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Validation and revision of far-field-current relationship for the lightning strike to electrically short objects

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\textbf{ABSTRACT}

In this paper we have validated and revised the general expressions for far-field-current factors presented by Bermudez et al. (2005, 2007) for lightning strike to tall objects on perfectly and finitely conducting ground, respectively. For the perfectly conducting ground, it is found that when the risetime of lightning return stroke current is larger than 5\(h/c\) (\(h\) is the height of tall object and \(c\) is the light speed), the overestimation caused by the traditional method predicting the lightning current peak is within 10\% beyond a distance of 20 km from the lightning channel, and with the decrease of observed horizontal distance \(d\), the error will increase due to the effect of induction field component. For example, when \(d\) is 10 km, the overestimation is about 20\% for strike to a 300-m-tall object. For the finite conductivity ranging from 0.01 S/m to 0.001 S/m, when the lightning strikes the 300-m-tall object, the lightning current peak predicted from the measured magnetic field peak according to the traditional method is overestimated ranging from about +5\% to +20\% (positive means overestimation while negative means underestimation) and the derivation value is more within a distance of 20 km because of induction field component; When the lightning strikes the 50-m-tall object, the predicted current peak according to the traditional method has an error ranging from about +5\% to −15\%.

\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure1.png}
\caption{Example figure caption.}
\end{figure}

1. Introduction

The widespread use of lightning location systems provide lightning return stroke peak currents estimated from measured magnetic field peaks. However, the theoretical estimation of return stroke currents from remote electromagnetic fields depends on the adopted return stroke model. Expressions relating radiated fields and return stroke channel base currents have been derived for various “engineering” return stroke models (Rakov and Uman, 1998). Based on the transmission line (TL) model, for an observation point at ground level, the radiated (far) electric and magnetic fields produced by a vertical lightning channel terminated directly at ground are simply proportional to the channel base current (Uman et al., 1975; Qie et al., 2007, 2009, 2011; Yang et al., 2010), with the proportionality coefficient being determined for strike to flat ground with the perfect conductivity.

However, the lightning usually strikes tall buildings (e.g., tall telecommunication objects) (Diendorfer, 2011; Diendorfer et al., 2002; Romero et al., 2012; Bermudez et al., 2001, 2005, 2007; Baba and Rakov, 2007; Mosaddeghi et al., 2011; Petracek et al., 2005; Rakov and Uman, 1998; Rachidi et al., 2001; Pavanello et al., 2009; Jiang et al., 2014). For the case of strike to tall objects, as a result of transient process in the object, current waveforms can differ significantly at different heights along the object and can exhibit more than one peak (typically, secondary peak is larger than the initial one). The experimental observations at the 553-m-tall Canadian National Object (CN Object) in Canada showed that the presence of the object tends to increase substantially the electric and magnetic field peak values and their derivatives (Motoyama et al., 1998; Bermudez et al., 2001; Laftocici et al., 2006; Pavanello et al., 2009; Mosaddeghi et al., 2011; Shostak et al., 2012), which implies that the presence of the elevated object cannot be disregarded in relationship between the radiated field and channel base current. Rachidi et al. (2001) further theoretically showed

