Simulation of corona at lightning-triggering wire: Current, charge transfer, and the field-reduction effect

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[1] We have examined, using the finite difference time domain (FDTD) method for solving discretized Maxwell's equations, the effect of upward extending wire, used for artificial lightning initiation from natural thunderclouds, and corona space charge emanated from this wire on the close ground-level electric field (prior to lightning initiation). The wire current and charge transfer are also estimated. The lightning-triggering wire is assumed to be perfectly conducting and extending vertically upward with a constant speed of v = 150 m/s. Owing to the limitations of the FDTD method, the wire radius is set to r = 0.27 m, larger than the actual radius (0.1 mm), but the results are not expected to be much influenced by this assumption. The corona space charge that emanated from the wire surface is represented by a conducting cylindrical sheath of outer radius r = 2, 4, 8, and 16 m, coaxial with the wire (the dynamics of corona discharge are not considered here). Other geometries of the corona space charge sheath are considered as well. It has been found that the results presented here are insensitive to the value of corona sheath conductivity ranging from 10^{-8} S/m to infinity. The corona space charge layer at the ground is simulated by perfectly conducting cylindrical tubes placed on the ground surface, coaxial with the upward extending conductor. The quasi-static electric field between the thundercloud charge source and the ground is simulated by creating a quasi-uniform, upward directed electric field of 43 kV/m between two parallel conducting plates limiting the FDTD computational domain. The simulated corona space charge at the ground reduced the electric field at the ground surface to 5.5 kV/m, a typical value at the time of rocket launch. The upward directed electric field E_z on the ground surface in the vicinity of triggering wire decreases with increasing the altitude of the wire top. When the wire-top altitude is 200 m, the reduction of E_z at horizontal distance d = 60 m is about 17, 26, 31, 40, and 52% relative to the background value of 5.5 kV/m for r = 0.27, 2, 4, 8, and 16 m, respectively, while the corresponding reduction of E_z at d = 360 m in all cases is only 1% or less. The calculated results for $r \approx 4$ to 16 m agree reasonably well with E_z variations measured at d = 60 and 350 m from the triggering wire by *Biagi et al.* (2011). This indicates that the electric field reduction in the vicinity of triggering wire, prior to lightning initiation, is primarily caused by the presence of corona space charge emanated from the wire to a radius of about 4 m or more, as opposed to the presence of wire alone. The total charge transfer from the ground to the wire (whose top is at an altitude of 200 m) is 1.2, 4.5, 6.6, 9.5, and 14 mC for r = 0.27, 2, 4, 8, and 16 m, respectively. The corresponding currents flowing in the wire are 2.1, 7.9, 11, 15, and 22 mA. The model-predicted charges and currents for r = 2 to 4 m are consistent with limited measurements available in the literature, smaller than the values based on the field-reduction calculations, but still of the order of meters. The radial electric field near the top of 200 m high cylindrical conductor can exceed 400 kV/m (which is sufficient for positive streamer propagation) when its radius is up to 8 m, confirming corona sheath radii of the order of meters inferred from the field-reduction and wire charge/current analyses.

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1. Introduction

[2] The artificial triggering of a lightning discharge from a natural thundercloud to a designated point on ground by means of the so-called rocket-and-wire technique [e.g., *Newman et al.*, 1967; *Fieux et al.*, 1975; *Rakov and Uman*,

2003] has been used for studying various lightning processes and effects and for testing various lightning models and lightning locating systems.

[3] The classical triggering involves the launching of a small rocket extending a grounded thin wire toward the charged cloud overhead. The triggering rocket is usually launched when the absolute value of vertical electric field at ground level is 4 to 10 kV/m, which indicates favorable conditions for negative lightning initiation (at least for negative lightning in Florida). When the rocket, ascending at a speed of 150 to 200 m/s, is at an altitude of 200 to 300 m, the electric field enhancement near the rocket tip launches an upward positive leader. This upward positive leader vaporizes the trailing wire, bridges the gap between the cloud charge source and ground, and establishes an initial continuous current. The upward positive leader and initial continuous current constitute the initial stage of a classical triggered lightning discharge. After the cessation of the initial continuous current, usually one or more downward dart leader/upward return stroke sequences traverse the same path to the triggering facility.

[4] *Standler* [1975], working in New Mexico (at an altitude of about 3.2 km above sea level), measured the upward directed electric field on the ground surface at a close distance (not specified, but about 100 m according to W. Winn (personal communication, 2011)) from the upward extending grounded triggering wire and the corresponding current at the bottom of the wire. These measurements were obtained in 1974 for one event only. The rocket was launched at an elevation angle of 68°. No accurate rocket trajectory is available. The electric field decreased by about 60%, from about 10 kV/m at the time of rocket launch to about 4 kV/m just prior to lightning triggering. The current measured at the bottom of the triggering wire was about 50 μA at 5.4 s after the launch (the corresponding estimated rocket altitude was 400 m), and increased to about 10 mA at 7.6 s after the launch (the corresponding estimated rocket altitude was 550 m). The positive charge transfer from the ground to the wire was 11.4 mC. The expected nominal rocket speed was 80 m/s. The observed electric field reduction was attributed to glow corona on the wire.

[5] *Fieux et al.* [1978] have reported, from their measurements in France (at an altitude of about 1.1 km above sea level), that the upward directed electric field on the ground surface at a distance of 100 m from the triggering wire decreased by about 50% in 0.65 s, from about 3 kV/m at the time of rocket launch to about 1.5 kV/m just prior to lightning initiation. If we assume a constant rocket speed of 180 m/s, the corresponding rocket altitude will be 117 m. The corresponding current was not reported. The field reduction was attributed to corona on the wire with a possible contribution from the charge produced by the rocket exhaust.

[6] *Nakamura et al.* [1987] have measured, at Kahokugata reclaimed land (at sea level) in Japan, the upward or downward directed electric field on the ground surface at distance d = 40 or 57 m from the triggering wire (prior to lightning initiation) along with the corresponding current at the bottom of the wire for several events in 1979 to 1982. The electric fields decreased with increasing the wire-top height. For example, the magnitudes of electric fields at d = 57 m for two events reduced from 5.7 kV/m to 3.9 kV/m (about 30% reduction) and from 7.4 kV/m to 1.6 kV/m (about 80% reduction) when the wire top attained an altitude of 200 m [see *Nakamura et al.*, 1987, Figure 12]. In the latter event, the electric field decreased to zero when the wire top attained an altitude of about 230 m. In another event, the polarity of the electric field measured at d = 40 m changed. The slowly varying currents measured at the bottom of the triggering wire were up to 5 to 10 mA. *Horii and Sakurano* [1985] and *Horii and Ikeda* [1985], from their measurements of current at the bottom of triggering wire at the same site, found that the current increased from about 1 μA to about 10 mA with increasing the wire length, prior to lightning initiation. There were tens of amperes scale pulses (similar pulses were also observed by *Standler* [1975]) superimposed on the later part of the slowly varying current. These pulses were accompanied by faint light emissions at the wire top and were later termed "precursors" by *Willett et al.* [1999]. Further, *Nakamura et al.* [1987] used the charge simulation method (CSM) [e.g., *Steinbigler*, 1969] to compute the electric field at ground versus the length of triggering wire assuming that the charge transfer to the wire (found by integrating measured current) was distributed within 1 or 4 m radius cylinder simulating the corona sheath surrounding the wire. They have shown for two events that the CSM-calculated electric field reduction at d = 40 m agrees well with corresponding measured electric field reduction. In contrast, the calculated electric field reduction, 13%, for the case of wire without corona at d = 57 m for the triggering wire length equal to 200 m was considerably smaller than observed for most of the events.

[7] *Liu et al.* [1994, Figure 2], working in Gansu province (at an altitude of about 2.7 km above sea level), China, have measured about 3.5 to 4 kV/m decrease in downward directed electric field on the ground surface at d = 75 m from the triggering wire, about 3 s from the launch (when the rocket altitude was 400 m). The corresponding current was not reported. The electric field change was measured using a system with a decay time constant of 6.8 s, so that the actual field change should be larger. The initial field at the time of launch was 4.4 kV/m, which implies about 100% field reduction prior to lightning initiation.

