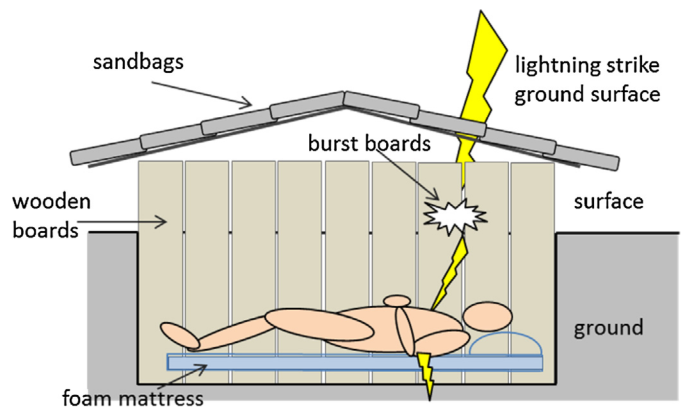

Fig. 2. Schematic representation of Case A, in which a soldier was resting inside of a semi-underground military shelter, which was struck by lightning.

According to GLD360 data of Vaisala, in the lapse of time between 19:00 h and 20:00 h on a radius of 20 km around the site, the area was struck at least by 27 strokes with currents between −57,8 kA and +88,9 kA as shown in Fig. 3 (Holle R., personal communication, October 20, 2016). According to the accident's local time reported and to the geographical uncertainties of the data set, the lightning flash current amplitude was identified as +88,9 kA.

Lightning struck directly on the ground surface circa 1 m from the shelter roof and the lightning current, instead of being dissipated on the surrounding ground, part of it flowed across the trench walls arrangement, breaking them and reaching the soldier's right side. The indirect lightning current left three diverted recognizable burn paths on the sergeant's skin, as shown in the photographs in Fig. 4. From these images, the indirect lightning current paths in the victim's body could be reconstructed. The lightning probably hits initially close to his right shoulder. Thereafter the current crossed superficially his right shoulder and was routed to the portable communication radio placed over the sergeant's torso and through the necklace he wore, ending at the elbow's area of his left arm. Fig. 4(a)–(f) shows the burns left by the lightning current on the soldier's body, on the necklace and on the sergeant's portable communication unit.

The necklace conducted a branch of the lightning current overheating it, burning around the soldier's neck, while it was melted and broken in small pieces, as it can be seen in Fig. 4(c). The overheated necklace left partial-thickness and full-thickness burns

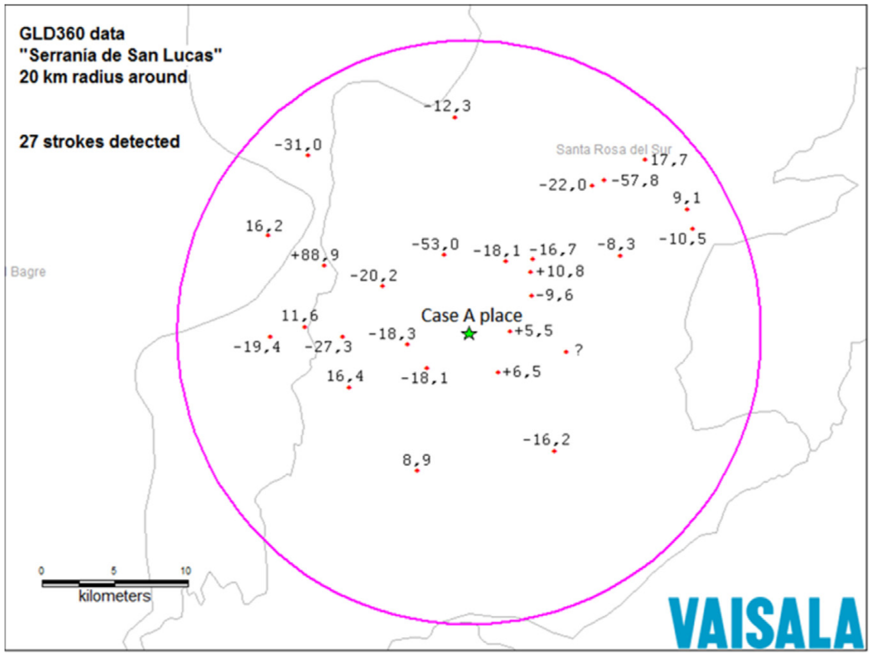

Fig. 3. GLD360 lightning data from Vaisala, in the lapse of time between 19:00 h and 20:00 h on a radius of 20 km around the reported place for Case A. This area was struck by at least by 27 lightning strokes with currents between −57,8 kA and +88,9 kA (Holle R., personal communication, October 20, 2016).