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that the vertical electric field and azimuthal magnetic field for a strike to a 553-m-tall object at a distance of 2 km from the lightning channel are 2.6 times larger than that produced by the same lightning attaching to flat ground. Baba and Rakov (2005a) also found that at larger distances the lightning-radiated electromagnetic field for the strike-object case can become greater than that for the flat ground. Cooray et al. (2006) found that the transient processes along the object with heights of 50–300 m increase the initial field peak by about 2 times at a distance of 100 km. Especially, it is worth noting that the high frequency content in the electromagnetic fields of lightning flashes striking tall structures may differ from the ones striking flat ground (Petracek et al., 2005; Cooray et al., 2006). The attenuation of the initial radiation field resulting from the propagation over a perfectly conducting ground strongly depends on the current risetime, the object height, the ground conductivity and so on. When the lightning strikes tall objects, the high frequency content increases due to the transient process, the corresponding attenuation will become more seriously, because of the selective attenuation of the high frequency components along the finitely conducting ground (e.g., Rubinstein, 1996; Cooray, 1987, 2003, 2008, 2009; Cooray and Ming, 1994; Cooray and Perez, 1994; Cooray et al., 2000; Delfino et al., 2008a, 2008b; Shoory et al., 2011a, 2011b; Zhang et al., 2012a, 2012b, 2012c, 2012d, 2013; Li et al., 2013, 2014). As a result, the peak and peak derivatives of the electromagnetic radiation field far away from a lightning strike point may deviate from their ideal values. Therefore, the difference between the high frequency contents for tall structures and flat ground may result in the different field propagation effect along a finitely conducting earth (Petracek et al., 2005; Cooray et al., 2006). For example, Cooray et al. (2006) found that in the case where the ground conductivity is extremely poor, namely 0.0001 S/m, the attenuation of the field peak may reach as much as 70% in the case of lightning flashes striking a 300-m-tall object. The transient processes along the tall object will cause a more significant attenuation of the radiated field when the current risetime is similar to the propagation time along the object. However, with the increase of the lightning current risetimes, the transient processes of the object will decrease and the effect of tall object on the lightning electromagnetic fields also decreases. For the lightning current RT less than 20 h/c (h is the height of object and c is the light speed), Baba and Rakov (2005a, 2007) and Bermudez et al. (2005, 2007) have derived the field-to-current conversion factors (FCCFs) for the initial current peak at the object top, the largest peak current at the object top and the peak current at the object bottom. Zhang et al. (2014) have also studied the accuracy of FCCFs presented by Baba and Rakov (2005a, 2007) for the perfectly conducting earth and further extended FCCFs into the finitely conducting earth, and found that their revised FCCFs have much better accuracy for the lossy ground.

For the lightning current with RT much larger than h/c (RT ≫ h/c), Bermudez et al. (2005, 2007) obtained the general expressions relating lightning return stroke currents and far radiated electric and magnetic fields, taking into account the effect of an electrically short object. The general expressions are very important for us to estimate the lightning current peaks from observed far fields. However, no one has validated the accuracy of the general expressions both for the perfectly and finitely conducting earth, and no one has given the particular value of RT, which gives some difficulties for us to use their expressions in a typical case. Also, although Cooray et al. (2006) have studied the propagation effect of the finitely conducting ground on the far field radiated by lightning flashes with RT of 0.2–1 μs for strike to 50-m and 300-m tall objects, respectively, the propagation effect for RT ≫ h/c has not been studied.

Therefore, in this paper we will validate the general expressions presented by Bermudez et al. (2005, 2007) for perfectly and finitely conducting ground, respectively, and give the detailed particular value of RT on how to use the general expression, and further revise the general expressions of the far-field-current relationship for electrically short objects both on perfectly and finitely conducting ground.

2. The model introduction

2.1. The general methods for computing azimuthal magnetic field when lightning strikes tall objects

Here, we will use the lumped sources in lightning return stroke models extended to include the presence of a tall strike object (Baba and Rakov, 2005b). The object is modeled as a single, uniform and lossless transmission line, because the characteristics wavelength of the input lightning current is comparable to the height of tall object. The general equations for the spatial-temporal distribution of the current along the lightning channel and along the strike object are given by Baba and Rakov (2005b).

In the analysis, we firstly calculate the lightning return stroke current distribution along the objects and the channel by using the formulae (Baba and Rakov, 2005b), and then calculate the far azimuthal fields on a perfectly conducting ground according to the equations presented by Bermudez et al. (2005). Where, the channel height is assumed to be H = 7.5 km and the return stroke speed is v = 1.5 × 10^8 m/s. The return-stroke discharging current includes two components—a breakdown current and a corona current. Each of the two components is calculated by using the analytical expression suggested by Heidler (1985) as below

\[
I_0 (h, t) = \frac{I_01}{2} \left( t/\tau_1 \right)^2 e^{-\left( t/\tau_1 \right)^2} + \frac{I_02}{2} \left( t/\tau_2 \right)^2 e^{-\left( t/\tau_2 \right)^2}
\]

\[
\eta_1 = \exp \left\lbrace \frac{\tau_{11}}{\tau_{12}} \left( \frac{2 \tau_{12}}{\tau_{11}} \right)^{1/2} \right\rbrace, \quad \eta_2 = \exp \left\lbrace \frac{\tau_{21}}{\tau_{22}} \left( \frac{2 \tau_{22}}{\tau_{21}} \right)^{1/2} \right\rbrace
\]

where, \(I_01\) and \(I_02\) are the current peaks of the breakdown current and corona current, \(\eta_1\) and \(\eta_2\) are the peak correction factors, \(\tau_{11}\) and \(\tau_{21}\) determine the risetime (RT) of the breakdown current and corona current, and \(\tau_{12}\) and \(\tau_{22}\) determine the decay time of the currents. Four current waveforms, as shown in Fig. 1, have been