[8] *Willett et al.* [1999] have measured, in Florida (at sea level), about 8 kV/m decrease in upward directed electric field on the ground surface at $d \approx 30$ m from the triggering wire over a time period of 2.22 s from the launch to the upward positive leader onset, when the wire-top height was 307 m. The electric field at the time of launch was about 7 kV/m, so that the field changed polarity, prior to lightning initiation. The corresponding current measured at the bottom of the triggering wire for this and 8 other triggered-lightning flashes presented by Willett et al. never exceeded the lower measurement limit of 9 mA.

[9] *Biagi et al.* [2011], from their measurements for six flashes in Florida (at sea level), have shown that the upward directed electric field on the ground surface at d = 60 m from the triggering wire decreased (prior to lightning initiation) by 1.7 to 3.4 kV/m (about 30 to 75%) with increasing the rocket altitude from nearly zero to 118–304 m (see Figure 1a), while the simultaneously measured field at d = 350 m decreases by about 8% at most (see Figure 1b). The wire-extending rockets were launched when the ground-level electric fields were 3.2 to 7.6 kV/m. The lower current

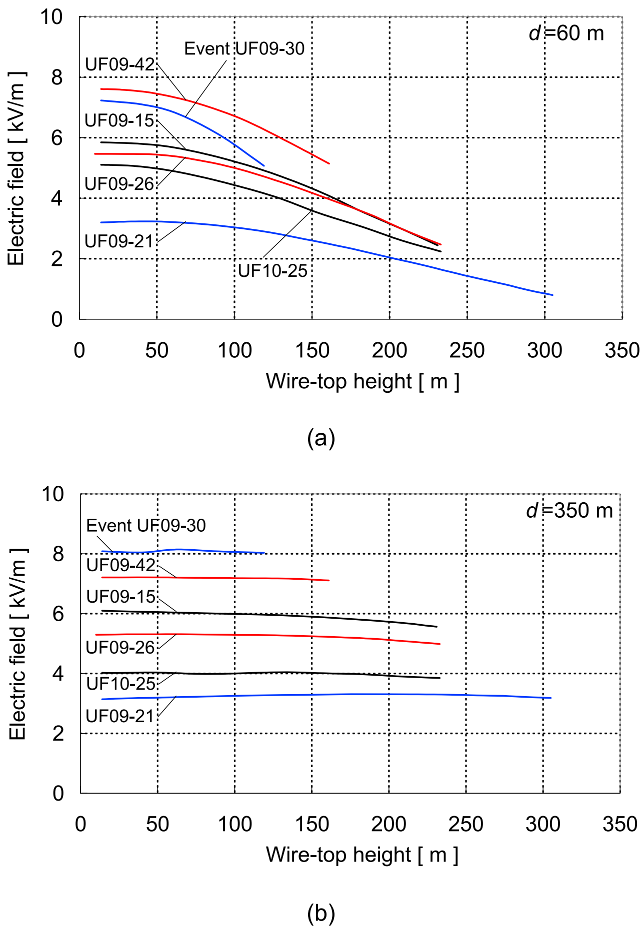

Figure 1. Variations of vertical electric field E_z (prior to lightning initiation) as a function of wire-top height (h) measured at (a) d = 60 and (b) d = 350 m from the triggering wire for six events studied by *Biagi et al.* [2011]. The same field variations, but in percent and as a function of h/d for direct comparison with other measurements found in the literature, are also shown in Figure 2a.

measurement limit was 1 A, so no currents in the microamperes to milliamperes ranges could be measured. For four of the six events the wire-top height was more than 200 m, and the field changes at the time when the rocket height was equal to 200 m were 35 to 50%. We will use these four events for evaluating our model predictions.

[10] Figure 2 summarizes variations of vertical electric field (in percent), relative to its prelaunch value measured on the ground surface in the vicinity of upward extending triggering wire as a function of h/d, where h is the wire-top height and d is the horizontal distance between the wire and the electric field observation point. As seen in Figure 2, close vertical electric field tends to decrease with increasing the h/d ratio, although the spread of curves is very large, even for the same experimental site. In some cases, the decrease approaches and even exceeds 100%.

[11] *Rizk* [2011] has proposed a semiempirical (engineering) model of corona emanated from the grounded lightning-triggering wire for studying critical conditions for triggering. The corona current is expressed as a function of rocket altitude, rocket speed, and ground-level electric field at the time of launch. The charge per unit length at different heights along the triggering wire is given as a function of rocket speed and ground-level electric field. The model apparently does not yield any specific spatial distribution of corona space charge, but four different possibilities are discussed: (1) corona space charge is concentrated on the surface of triggering wire (this actually means no corona sheath), (2) it is concentrated on a cylindrical shell at the outer boundary of the corona sheath, (3) its radial distribution is uniform within the corona sheath, and (4) its volume density is inversely proportional to the radial distance from the triggering wire axis. According to Rizk, the latter "yields most satisfactory results" in his analysis. His model predictions for ground-level electric field reduction due to corona on the extending triggering wire range from 13 to 38%, relative to the field at the time of rocket launch, for eleven cases simulating the experiments in New Mexico [*Standler*, 1975; *Hubert et al.*, 1984], France [*Fieux et al.*,

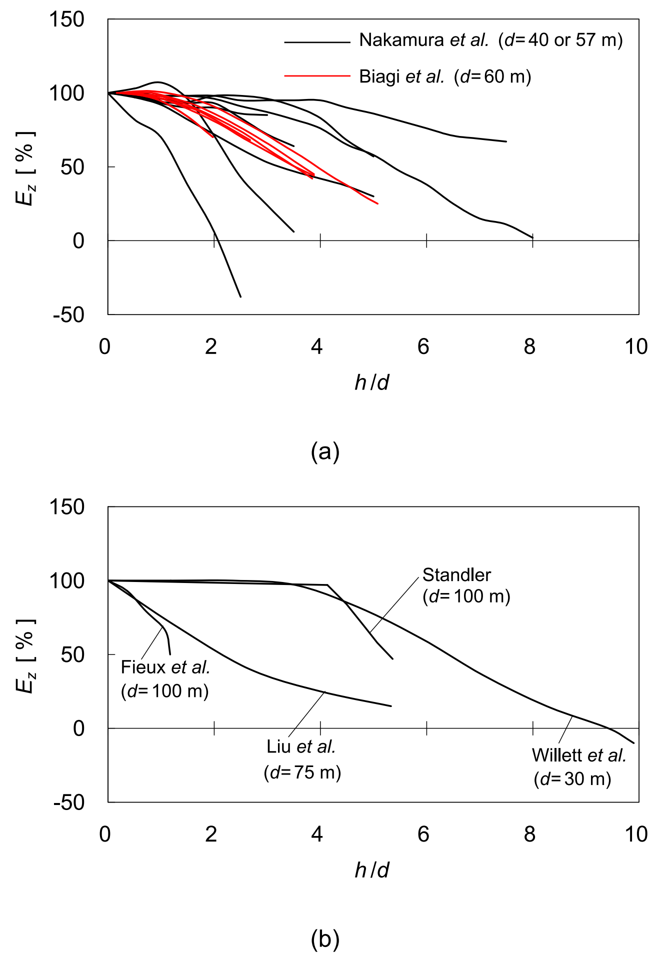

Figure 2. Measured variations of vertical electric field E_z (in percent) relative to its value at the time of rocket launch on the ground surface in the vicinity of upward extending triggering wire (prior to lightning initiation) as a function of the ratio of wire-top height and horizontal distance between the wire and the field observation point. (a) E_z measured by *Nakamura et al.* [1987] and *Biagi et al.* [2011]. (b) E_z measured by *Standler* [1975], *Fieux et al.* [1978], *Liu et al.* [1994], and *Willett et al.* [1999].

1978], and Florida [*Willett et al.*, 1999]. The model was also used to estimate total corona charge transfers and corresponding currents for different experiments, ranging from 1.63 to 12.6 mC and from 3.5 to 9.6 mA, respectively. Additionally, *Rizk* [2011] showed that for a 0.2 mm diameter triggering wire and ground-level electric fields above 3.5 kV/m the corona onset electric field is exceeded on the surface of the wire almost immediately after the rocket rises above the launcher.