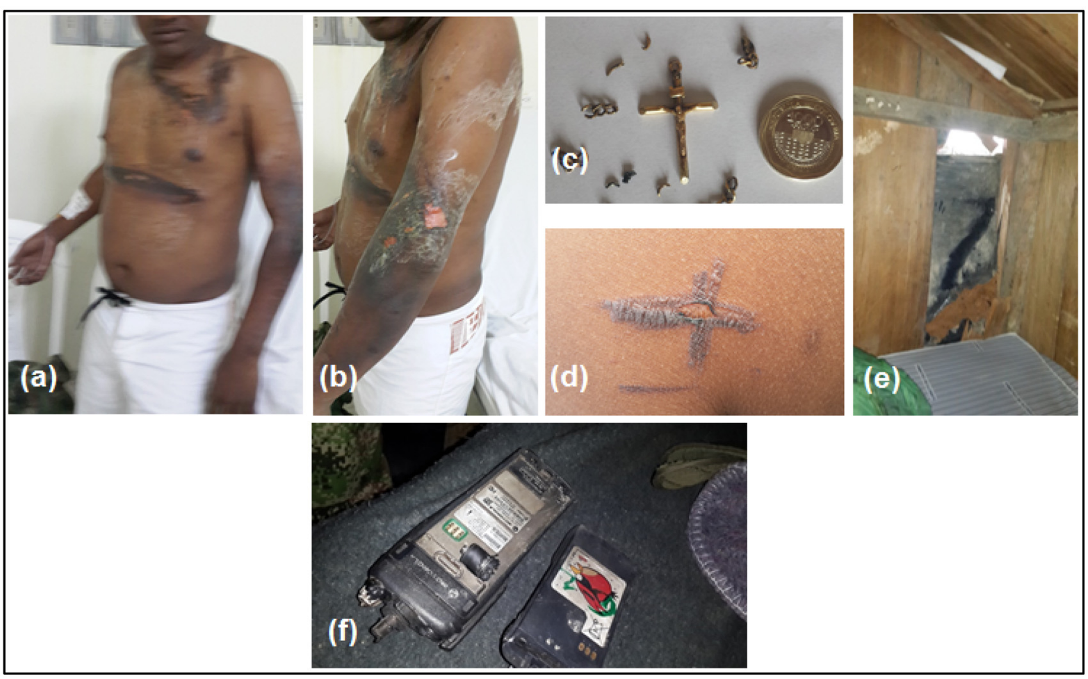

Fig. 4. Consequences of the lightning event in Case A: the current left superficial linear burn marks of the paths in the man's chest and neck (a), a full thickness burn in their left elbow (b), their metallic necklace burst in pieces (c), a burned cross tattoo in his skin (d) due to overheated cross pendant, the shelter condition after the lightning impact with burst wooden boards (e) and the burned soldier's communication radio (f).

around the victim's neck, leaving also a cross tattoo (of the cross pendant necklace) shown in Fig. 4(d) [14–16]. Finally, the current left the victim's body on his left hand side by the elbow, as it can be seen in Fig. 4(b).

The portable communication radio unit conducted also part of the lightning current, overheating it and leaving superficial linear burns on the soldier's chest [15] as well in the elbow region of his left arm leaving deep partial-thickness burns in the elbow proximal area [3]. The lightning current went to ground leaving the man's body through a foam mattress.

3.2. Case B: sandbag sentry box shelter

Case B occurred on March 4th, 2015 at 15:45, in the interior of a sandbag sentry box of a military fix base during a thunderstorm. This base was constructed to protect several telecommunication

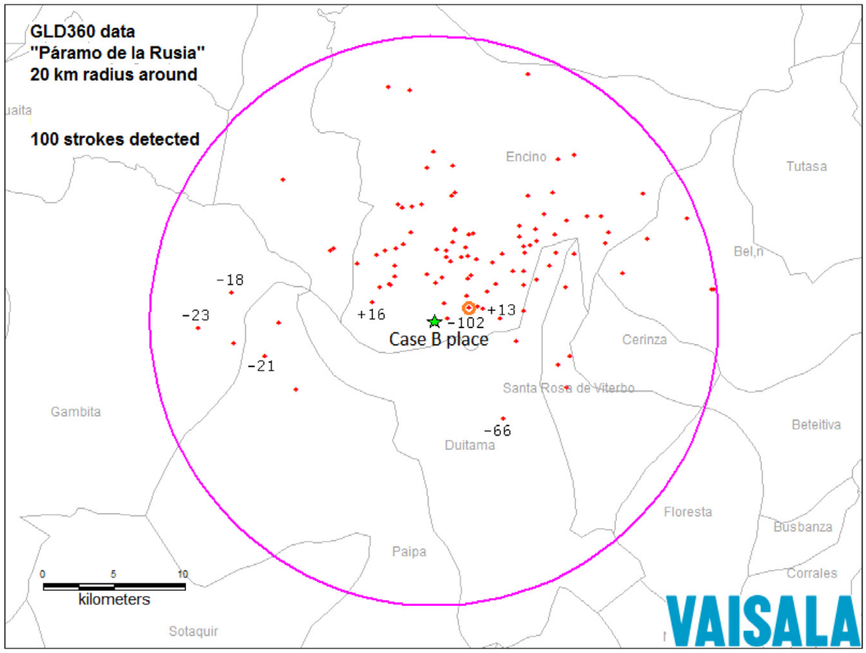

Fig. 5. Lightning strokes map for 20 km radius around the place reported for Case B. (Holle R., personal communication, October 20, 2016).

towers located on the hilltop of a 4.280 m altitude mountain. For this case, according to GLD360 data from Vaisala, between 15:00 h and 16:00 h on a radius of 20 km around the site, the area was struck at least by 100 strokes with currents between −101,7 kA and +24,1 kA, as shown in Fig. 5 (Holle R., personal communication, October 20, 2016).

The victim was a 28-year-old soldier wearing warm clothes (woolen scarf, sweat shirt, t-shirt, woolen sweater and jacket, used to endure the very low ambient temperatures of the high altitude location) and an institutional stainless steel ID necklace (ID dog tag type with ball chain). The "sandbag" shelter-type structure is used to protect soldiers from weather and enemy attacks. The roof was reinforced with a metallic roof plate supported by a timber structure, with an upper layer of more sandbags. Fig. 6 shows the recreation sketch of the related Case B accident scenario.

Lightning struck at the metal plate of the sandbag shelter roof with the soldier inside in declined sitting posture. The current flowed along the metal plate and across the sandbags wall until it reached the soldier's neck, leaving a burning hole in the man's scarf (see Fig. 6(d)), and flowing through the necklace. The instantaneous overheating of the necklace melts it, and left in the nape and chest of the soldier superficial and deep thickness linear burn marks. The melted necklace exploded in small pieces leaving most of overheated necklace small spheres remained on its sweatshirt (see Fig. 7(d)). The discharge path flowed from the necklace to the belt buckle and finally went out through his lateral right leg, below the knee, reaching the soldier's rifle.