**Fig. 1.** Short-circuit current waveforms with different RTs but the same peak value for our analysis.
considered in our paper. They are characterized by the same peak value (12 kA), but with different RTs, namely $3h/c$ and $5h/c$. The reflection coefficients are assumed to be constant and equal to $\rho_t = -0.5$ at the top of objects and $\rho_b = 1$ at the bottom of objects, respectively, as shown in Bermudez et al. (2003).

Based on the azimuthal magnetic field on the perfectly conducting ground as depicted above, the propagation effect of the finite conductivity of the earth can be computed as below (e.g., Shoory et al., 2011a, 2011b; Cooray and Ming, 1994; Zhang et al., 2012a, 2012b, 2012c, 2012d, 2013; Li et al., 2013, 2014).

$$H_{\text{all}, \infty}(0, d, t) = \int_0^t H_{\text{all}, \infty}(0, d, t - r)W(0, d, r)dr$$

where, $H_{\text{all}, \infty}(0, d, t)$ and $H_{\text{all}, \infty}(0, d, t)$ are the azimuthal magnetic fields radiated by lightning strike to tall objects on the perfectly conducting ground and the finitely conducting ground, respectively, as shown in Bermudez et al. (2003).

$$W(0, d, \omega) = 1 - j\sqrt{\frac{\omega \mu_0 \sigma}{2c}} \exp\left(-p\right) \text{erf}(j\sqrt{\frac{\omega \mu_0 \sigma}{2c}})$$

$$p = -\frac{j\omega d}{2c} \Delta^2$$

$$\Delta = \sqrt{\frac{1}{\epsilon_0} - \frac{1}{\epsilon_r}}$$

$$\epsilon_r = \mu_0 \sigma + j\omega \mu_0 \sigma$$

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\( \gamma_i = \sqrt{\rho_0 \sigma + \rho_0 \sigma r} \) \hspace{1cm} (7)

\( \gamma_0 = \mu_0 \rho \sigma r \) \hspace{1cm} (8)

where, “erfc” is the complementary error function, \( c \) is the light speed, \( j = \sqrt{-1} \), \( \Delta \) is the normalized impedance corresponding to the finitely conducting earth, \( \varepsilon \) is the relative dielectric constant.

As for the accuracy of our codes, the comparison of our simulated results and that presented by Baba and Rakov (2007) shows that our codes are correct (see Fig. 2).

2.2. Far-field-current relationship for the lightning strike to electrically short objects

For the electrically short strike object (RT \( \gg h/c \)), on the basis of a distributed-source representation of the lightning channel (Rachidi et al., 2002), Bermudez et al. (2005, 2007) presented the approximate formula (far-field-current relationship) for computing the lightning electromagnetic fields on the perfectly conducting ground. Here, we have revised the approximate formula to be valid for the lumped sources in lightning return stroke models as below

\[ H_{\text{full}}(0, d, t + d/c) \approx \frac{\nu}{2\pi cd} I_0(h, t) + \frac{1}{2\pi c d} h \frac{d}{dt} I_0(h, t) \] \hspace{1cm} (9)

where, \( d \) is the distance from observed point to the lightning channel, \( \nu \) is the return stroke speed, \( c \) is the light speed, \( h \) is the height of objects, \( I_0(h, t) \) is the short-circuit current that would be measured at an ideally grounded object with a negligible height.

The first one, which is the traditional term for predicting the lightning current peak (the traditional method), is proportional to the short-circuit current and it represents the contribution of the channel, and the second one depends on the current derivative which represents the contribution of tall objects (we can call it an extra term). Therefore, for the electrically short strike object (RT \( \gg h/c \)), the approximate formula is consisted of the traditional term and the extra term.