[12] The observations and computations reviewed above indicate that the reduction of ground-level electric field in the vicinity of upward extending grounded triggering wire is related to corona charge released from the wire. However, the radial extent of corona space charge and its effects on the reduction of ground-level electric field, as well as on the wire current and charge transfer, are presently unknown.

[13] In this paper, using the finite difference time domain (FDTD) method [*Yee*, 1966] for solving discretized Maxwell's equations, we examine the effect of upward extending triggering grounded wire and the corona space charge emanated from this wire on the close electric field on the ground surface. Further, we evaluate the charge transfer from the ground to the wire surface and the corona sheath and the corresponding current, each as a function of wire-top height. The computed results will be compared to observations found in the literature in an attempt to infer the radial extent of the triggering–wire corona sheath.

2. General Approach

[14] It is known that a tall metallic object serves to reduce the ground-level electric field in its vicinity [*Baba and Rakov*, 2007, p. 637; *Mosaddeghi et al.*, 2009]. This effect can be explained in terms of the electric field boundary condition on the surface of a good conductor, which requires that the tangential component of electric field there vanishes. Thus, as the observation point is moved closer to the metallic object, the vertical electric field will decrease to become zero at the surface of the object. This can be viewed as an object shielding effect that should also occur in the case of upward extending, grounded triggering wire. The vanishing tangential component of electric field on the conductor surface means that this surface is equipotential, which, in the presence of external electric field, requires conductor polarization, in a sense that charges of opposite polarity accumulate at the upper end of the conductor and the lower end of its image. For the case of predominantly negative charge overhead, positive charge will move from the ground to the triggering wire, with the largest line charge density being near the wire top. This positive charge, electrostatically induced on the wire, will produce the electric field on the ground surface whose direction is opposite to that of the electric field from the negative charge overhead. Thus, the triggering-wire shielding effect can be viewed as being a result of the electric field of induced charges that opposes the field of overhead cloud charges.

[15] When the electric field intensity (normal component) on the surface of triggering wire exceeds the corona onset value, some charge induced on the wire will be pushed to the surrounding air, creating a corona space charge sheath there. As noted in section 1, *Rizk* [2011] showed that conditions for the corona onset on a triggering wire are satisfied almost immediately after the wire-extending rocket leaves the launching facility. Both the charge on the wire surface and the space charge in the surrounding air will contribute to the wire shielding effect (reduction of ground-level electric field). Further, when the triggering wire length exceeds 100 m or so, additional space charge will be injected into the region above the wire top by so-called precursors [*Willett et al.*, 1999], which can be viewed as aborted upward positive leaders or, perhaps, as particularly intense (impulse) corona streamers. Although the precursors are transients superimposed on "steady state" glow corona, we will not distinguish between these two processes, assuming that their net effect is the same: production of space charge causing reduction of ground-level electric field.

[16] It is also known that under thunderstorm conditions the corona onset electric field is exceeded at various sharp points that always exist at the ground surface, before the rocket extending the triggering wire is launched. As a result, the triggering wire is pulled through a layer of positive space charge of some hundreds of meters in vertical extent. Similarly to the corona space charge originated from the wire surface, the corona space charge layer near ground (sometimes referred to as "bush corona" [*Rizk*, 2011]) serves to reduce the ground-level electric field of overhead cloud charges. It also makes the vertical electric field profile nonuniform, increasing from 5 to 10 kV/m at ground level to some tens of kV/m at an altitude of several hundreds of meters above ground [e.g., *Soula and Chauzy*, 1991; *Willett et al.*, 1999]. The corona space charge layer near ground serves to enhance the electric field intensity above its upper boundary (although this boundary is not sharp and the space charge layer can even extend into the cloud) [*Chauzy and Soula*, 1999; *Nag and Rakov*, 2009].

[17] It follows from the above that characteristics and effects of corona on triggering wire depend on many factors, some of which are poorly understood. Since our method of analysis (FDTD) is computationally expensive, we have to limit the number of configurations and the number of different sets of input parameters. The primary focus of this paper is the radial extent of the triggering-wire corona sheath, which will be our free parameter. We will assume reasonable (typical) values for wire extension rate (rocket speed), 150 m/s, wire-top height at the time of initiation of sustained upward positive leader, 200 m, as well as a reasonable vertical profile of upward directed electric field, 5.5 kV/m at ground level and 43 kV/m aloft. Model predictions in terms of wire current, charge transfer from the ground to the wire, and reduction of ground-level electric field will be compared with available measurements and used as constraints on the model free parameter. We will assume that the triggering-wire corona sheath is cylindrical. Its actual geometry is probably more like an inverted cone (since the line charge density and hence the horizontal extent of radial electric field needed for corona streamer propagation is larger near the wire top), but the shielding effects of these two geometries are similar (see Appendix A).

[18] Our approach is different from that of *Biagi et al.* [2011] in two main respects: (1) in finding induced charges, they assumed the triggering wire to be infinitely thin and without corona, while in our model the radius of corona sheath is the free parameter, and (2) they assumed the wire shielding effect to be independent on whether the induced

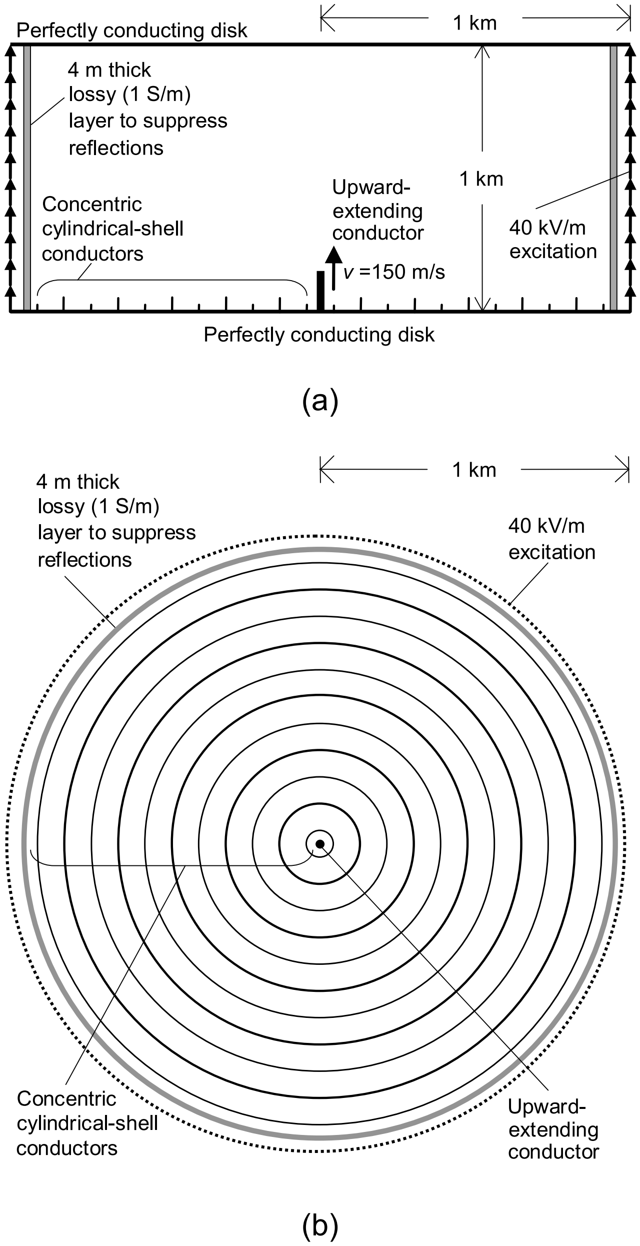

Figure 3. (a) Side view and (b) plan view of the configuration to be analyzed using the FDTD method, including a grounded conductor of radius 0.27, 2, 4, 8, and 16 m, which extends upward at a constant speed v = 150 m/s in a quasi-static upward directed electric field. The quasi-static upward directed electric field is formed between two perfectly conducting disks of 1 km radius and 1 km apart. Perfectly conducting cylindrical tubes on the ground surface, coaxial with the upward extending conductor, represent the presence of a corona space charge layer at the ground.

charge resides on the wire surface or in the corona sheath, while we find the charge transfer to the wire and its shielding effect to be each a function of corona sheath radius (because more charge is induced on a thicker cylinder). Further, in the work of Biagi et al., parameters of the vertical electric field profile (except for the ground-level field, which was measured) were free parameters, while we assumed this profile to be fixed. Finally, as noted above, we do not distinguish between the space charge of glow corona and that of transient precursors.