As in Case A, the current discharge was superficial avoiding injuries or damage in the soldier's vital organs. Most of the lightning current branch was probably conducted along the metal necklace avoiding it to enter into the victim's body. The molten necklace caused puncture-like deep thickness burn marks on the soldier's skin, around the neck and in the left side of his chest, as it is indicated by the arrows in Fig. 7(b) and (c).

From the necklace, the indirect lightning current flows toward the belt buckle leaving linear burns between the chest and the waist and some superficial and deep burns in both the input and the output of the discharge. Moreover, a burned point in the area of its right kidney was left, close to a bag with metallic objects that the soldier was carrying [3].

4. Electric field numerical simulation for the dug-out type shelter

To calculate the electric field inside of a simplified model of the dug-out type shelter of Case A, the following conditions were taken into consideration: 1—based on the physical aspect of the actual scenario, it was assumed a lightning current strike located at 1,0 m from of the shelter wall and penetrating 0,2 m into the ground. 2—The lightning channel is assumed as a vertical 10 m long straight cylindrical source above the ground. 3—Polarization, ionization or plasma formation in the soil is not considered in spite of its possibility, neither in the main current channel nor in the discharge current paths. 4—The shelter area was simulated as a roofless cuboid-shaped air volume inside ground. 5—A single isotropic and homogeneous soil layer was considered.

Fig. 8 shows the dimensions of the simplified scenario of Case A which was numerically simulated using the transient solver of the computer program CST Microwave Studio. Fig. 8(a) and (b) shows the respective lateral and perspective views of the shelter model. Fig. 8(c) is a top view of the shelter while Fig. 8(d) shows a cross section along the lightning strike point. In this cross section, the electric field was calculated along 7 horizontal lines, which were plotted every 0,25 m from the earth surface to the bottom of the shelter.

The computer program CST was used to calculate the electric field distribution in the inner part of the shelter for a 100 kA, 10/350 μs current impulse. This current value is proposed by the lightning protection standard IEC 62305-1, level III scenario and was selected in spite of the fact that in the accident area, the lightning flash parameters may widely vary from the proposed in the standard [17]. In addition, the ground was modelled as a wet soil with an electric conductivity of σ = 0.01 S/m and relative permittivity of ε_r = 40. These values were taken considering the sandy-clay nature of the soil, its saturation with a water content of 50% (because the accident occurs in a rainy night) and from the

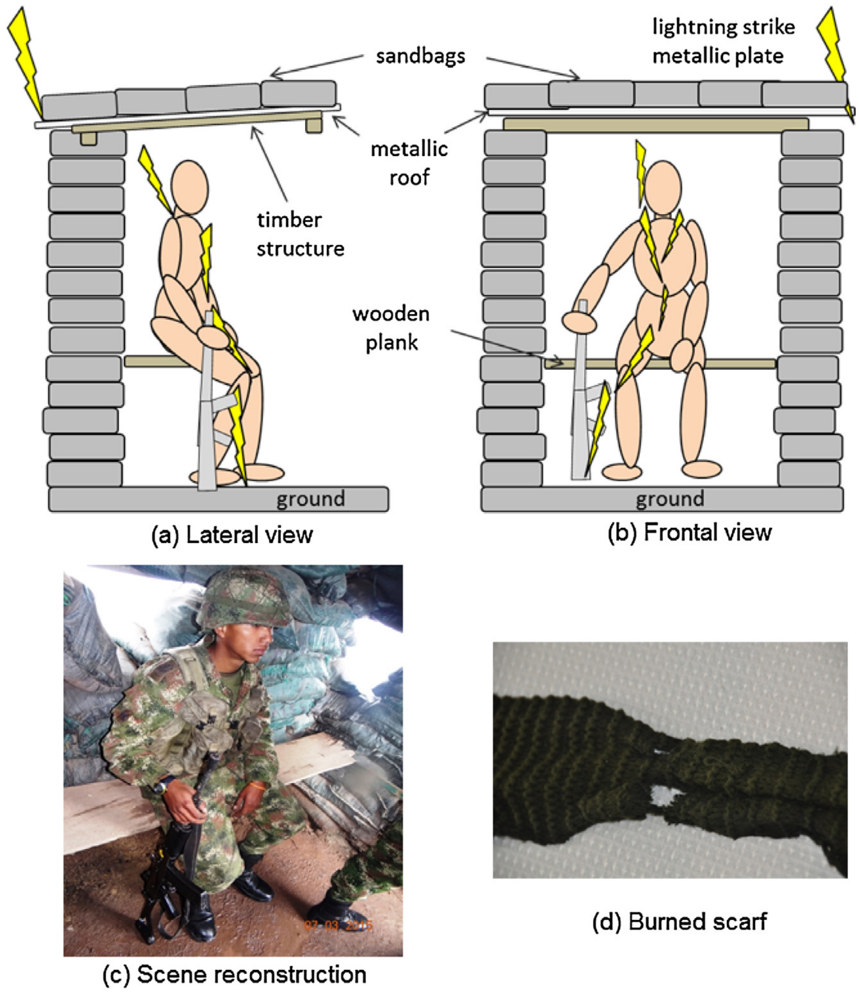

Fig. 6. Sketch recreation of Case B scenario in lateral (a) and frontal view (b) in which a man inside of a hilltop sandbag shelter was struck by a lightning where it is shown the flashover path. In (c) a soldier illustrates the victim's actual position and in (d) a detail of the burned scarf.

resistivity reference value for wet soil at 20 °C, according to the report REP-P.229-6-1990 of ITU (International Telecommunication Union) [18,19].

Fig. 9(a) shows the CST calculated electric field intensities produced by the lightning current inside the shelter while Fig. 9(b) shows the variation of the electric field along the horizontal lines showed in Fig. 8(d), as a function of the horizontal distance from the shelter wall. These results allow to estimate the regions in the shelter where the air breakdown electric field is exceeded.

Fig. 9(b) shows how at the shelter wall (length = 1 m), the electric field increases from the bottom to the surface. Particularly, electric field magnitudes of 900 kV/m were calculated at H = 0,75 m, the middle plane of the shelter wall were the victim was resting. This high electric field could easily initiate negative streamers at the shelter wall. The top view of the calculated electric field distribution is shown in Fig. 10(a). It can be observed in this figure that the highest electric fields are closer to the strike point. This result is also observed in Fig. 10(b) which corresponds to a perspective view of the electric field distribution inside the shelter for a constant height of 0,75 m.

Considering that a metallic object inside the shelter could modify the electric field distribution shown in Fig. 10(b), a 0,20 m diameter perfect conducting material (PEC) sphere was simulated inside the shelter. The metallic sphere was centered in the middle of the shelter as shown in Fig. 11(a).

Fig. 12(a) shows a top view of the CST calculated electric field at 0,75 m height measured from the shelter bottom. Fig. 12(b) and (c) presents the calculated values with and without a PEC sphere in a perspective view at H = 0,75 m. Comparing Fig. 10 with Fig. 12, it is noticeable the increase of the electric field due to the presence of the metallic object. That electric field increase can be observed in Fig. 13.

5. Electric field numerical simulation for the sentry box type shelter

The electric field calculation of sentry box shelter of Case B was also performed using a 100 kA, 10/350 μs current source and taking the conditions considered for Case A. Fig. 14 shows the dimensions of the simplified scenario model. The shelter roof was simulated as a perfect electric conductor material and the walls were assumed as made of sand with a conductivity of 5,0 mS/m, while the soil conductivity was assumed as 0,2 mS/m. As in Case A, the electric field distribution inside the sentry box was calculated with and without a 0,2 m diameter PEC sphere.

Fig. 15 shows the electric field magnitudes obtained for two simulation conditions: empty sentry box and sentry box with a perfect electric conductor sphere in its center. Inside the shelter without sphere, the electric field reaches more than 30 MV/m and with sphere is intensified above to 50 MV/m. It is noticeable the

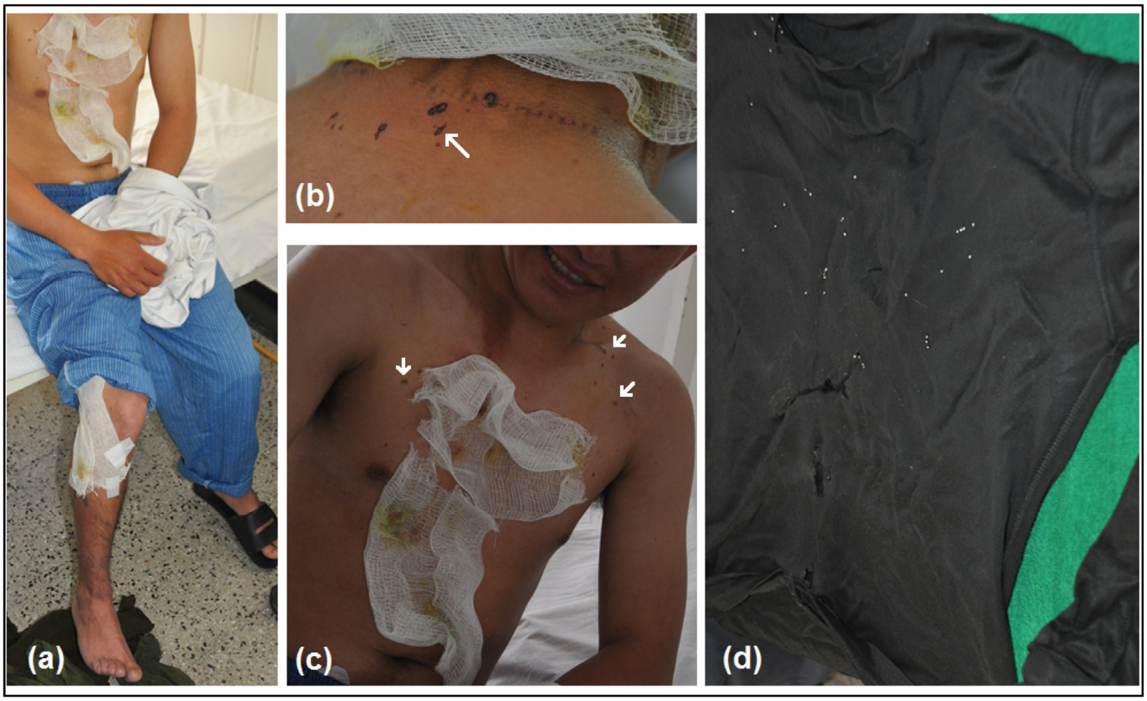

Fig. 7. Consequences of the lightning event in Case B: burns in the victim's trunk and right lower limb (a) and in his nape (b) and chest (c). The indirect lightning current flowed through his necklace, reaching the buckle belt and went out below its right knee. Note the puncture-like burned marks in the nape area and chest in (b) and (c) due to the overheated metal necklace spheres remained trapped inside the soldier's sweatshirt (d).