[19] To the best of our knowledge, this is the first study in which both the charge transfer to the triggering wire and radial extent of its corona sheath are estimated from the same computational procedure. The engineering model proposed by *Rizk* [2011] might be capable of predicting both the size of the triggering-wire corona sheath and charge transfer to the wire, but only the latter was presented.

3. Model

[20] Figure 3 shows the configuration to be analyzed using the FDTD method in the two-dimensional (2-D) cylindrical coordinate system. It includes a grounded perfect conductor, representing a triggering wire and its corona sheath, which extends upward at a constant speed of v = 150 m/s and perfectly conducting cylindrical tubes, which are located on the ground surface, coaxial with the upward extending conductor, and simulate the presence of corona space charge layer that is emitted during thunderstorms from irregularities such as grass on the ground surface [*Soula and Chauzy*, 1991]. The tubes have a thickness of 2 m and three different heights, 40, 50, and 100 m. The 40 m high tube has an inner radius of 30 m, 50 m high tubes have inner radii of 210, 390, 570, 750, and 930 m, and 100 m high tubes have inner radii of 120, 300, 480, 660, and 840 m. The quasi-static upward directed electric field is formed between two perfectly conducting disks of 1 km radius and 1 km apart by a 40 kV/m uniform vertical electric field source placed at the periphery of the cylindrical computational domain. Figures 4a and 4b show height profiles of vertical electric field and space potential up to an altitude of 200 m at horizontal distances d = 60, 180, and 360 m from the axis of the computational domain in the absence of upward extending conductor. Owing to the shielding effect of grounded cylindrical tubes, electric field on the ground surface at d = 60, 180, and 360 m, is about 5.5 kV/m, while it is about 43 kV/m aloft (well above the tubes). The latter is 3 kV/m higher than the 40 kV/m uniform excitation field owing to the presence of grounded cylindrical tubes simulating corona space charge at ground. Note that (1) the alternating tube heights simulate a decrease of corona charge density with height and (2) the reason why the height of the tube of radius 30 m is set to 40 m instead of 50 m is to make the electric field on the ground surface at a horizontal distance of 60 m from the axis of upward extending conductor about 5.5 kV/m (it is 4.8 kV when the height of the 30 m radius tube is set to 50 m). In order to suppress oscillations, associated with successive reflections between the cylindrical electric field source and the vertical axis of the cylindrical computational domain, a lossy cylindrical tube of thickness 4 m and conductivity 1 S/m is placed in front of the cylindrical electric field source (see Figure 3). The actual 2-D working space for the present FDTD simulations is 1 km × 1 km, which is divided into rectangular cells of 2 m × 5 m. The time increment is set to 5 ns (about 80% of the upper limit time increment of the Courant stability condition), but calculated values are taken every 33.3 ms in order to reduce the amount of output data.

[21] The upward extending grounded triggering wire, whose radius is typically 0.1 mm, is represented by a ver-

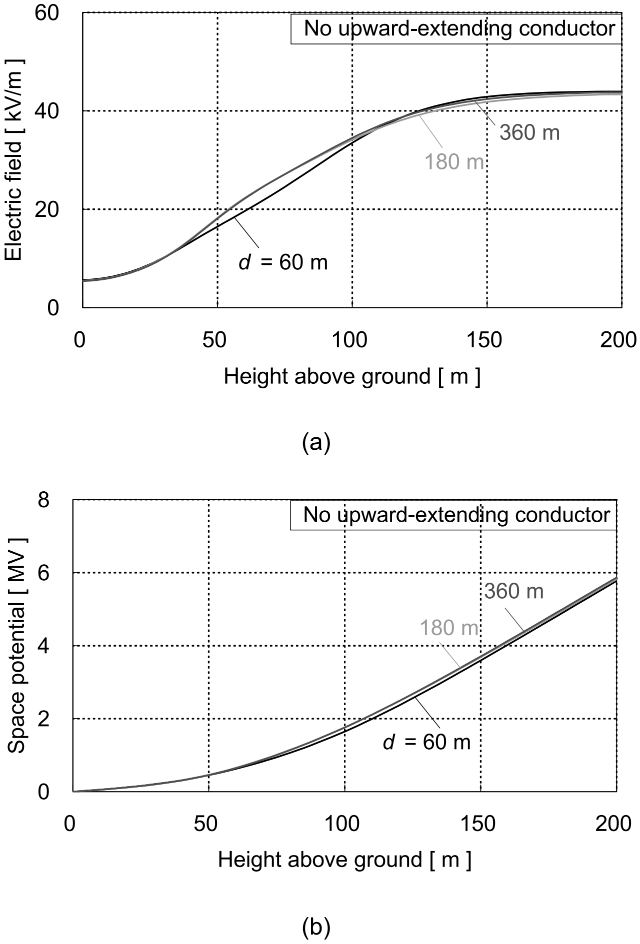

Figure 4. (a) Vertical electric field and (b) space potential as a function of height above ground at horizontal distances d = 60, 180, and 360 m from the axis of the computational domain in the absence of an upward extending conductor.

tical perfect conductor of radius 0.27 m (0.135 times the lateral side length of the rectangular cell employed [*Taniguchi et al.*, 2008], which is 2 m in the present simulations). In order to estimate errors involved in this approximation, we examine the reduction of upward directed electric field on the ground surface at d = 60 m, calculated for the conductor-top height equal to 200 m for conductors of different radii, r = 0.027 (27 mm), 0.2, 0.27, 2, 4, 8, and 16 m. Note that the FDTD calculations for r = 0.027 m (≈0.135 × 0.2 m) and 0.2 m are performed with rectangular cells of 0.2 m × 5 m and a time increment of 0.5 ns. As shown in Figure 5, the electric field reduction is 12, 16, and 17% for r = 0.027, 0.2, and 0.27 m, respectively. By extrapolation, it appears that for r = 0.1 mm the electric field decrease would be roughly around 10%; that is, within a factor of 2 of that for r = 0.27 m. Since specification of actual wire radius requires unreasonably large computation time, we will employ the wire radius of 0.27 m in the rest of this paper. This will still allow us to distinguish between corona sheath radii of a few tens of centimeters and a few meters or more.

[22] The wire extends upward at a constant speed of v = 150 m/s (different speed could be employed, but only one value is considered here). The extension is not continuous: it extends 5 m abruptly from the ground surface or the top end of the conductor at 33.3 ms, 66.7 ms, 100 ms, and so on, since the side length of the employed FDTD rectangular cell is 5 m. The wire stops extending when it attains an altitude of 200 m at time equal to 1.33 s.

[23] The corona space charge emanated from the triggering wire is represented by a perfectly conducting (this assumption is discussed in the next paragraph) cylindrical sheath of outer radius r = 2, 4, 8, and 16 m, coaxial with the triggering-wire-representing perfect conductor of radius 0.27 m. The presence of thin Kevlar coating of the wire is neglected. The corona sheath is also assumed to extend upward at the same speed as the wire-representing conductor does. Thus, we do not consider here the dynamics of corona discharge at the triggering wire and evolution of resultant space charge in the air surrounding the extending wire. We assume a cylindrical distribution of corona space charge along the wire, but do consider for comparison other geometries as well.