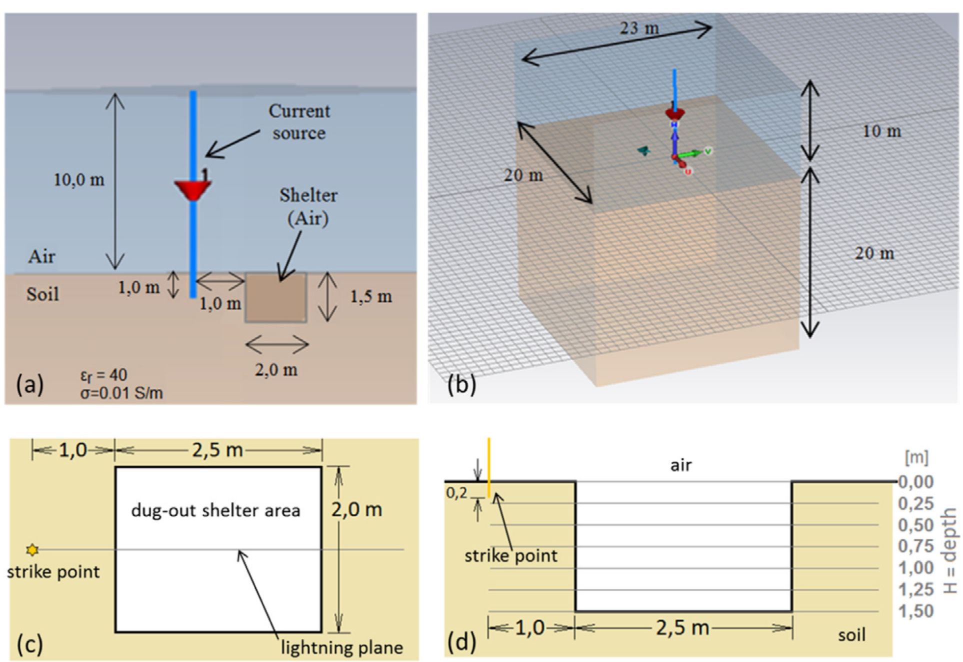

Fig. 8. Simplified scenario of Case A to calculate the electric field produced by a lightning discharge with the transient solver of the computer program CST Microwave Studio. A side view of the simulated scenario is shown in (a), the prospective view is shown in (b), and a top view is shown in (c). The cross sectional view along the Lightning strike point is shown in (d). Electric field was calculated along the parallel horizontal lines separated 0.25 m and plotted from the earth surface to the shelter bottom at 1,5 m.

20 MV/m increase in the electric field due to the presence of the metallic sphere inside the shelter.

6. Discussion

The most evident injuries and wounds caused by lightning are visible burns. They can be subdivided into five main categories: linear burns, punctate burns, feathering or flowers (as Lichtenberg figures), thermal burns from ignited clothing or contact with overheated objects, and combinations [14,20].

In Case A, as it can be seen in the reported photographs, lightning currents cause linear burns due to the flash vaporization of water, of the moisture and sweat, into steam in an evaporation flashover process [13]. Also, the current effect left thermal burns by con-

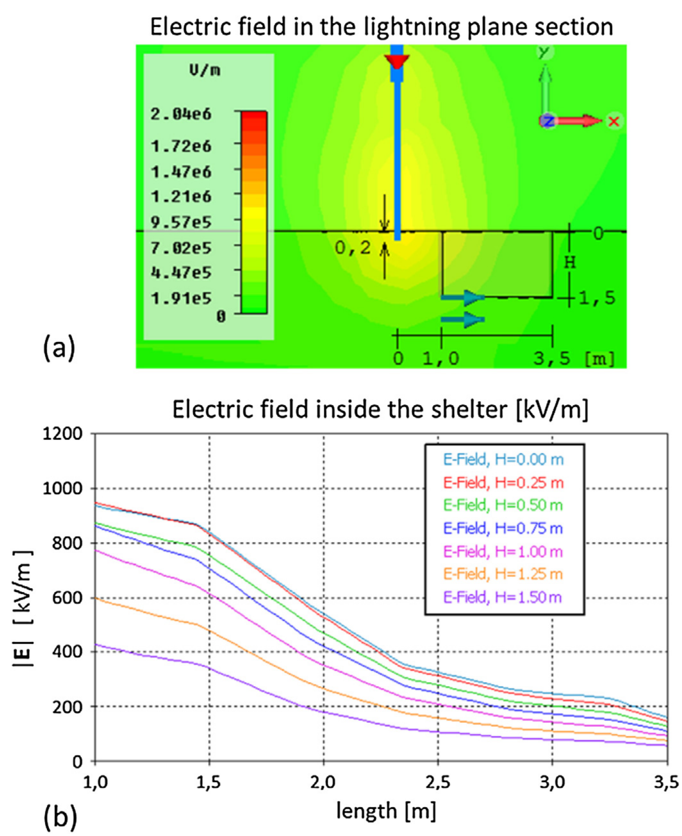

Fig. 9. (a) CST calculated electric field intensities produced by a 100 kA, 10/350 μs lightning current inside the shelter in the lightning plane and (b) variation of the calculated electric field along the horizontal lines shown in Fig. 8(d). Notice the calculated electric field magnitudes of several hundreds of kV/m obtained at the shelter wall. These fields could initiate streamers inside the shelter.