[24] Figure 6 illustrates the lack of dependence of shielding effect on corona sheath conductivity. It shows FDTD-calculated variations of ground-level electric field E_z at d = 60 m from an upward extending perfect conductor of radius 0.27 m with a 4 m radius corona sheath of different conductivities, σ = infinity, 10^{-6}, and 10^{-8} S/m, as a function of the conductor-top height. The prelaunch electric field at ground was 5.5 kV/m and 43 kV/m aloft. In Figure 6 the upward directed electric field is shown positive, as per the physics sign convention [e.g., *Rakov and Uman*, 2003]. We will use this sign convention throughout this paper. Note that, according to *Maslowski and Rakov* [2006], the conductivity of corona sheath surrounding the lightning channel at the beginning of the return-stroke stage is a few μS/m or so. Further, *Maslowski et al.* [2011] estimated the apparent conductivity of return-stroke corona sheath to be of the order of 10^{-8} S/m. It follows from Figure 6 that the influ-

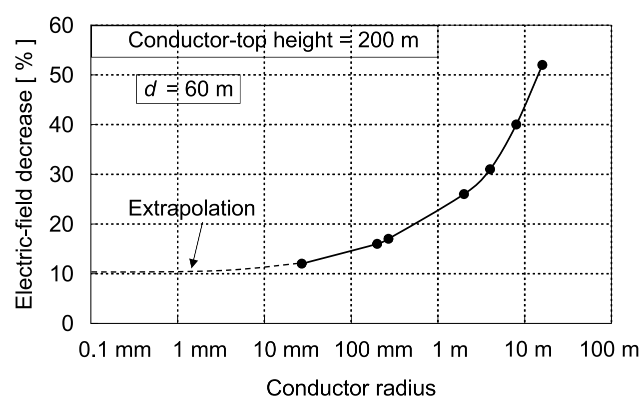

Figure 5. Dependence of shielding effect on conductor radius: FDTD-calculated reduction of the ground-level electric field E_z (relative to its prelaunch value of 5.5 kV/m) at d = 60 m for 200 m high cylindrical conductors of different radii r = 0.027 (27 mm), 0.20, 0.27, 2, 4, 8, and 16 m. The FDTD calculations for r = 0.027 m (≈0.135 × 0.2 m) and 0.2 m are performed with rectangular cells of 0.2 m × 5 m, and those for other radii are performed with rectangular cells of 2 m × 5 m.

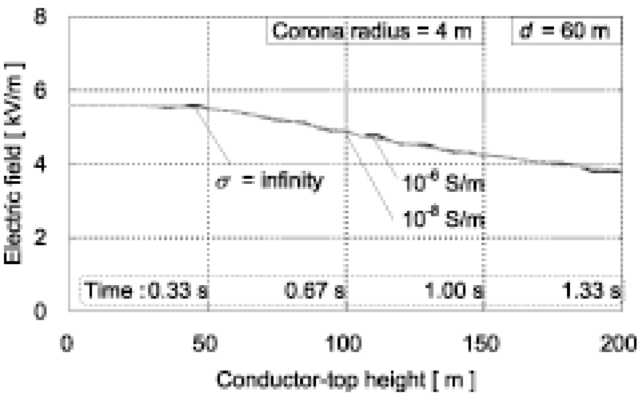

Figure 6. Lack of dependence of the shielding effect on corona sheath conductivity: FDTD-calculated variations of ground-level electric field E_z at d = 60 m as a function of conductor-top height. The conductor has a perfectly conducting core, simulating the triggering wire, of 0.27 m radius surrounded by a concentric cylindrical shell of outer radius of 4 m, simulating the corona sheath, and different conductivities (σ = infinity, 10^{-6}, and 10^{-8} S/m). The prelaunch electric field at ground was 5.5 and 43 kV/m aloft.

ence of corona sheath conductivity on the nearby ground-level electric field is negligible, so that the corona sheath can be assumed to be perfectly conducting. This is not surprising, because the field relaxation time constant ($=\varepsilon_0/\sigma$) in the corona sheath, which is of the order of tens of microseconds for $\sigma = 10^{-6}$ S/m and of the order of milliseconds for $\sigma = 10^{-8}$ S/m, is much shorter than the time scale of interest (of the order of hundreds of milliseconds). In the rest of this paper, we will employ σ = infinity for the corona sheath; that is, make no distinction between the triggering wire and its corona sheath (both will be represented by a single perfectly conducting cylinder).

4. Analysis and Results

[25] In this section, we consider variations of ground-level electric field as a function of wire-top height, at different distances from the wire. The results, as well as corresponding wire currents and charge transfers, will be compared to measurements. It is important to note that data on charges and currents are very limited and that there are no corona current measurements corresponding to the four *Biagi et al.* [2011] events that are used here as the primary ground truth in the electric field-reduction analysis.

[26] Figure 7 shows FDTD-calculated variations of upward directed electric field E_z on the ground surface as a function of conductor-top height at horizontal distances d = 60, 180, and 360 m for different conductor radii ranging from 0.27 to 16 m. When the conductor-top height is 200 m, E_z at d = 60 m is about 17, 26, 31, 40, and 52% lower than the prelaunch field of about 5.5 kV/m at ground level for r = 0.27 m, 2, 4, 8, and 16 m, respectively, while the corresponding reduction of E_z at d = 360 m in all cases is only 1% or less. These calculated results agree reasonably well with E_z measured by *Biagi et al.* [2011], which are reproduced in Figure 1. The reduction of measured E_z at d = 60 m ranges from about 35 to 50% for wire-top height equal to about 200 m, which corresponds to $r \approx 4$ to 16 m in calculated results. This indicates that the electric field reduction in the vicinity of triggering wire, prior to lightning initiation, for the events presented in Figure 1a (see also Figure 2a) is primarily caused by the presence of corona space charge emanated from the wire, and the radius of corona sheath (assumed to be cylindrical) should be about 4 to 16 m. Note that the 0.27 m radius conductor, representing the nearly no corona case, is responsible for only 17% field reduction at d = 60 m. Actually, for the 0.1 mm radius, the field decrease is expected to be a factor of 2 smaller (see Figure 5). This agrees reasonably well with the 13% field reduction at d = 57 m for the case of a 200 m long vertical wire without corona, computed by *Nakamura et al.* [1987], who used the charge simulation method (CSM).

[27] Figure 8 shows FDTD-calculated time variations of charge on the surface of upward extending conductor for different conductor radii. Note that the conductor represents both the wire and its corona sheath; that is, both charges residing on the wire and space charges in the surrounding air are accounted for. The apparent irregularities (superimposed oscillations) observed in Figure 8 are related to the presence of conducting tubes simulating the effect of corona space charge layer at ground. Dashed curves are approximations of the FDTD-calculated time variations of the total charge by quadratic functions. The charge magnitude increases with increasing the height of the top of the upward extending conductor. The charge transferred from ground to the wire whose top is at a height of 200 m, mostly to the corona sheath, is 1.2, 4.5, 6.6, 9.5, and 14 mC for r = 0.27, 2, 4, 8, and 16 m, respectively. Note that total charge on the surface of an upward extending conductor in our model does not depend on its upward extending speed. *Standler* [1975] reported the charge transfer from the ground to the triggering wire whose estimated top height was 550 m to be 11.4 mC. The charge transfer to the 200 m long triggering wire and its corona sheath is expected to be smaller. *Rizk* [2011], using his engineering model, estimated corona charges from 1.63 to 12.3 mC for different triggering-lightning experiments. We assume here that the most likely range is 4.5 to 6.6 mC, which corresponds to $r \approx 2$ to 4 m.

[28] Figure 9 shows time derivatives of quadratic-function-approximated charge curves of Figure 8, representing smoothed currents flowing in the upward extending conductor for different conductor radii. Note that time derivatives of charge curves depend on the upward extending speed of the conductor, increasing linearly with the speed. At time equal to 1.33 s, when the top of the conductor attains an altitude of 200 m, the magnitude of current flowing in the conductor is 2.1, 7.9, 11, 15, and 22 mA for r = 0.27, 2, 4, 8, and 16 m, respectively. *Standler* [1975] measured a current of about 10 mA at the bottom of triggering wire, when its top was at an estimated altitude of 550 m, and *Nakamura et al.* [1987] reported measured currents up to 5 to 10 mA. Further, *Rizk* [2011], using his engineering model, estimated maximum corona currents for different triggered-lightning experiments to be in the range of 3.5 to 9.6 mA. Our model predictions for $r \approx 2$ to 4 m (corresponding currents are 7.9 to 11 mA) agree with most of the above values.

[29] The range of corona sheath radii estimated from the charge and current analyses is the same, 2 to 4 m, and differs from that based on the field-reduction observations, 4 to

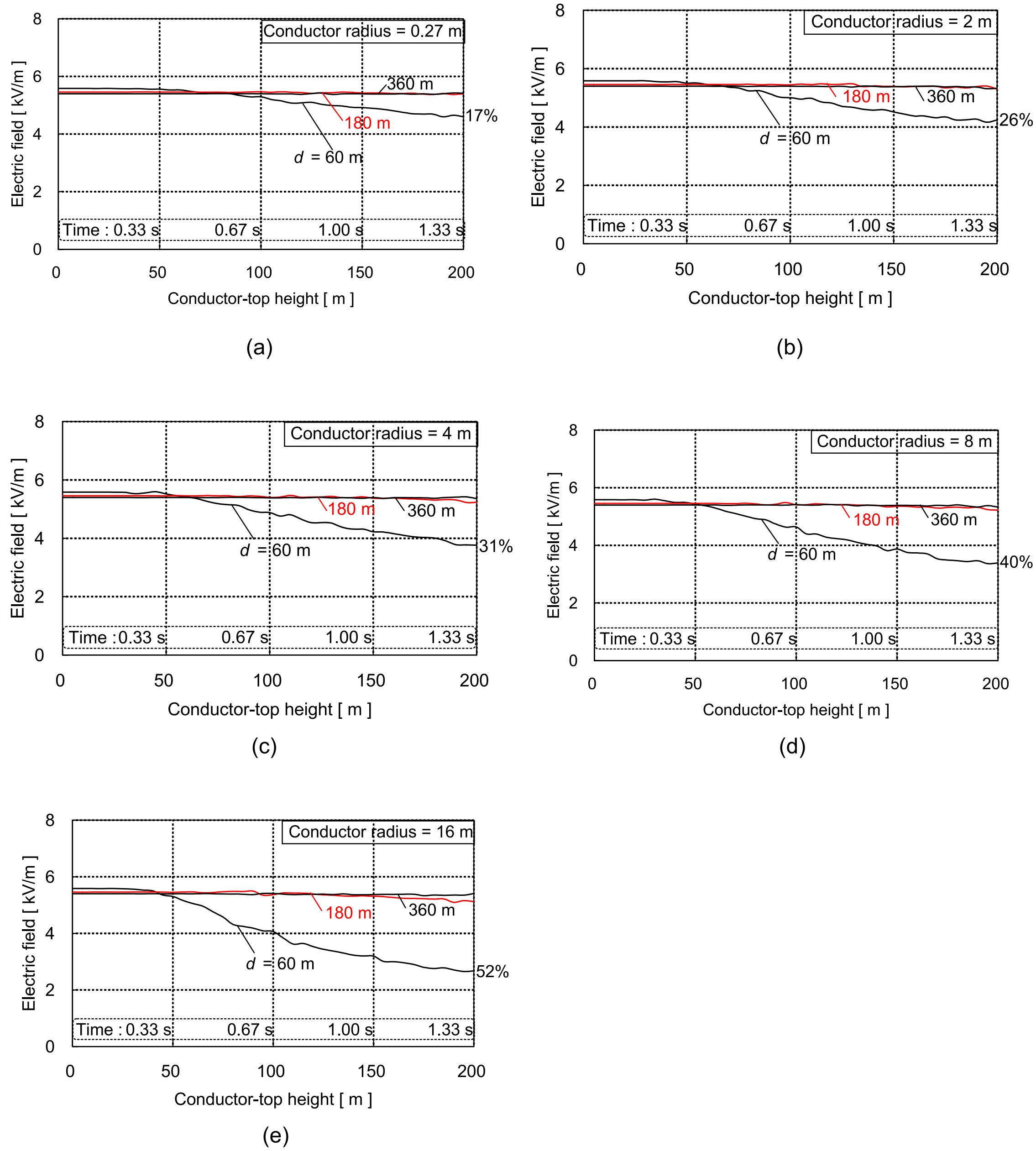

Figure 7. FDTD-calculated variations of the upward directed electric field E_z on the ground surface as a function of conductor-top height (or time) at d = 60, 180, and 360 m for different conductor radii: (a) 0.27 m, (b) 2 m, (c) 4 m, (d) 8 m, and (e) 16 m. The conductor extends upward at a speed of 150 m/s up to an altitude of 200 m. The prelaunch electric field on the ground surface is 5.5 and 43 kV/m aloft. The percent electric field change at d = 60 m for h = 200 m is shown near the right edge of each panel.

16 m. It appears that the corona sheath radius of about 4 m is plausible from the three points of view: close electric field reduction, charge transfer, and current. The most important inference here is that the corona sheath radius is of the order of meters (much greater than the wire radius), as we additionally confirm in section 5 by examining radial electric fields near the surface of conductors of different radii.

5. Discussion

[30] As noted in section 1, *Nakamura et al.* [1987] calculated ground-level electric fields at d = 40 m from a vertical perfectly conducting wire surrounded by point charges, which represented corona space charges emanated from the wire and were distributed uniformly within an assumed 1 m or 4 m radius cylindrical region. The total amount of the distributed point charges was determined from the measured total charge transferred from the ground to the wire. The calculated electric field reduction at d = 40 m agreed well with the corresponding measured ones (agreement for 1 m radius was better than for 4 m radius). We found from our FDTD calculations that the total charge on the surface of a perfectly conducting cylinder (representing both the wire and its corona sheath) of radius 4 m is close

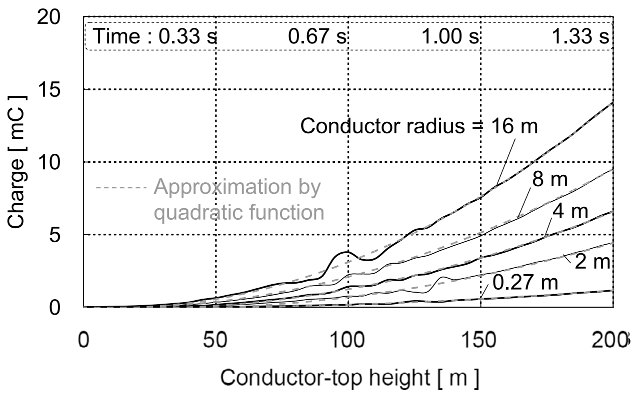

Figure 8. FDTD-calculated variations of total charge on the surface of an upward extending conductor (representing both the triggering wire and its corona sheath) as a function of conductor-top height (or time) for different conductor radii r = 0.27, 2, 4, 8, and 16 m. The apparent irregularities (superimposed oscillations) are related to the presence of conducting tubes simulating the effect of a corona space charge layer at the ground. Dashed curves are approximations by quadratic functions used for evaluating corresponding currents shown in Figure 9.

to the total amount of point charges placed by Nakamura et al. within the 1 m or 4 m radius cylindrical region for simulation of the wire corona sheath.

[31] Figure 10 shows FDTD-calculated variations of ground-level electric field E_z at d = 60, 180, and 360 m as a function of conductor-top height for r = 4 m in the absence of grounded conducting tubes that simulate the corona space charge layer at ground. In these calculations, the magnitude of vertical electric field source placed at the periphery of the cylindrical computational domain is set to 43 kV/m. The electric field starts decreasing earlier than the corresponding electric field in the presence of the conducting tubes (see Figure 7c). We also performed calculations for different values of r, although the results are shown graphically only for r = 4 m. When the conductor-top height is 200 m, the reduction of E_z at d = 60 m is about 16, 24, 29, 36, and 48%

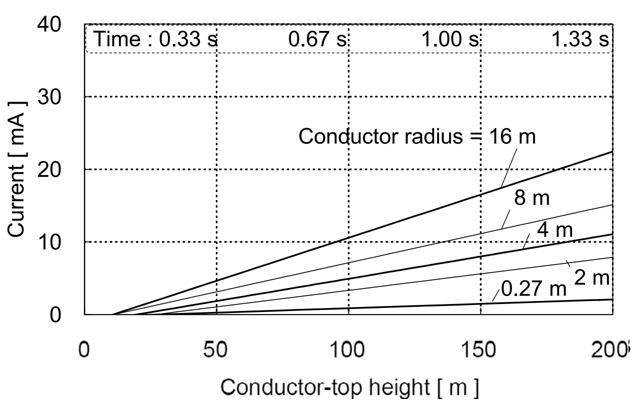

Figure 9. Currents flowing in the upward extending conductor as a function of conductor-top height (or time) for different conductor radii r = 0.27, 2, 4, 8, and 16 m, estimated as time derivatives of quadratic-function-approximated variations of charge shown in Figure 8.