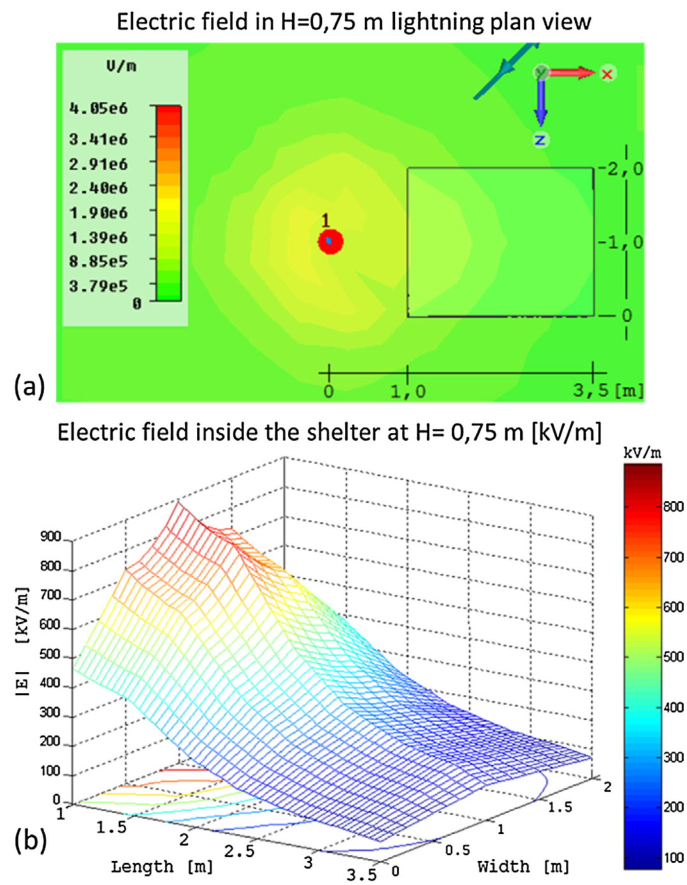

Fig. 10. (a) Top view of the CST calculated electric field intensities inside the shelter at a height 0,75 m from the bottom produced by a 100 kA, 10/350 μs current impulse. (b) Prospective view of the electric field distribution inside the shelter for a constant height of 0,75 m. Calculations were performed for a wet soil ($\varepsilon_r = 40$; $\sigma = 0.01$ S/m). Notice that the highest electric field in the wall at 0,75 m is almost 900 kV/m. This high electric field value could initiate negative streamers in the shelter wall.

tact, between the skin and the overheated necklace and pendant, producing superficial and deep thickness burns.

In Case B, due to the low temperature and humidity content of the environment at the high altitude accident scenario, the sweat and moisture of the man's body is low. Then, linear burns marked in the man's skin, because of a flashover path directed by the necklace toward the metallic belt buckle and finally toward the right knee area, close to the rifle. Thus, thermal burns by contact were produced in the victim's skin leaving superficial partial thickness marks by the overheated necklace, and later, after it burst, punctate-like deep partial thickness burns left by the overheated small spheres trapped between the sweatshirt and the skin.

Both accidents reported have several similarities. In these two cases, soldiers wore metallic necklaces that melted after conducting large indirect lightning currents. This fact could force the lightning current to flow superficially, avoiding it to enter into the victim's bodies. In both Cases A and B, a possible coupling mechanism between the lightning current and the victim's body was a side flash. However, in Case A, the possible flashover between the metallic necklace and the shelter walls could be due to an electric field enhancement caused by the lightning current on the shelter boundaries.

According to the simulation results for Case A, the electric field at the shelter wall was about 900 kV/m. This high electric field could initiate negative streamers. In spite of this, for electric field calculation, soil breakdown was not considered. Knowing that the critical breakdown field is about 600 kV/m for the sand-clay soil type and 300 kV/m for a soil with 0,01 S/m of conductivity [18], soil breakdown could be expected. This effect is more critical in the case when a metallic sphere is located inside the shelter. This sphere produces an electric field enhancement rising to *circa* 3000 kV/m, which is the air breakdown electric field for homogeneous conditions.

On the other hand, the earth potential rise could be enough to produce an electric discharge on the shelter bottom soil. Considering the electric field at the bottom of the shelter at 1,5 m depth in Fig. 11(b), a differential of electric field between the opposite shelter walls is about 300 kV/m. This electric field amplitude could initiate a discharge process in the soil, but it is not be enough to produce a discharge in the air.

Large caves and valleys seem lightning protective, but small caves, overhangs and wet stream beds may be more dangerous than open areas [11]. In the literature reviewed, a case was reported in which the survivor was 'paralyzed from the neck down' so that a side flash from the wall of the cave must be held responsible [21]. According to the numerical simulation results from the Case A, the space inside of a dug shelter is not a safe place against lightning currents, because of the internal electric field intensification. The change of dielectric properties in the interface soil-air, increases the electric field in air region. In the interface wet soil and air, the electric field intensification could give more than 500 kV/m, able to initiate hazardous streamers coming out from the shelter walls when lightning hits the nearby ground. This effect is suggested by the calculated electric field inside the shelter, shown in Figs. 7 and 8, in which the absolute value is larger in the interface soil–air. However, it is required further investigation considering also the soil potential rise and the change in electric character-

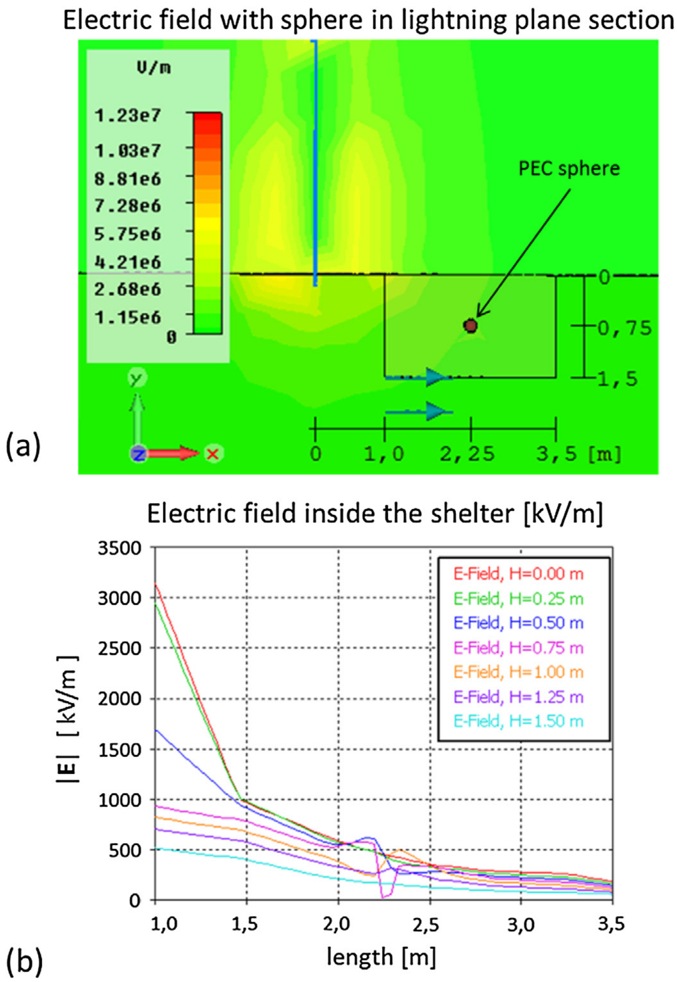

Fig. 11. (a) CST calculated electric field intensities produced by a 100 kA, 10/350 μs lightning current inside the shelter in the lightning plane, when a 0,20 m diameter metallic sphere (PEC sphere) is placed in the middle of the shelter. (b) shows the variation of the calculated electric field along the horizontal lines shown in Fig. 8(d), but including the metallic sphere. Notice that the magnitudes of the electric field at the shelter wall increase almost three times when compared with the calculated values shown in Fig. 9(b).

istics of the ground due to the soil ionization. It is important to consider also the effect of the atmospheric conditions on the air dielectric strength. For an example, in the event of Case A, which was located at 1900 m above the sea level, the air losses about 9% of its dielectric strength at normal conditions, while in the Case B, located at 4300 m above sea level, a reduction of 32% in the dielectric strength is expected [22]. Moreover, the electric field could be intensified around non-grounded metallic elements inside, such as the soldiers' necklaces acting as floating electrodes, made clear in the simulation of Case B scenario.

In the technical literature [16,23–25] and other media [26–28], there are some other reported cases of nonfatal lightning accidents involving persons wearing metallic objects that could dissipate part of lightning energy. However, to understand the consequences of this fact on lightning protection of people, military installations, underground and outdoor shelters, further research work must be performed.

Thus, the mechanism of lightning trauma for Case A may also be considered as earth potential rise (EPR) or step voltage according to presented in Ref. [12] for shallow caves. In this case, a superficial arc discharge may appear caused by the spreading of lightning current into the ground. Such a trauma event is more likely to occur to a person sheltering inside on a shallow cave in a mountainside, small cliff or outcropping of terrain, that feels has achieved some degree of safety [12]. However, in this case it seems more accurate to consider side flash as the injury mechanism instead of earth potential rise, given by the evidence of a flashover or an arc discharge.

The simulation about Case B shows that floating electrodes, as the ungrounded metallic sheet used as roof, could intensified the electric field below it far above hazardous levels. There are some other reported cases linked to floating electrodes, such as ungrounded metallic roofs or structures [21,29,30], involving multiple injured persons with fatal and nonfatal consequences. Shelters with electrically isolated metallic roofs (as sentry boxes, newsstands, kiosks, gazebos or rotundas) are not safe against lightning discharges.

Although there are no completely safe places against lightning, outdoors, hilltops, mountainside, or similar areas of high lightning risk should be avoided when choosing the site for the shelter in order to reduce the probability of strike and consequent hazard for the personnel [31]. Nevertheless, lightning can strike the ground in open backcountry areas even close of tall objects as tree lines. It all depends on where the charges accumulate [32]. A best way to avoid hazards is to check and to use reliable weather service as well forecasts and lightning statistical information about the target place to adequate risk assessment [33].

For any outdoor activity the balance between the risk of being struck by lightning and the inconvenience needed to be safe always must be considered. On the other hand, there is a tendency to underestimate the hazards associated with lightning and the threads derived from the lack of sufficient and accurate knowledge about it, particularly since people often make decisions based on previous personal experiences where they were involved in unsafe activities without being struck by lightning [34]. Also, due to that feeling of underestimate the risk at the beginning and at the end of a thunderstorm, it is very important to have in mind that just that time becomes in more dangerous [11,35–37].

7. Conclusions

Two nonfatal lightning accidents were reported and analyzed in which the indirect lightning current was guided superficially by metallic necklaces avoiding current flow into the victims' bodies. In both cases, the coupling mechanism between the lightning currents and the victims were side flashes. Due to this mechanism, the current split between both the victim's bodies and the earth. In both cases a large current flowed through the metallic necklaces, melting and bursting them, albeit were just a fraction of the total lightning current. As presented in numerical simulation for a dug-out type refuge, when a lightning hits the ground surface close to it, the electric field inside is intensified and could be able to reach the streamers-onset electric field. This suggests that this type of shelter excavated in the ground is not safe against lightning currents. The simulation results of the sentry box type shelter showed that the electric field is also intensified above hazardous levels inside the structure due to the presence of an ungrounded metallic sheet used as roof, which acts as a floating electrode.

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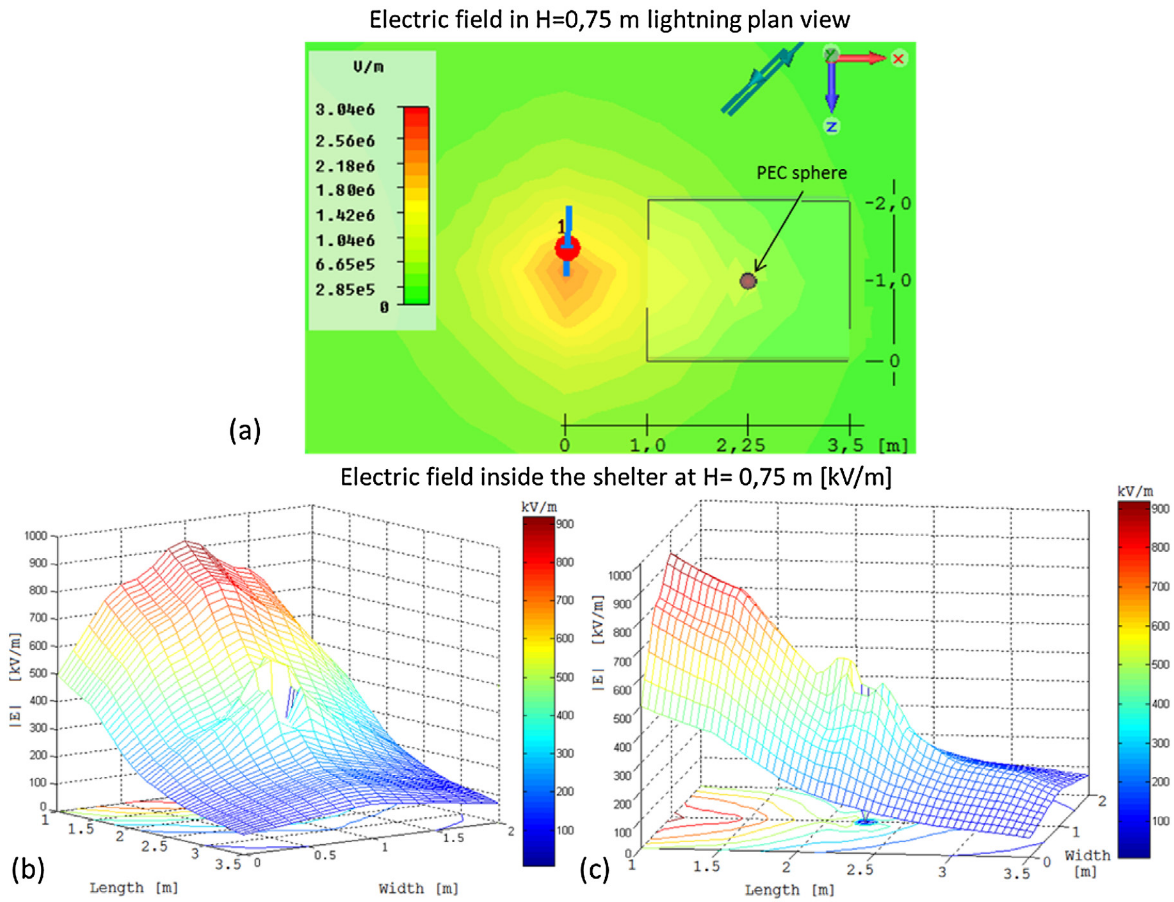