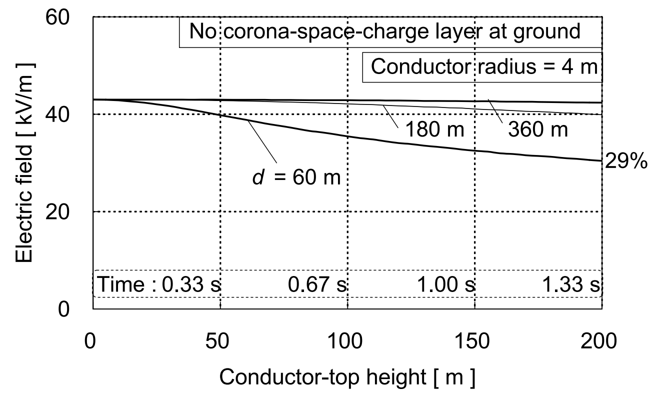

Figure 10. Same as Figure 7c but for the case of no corona space charge layer at the ground (the prelaunch electric field is equal to 43 kV/m both at ground level and aloft).

lower than the prelaunch value of 43 kV/m (not attainable in practice because of corona at ground) for r = 0.27 m, 2, 4, 8, and 16 m, respectively. The corresponding reduction of E_z at d = 360 m is only 1, 1, 1, 2 and 3%. These field-reduction values are almost the same as those calculated with the conducting tubes reducing the ground-level field to 5.5 kV/m. The vertical electric field along the wire trajectory is 25, 35, 44, and 47 kV/m at heights 50, 100, 150, and 200 m, respectively, in the presence of the grounded conducting tubes, while it is 43 kV/m at all those heights in their absence. It appears that the percent field reduction is insensitive to the presence of corona space charge at ground. However, the charge transfer is significantly reduced by the presence of conducting tubes, from 12 mC (in the absence of the tubes; see Figure 11) to 6.6 mC.

[32] The positive streamer propagation speed is about 2 × 10^5 m/s [*Cooray*, 2003, p. 79]. Therefore, the corona space charge emanated from the wire can be carried by streamers over a few tens of meters in 100 μs or so, provided that the radial electric field along their path exceeds the critical value required for their propagation (about 400 kV/m for positive streamers) [*Guillier et al.*, 1995]. Table 1 shows FDTD-calculated radial electric field at a horizontal distance of 1 m from the surface of 200 m high cylindrical conductor for different conductor radii. Note that when the radius is

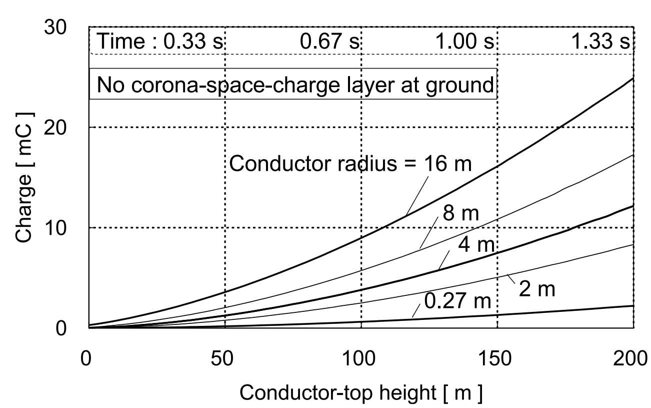

Figure 11. Same as Figure 8 but for the case of no corona space charge layer at the ground (the prelaunch electric field is equal to 43 kV/m both at ground level and aloft).

Table 1. FDTD-Calculated Radial Electric Field at a Horizontal Distance of 1 m From the Surface of 200 m High Cylindrical Conductors of Different Radii[a]

	Conductor Radius (m)				
Height Above Ground (m)	0.27	2	4	8	16
200	1400	840	660	510	380
150	640	320	230	160	110

[a]Values given are in kilovolts per meter. For r = 0.27 m, the distance of 1 m is measured from the conductor axis.

0.27 m the distance is measured not from the conductor surface but from its axis. The results are given for two heights above ground, 150 and 200 m, the latter being at the conductor top. As seen in Table 1, the radial field exceeds 400 kV/m near the conductor top for radii up to 8 m. However, at 150 m, the field exceeds 400 kV/m only for the 0.27 m radius. Thus, positive corona streamers can propagate over several meters near the conductor top. The above discussion is concerned with corona developing from the lateral surface of the wire, but it is likely that corona streamers primarily extend in the upward (not radial) direction. If the streamers at the wire tip form an inverted cone with an angle of 45° and a spherical cap at its base, a radial corona sheath of 4 m radius can be formed (via the wire being pulled through the wire-tip streamer zone) if the streamer length is $4\sqrt{2} = 5.7$ m. This is comparable to the vertical extent of precursor luminous channels, which can be possibly viewed as particularly intense (impulse) corona streamers [*Biagi et al.*, 2009]. It is likely that corona on the triggering wire occurs both at its tip and on its lateral surface, with the largest spatial extent being near the tip.

[33] Sometimes, the extension of triggering wire causes a change of polarity of ground-level electric field (see Figure 2). One possible explanation is a wire tilt toward the field meter. Figure 12a shows E_z on the ground surface as a function of conductor-top height at horizontal distances d = 60 and 350 m from the bottom of a tilted (at 45° with respect to vertical) conductor of cross section 20 m × 20 m, calculated using the three-dimensional (3-D) FDTD method. The larger cross section is used to reduce computation time. The fields are computed on either side of the tilt. The prelaunch electric field on the ground surface was set to 43 kV/m, and no corona space charge layer at ground was considered (since the nonvertically extending conductor would come in contact with the 40 m high grounded tube located at a horizontal distance of 30 m). The 3-D FDTD working volume was 2 km × 2 km × 1 km, which was divided into cubic cells of 10 m × 10 m × 10 m. The time increment was set to 10 ns. The 45 degree tilted conductor was staircase approximated. Figure 12b shows (all other conditions being the same) E_z on the ground surface at d = 60 and 350 m for an upward extending (vertical) conductor. The reductions of E_z at d = 60 m on the tilt side for the conductor-top height equal to 200 m is 83%, while it is 19% on the opposite side. This is to be compared with the reduction of E_z of 44% at d = 60 m for the vertical conductor (see Figure 12b). Although E_z on the tilt side does not change its polarity, the field reduction is twice that for the vertical conductor. This result indicates that a triggering-wire tilt can contribute to a change of polarity of ground-level electric field when the tilt is toward the electric field meter, although additional (presently unknown) factor(s) should exist to fully explain this phenomenon.

[34] When the field meter is located on the side opposite to the wire tilt, the field reduction there is smaller than for the vertical wire. Therefore, relatively small field reductions seen in some cases shown in Figure 2a can be due to wire tilts in the direction opposite to that to the electric field meter. Another possible explanation is a relatively small radial extent of wire-corona space charge (see Figure 7).

6. Summary

[35] We have examined, using the FDTD method, the effect of upward extending wire, used for artificial lightning initiation from natural thunderclouds, and corona space charge emanated from this wire on the close ground-level electric field E_z (prior to lightning initiation). E_z on the ground surface in the vicinity of the triggering wire decreases with increasing the wire-top height. When the wire-top height is 200 m, the reduction of E_z at horizontal distance d = 60 m is about 17, 26, 31, 40, and 52% relative to the background value of 5.5 kV/m for the corona sheath radius r = 0.27 m,

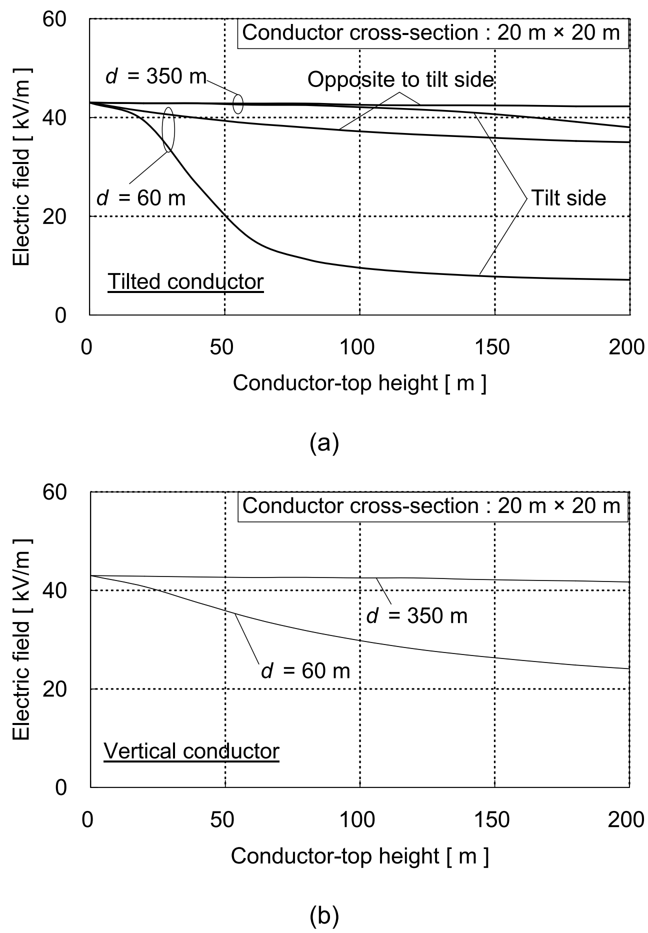

Figure 12. Three-dimensional FDTD-calculated variations of the upward directed electric field E_z on the ground surface as a function of conductor-top height at horizontal distances d = 60 and 350 m from the bottom of (a) 45° tilted and (b) vertical conductors of cross section 20 m × 20 m. The prelaunch electric field on the ground surface is 43 kV/m, and no corona space charge layer at the ground is considered.

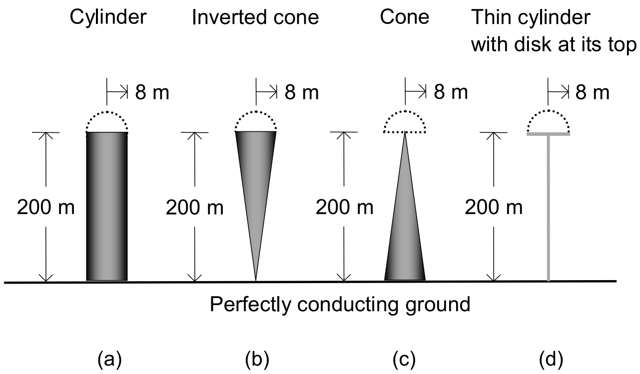

Figure A1. Four 200 m tall conductors of different geometry used in computing field reduction at d = 60, 180, and 360 m (see Table A1): (a) a cylinder of radius 8 m, (b) an inverted cone of base radius 8 m, (c) a cone of base radius 8 m, and (d) a cylinder of radius 0.27 m with a disk of radius 8 m at its top. Influence of a hemispherical conducting cap (shown by dotted curves) of radius 8 m at the conductor top was also considered.

2, 4, 8, and 16 m, respectively, while the corresponding reduction of E_z at d = 360 m in all cases is only 1% or less. The calculated results for $r \approx 4$ to 16 m agree reasonably well with E_z variations measured at d = 60 and 350 m by *Biagi et al.* [2011]. Specifically, the reduction of measured E_z at d = 60 m for four different events (at the time when the wire-top height was equal to 200 m) ranges from about 35 to 50%. This indicates that the electric field reduction in the vicinity of triggering wire, prior to lightning initiation, is primarily caused by the presence of corona space charge emanated from the wire to a radius of about 4 m or more, as opposed to the presence of wire alone. The total charge transfer from the ground to the wire whose top is at an altitude of 200 m is 1.2, 4.5, 6.6, 9.5, and 14 mC for r = 0.27, 2, 4, 8, and 16 m, respectively. The corresponding currents flowing in the wire are 2.1, 7.9, 11, 15, and 22 mA. The model-predicted charges and currents are consistent with measurements for r = 2 to 4 m, smaller than the values based on the field-reduction calculations, but still of the order of meters. The radial electric field near the top of 200 m high conductor can exceed 400 kV/m, which is sufficient for positive streamer propagation, when the conductor radius is up to 8 m, confirming corona sheath radii of the order of meters inferred from the field-reduction and wire charge/current analyses.

Appendix A: Geometry of Wire Corona Sheath

[36] In Appendix A we compare conductors of different geometry, representing the wire-corona sheath, in terms of the reduction of E_z on the ground surface relative to its prelaunch value at d = 60, 180, and 360 m. The following geometries are considered (see Figure A1): (1) a cylinder of radius 8 m (Figure A1a), (2) an inverted cone of base radius 8 m (Figure A1b), (3) a cone of base radius 8 m (Figure A1c), and (4) a cylinder of radius 0.27 m with a disk of radius 8 m at its top (Figure A1d). Geometry 1 is the basic geometry considered in this paper, while geometry 2 is the most likely one, because the radial electric field is larger near the conductor top. Geometry 3 assumes that corona sheath near ground is larger because it has more time to develop, and geometry 4 assumes that most of corona space charge is localized near the conductor tip. The conductor height is assumed to be 200 m, and the influence of a hemispherical cap at the conductor top (representing the corona space charge emanated predominantly upward from the wire tip) is additionally considered. The prelaunch field at the ground surface is about 5.5 kV/m and 43 kV/m aloft. The results are summarized in Table A1. It is clear that the effect of hemispherical cap of radius 8 m is not significant at all the considered distances (it produces an additional field change of at most 3%). The electric field-reduction effect of the cone, the inverted cone, and the disk-topped thin cylinder is smaller than that of the thick cylinder, but the difference between the thick cylinder (the basic geometry considered in this paper) and the inverted cone (the likely actual geometry) is relatively small.

Table A1. Reductions of Ground-Level Electric Field E_z Owing to the Shielding Effect of a 200 m Tall Grounded Conductor, Simulating the Triggering Wire and Its Corona Space Charge[a]

Conductor Geometry	d = 60 m	d = 180 m	d = 360 m
(a) Cylinder of radius 8 m	40 (40)	4 (5)	1 (1)
(b) Inverted cone of base radius 8 m	35 (35)	4 (5)	1 (1)
(c) Cone of base radius 8 m	29 (32)	3 (4)	0 (1)
(d) Cylinder of radius 0.27 m with a disk of radius 8 m on its top	21 (22)	3 (3)	1 (1)
(e) Cylinder of radius 0.27 m without disk as its top	17	2	0

[a]In percent relative to its prelaunch value of 5.5 kV/m at horizontal distances d = 60, 180, and 360 m. Values in parentheses are for the case of a hemispherical cap of radius 8 m added to the top of the conductor (see Figure A1; parenthetical letters in first column also refer to Figure A1).

[37] Table A2 compares conductors of different geometry in terms of the charge transfer from the ground to the 200 m high conductor and corresponding current. The total amount of charge transfer for the cone, the inverted cone, and the disk-topped thin cylinder is smaller than that to the thick cylinder, but, again, the difference between the thick cylinder and inverted cone is relatively small.

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Table A2. Charge Transferred From the Ground to the 200 m Tall Grounded Conductor and Corresponding Current[a]

Conductor Geometry	Charge Transfer (mC)	Current (mA)
(a) Cylinder of radius 8 m	9.5 (9.9)	15
(b) Inverted cone of base radius 8 m	8.0 (8.5)	14
(c) Cone of base radius 8 m	4.9 (6.0)	–
(d) Cylinder of radius 0.27 m with a disk of radius 8 m on its top	2.1 (3.3)	–
(e) Cylinder of radius 0.27 m without disk as its top	1.2	2.1

[a]Values in parentheses are for the case of a hemispherical cap of radius 8 m added to the top of the conductor. Currents for geometries (c) and (d) are not given because of difficulties in their computation using the FDTD method. Parenthetical letters in first column refer to Figure A1.

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