Fig. 12. (a) CST calculated electric field intensities produced by a 100 kA, 10/350 μs current impulse, when a metallic sphere is placed in the center of the shelter at 0,75 m from the bottom; (b) and (c) are perspective views of the same calculated electric field inside the shelter at 0,75 m from the shelter bottom.

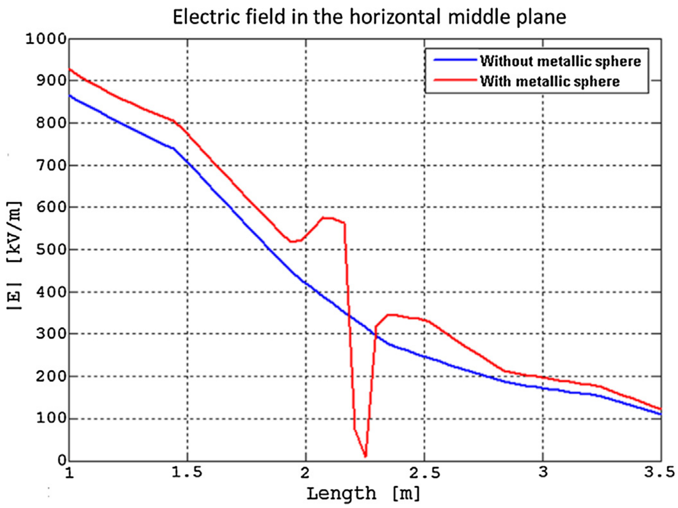

Fig. 13. CST calculated electric field intensities inside the shelter at 0,75 m from the bottom produced by a 100 kA, 10/350 μs current impulse, with and without a metallic sphere. Notice the electric field enhancement except inside the sphere placed in the middle of the shelter, where its value is zero.

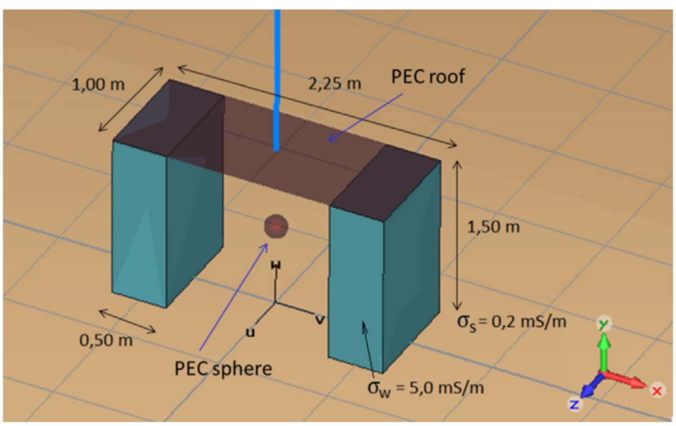

Fig. 14. Simulation setup of the sentry box type shelter for the CST electric field calculation.

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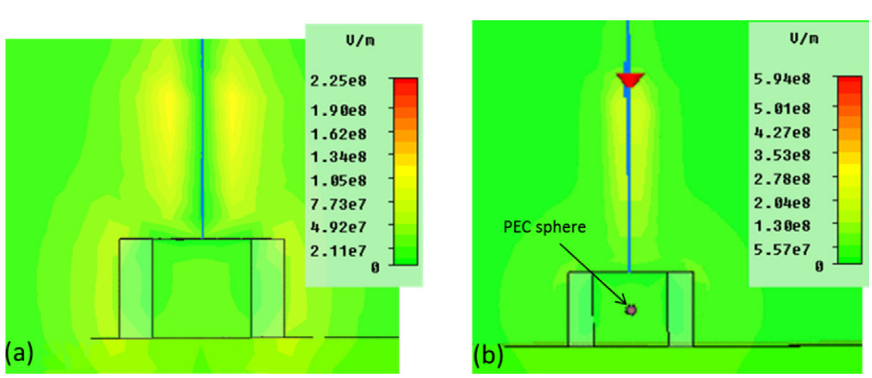

Fig. 15. CST electric field calculation produced by a 100 kA, 10/350 μs current impulse for an empty sentry box (a) and a sentry box with a perfect electric conductor (PEC) sphere inside (b). Note the strong intensification of the absolute value of the electric field due to the PEC sphere.

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