3. Results and analysis

3.1. For the perfectly conducting ground

Fig. 3 shows the comparison of the azimuthal magnetic field for strike to tall object, for strike to flat ground and from approximate Eq. (9) with different RTs of 3h/c and 5h/c at distances ranging from 10 km to 100 km from the lightning channel, respectively. In Fig. 3, the fields for strike to tall objects are calculated according to the analytical computation presented by Bermudez et al. (2005).

Note that, for RT with 3h/c, the transient processes along the tall object result into the sharp increase of the initial field value, and three cases have different field waveforms, with the increase of the RT, the effect of tall object decreases. When the RT is 5h/c, the case for strike to tall objects is about close to that for strike to flat ground at distances from 10 to 100 km, however, the field risetime for strike to tall object is shorter than that for the flat ground due to the transient process. Also, it is found that the results from approximate Eq. (9) have an accepted accuracy within
an error of 10% when the RT is 5h/c. Therefore, for the simplicity, we would rather use the approximate Eq. (9) for predicting the lightning current peak, however, in fact it is not convenient due to the second term (extra term). Fig. 4 further shows the comparison of the first term (traditional term) and second term (extra term), we can see that the extra term, representing the contribution of the strike to tall objects, is less than the traditional term, and the approximate formula (9) mainly depends on the traditional term which is proportional to the short-circuit current.

In order to further investigate the difference between the traditional term (or the traditional method) and the case for strike to tall objects, let us define the coefficient \( A(\infty) \) for perfectly conducting ground, \( H_{\text{tall, peak}} \) presents the case for strike to tall objects according to the analytical computation presented by Bermudez et al. (2005), and \( H_{\text{tradition, peak}} \) comes from the traditional term (the first term in approximate Eq. (9)). As shown in Fig. 5, we note that, the field error caused by traditional method is within 10% beyond distances of 20 km both for strike to 50-m and 300-m objects, and with the decrease of observed distance \( d \), the error will increase due to effect of induction magnetic field component. For example, when the horizontal distance \( d \) is 10 km, the overestimation caused by the traditional method is about 20% for strike to a 300-m-tall object. Also, with the decrease of tall heights, the traditional method has a better accuracy.

Here, the fitted coefficient \( A(d) \) from the computed values as a function of the observed distance \( d \) for perfect conductivity as below:

Fig. 5. Difference between the traditional method and the case for strike to tall objects with heights of 50 m and 300 m for perfectly conducting earth, respectively. The coefficient \( A = H_{\text{tall, peak}}/H_{\text{tradition, peak}} \) for perfectly conducting ground, \( H_{\text{tall, peak}} \) presents the case for strike to tall objects and \( H_{\text{tradition, peak}} \) comes from the traditional method (the first term in approximate Eq. (9)).

Fig. 6. Propagation effect of finite conductivity on the azimuthal magnetic field produced by lightning flashes strike to tall objects for different conductivity ranging from 0.01 to 0.001 S/m, and the traditional method (the first term in Eq. (9)) is presented for comparison. The risetime (RT) of the lightning current is assumed to be 5h/c.

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$A(d) = 0.039 \exp\left(-10.11 \times 10^{-5}d\right) + 1.054 \exp\left(-0.402 \times 10^{-7}d\right)$

$\sigma = \infty$ and $h = 50$ m

$A(d) = 0.210 \exp\left(-9.813 \times 10^{-5}d\right) + 1.117 \exp\left(-2.129 \times 10^{-7}d\right)$

$\sigma = \infty$ and $h = 300$ m

Therefore, for perfect conductivity, we can revise the traditional method for strike to electrically short objects.

$H_{peak}^{peak} \approx A(d) \frac{v}{2\pi c} \sigma^{peak}$

where, $A(d)$ is the coefficient as shown from Eqs. (10) and (11) for different height of objects, $H_{peak}^{peak}$ is the measured magnetic field peak on the perfect conductivity and $H_{peak}^{peak}$ is the lightning stroke current peak that would be measured at an ideally grounded object with a negligible height.

### 3.2. For the finitely conducting ground

Fig. 6 shows the propagation effect of finite conductivity on the azimuthal magnetic field produced by lightning flashes strike to tall objects, and the traditional term in Eq. (9) is presented for comparison.

The risetime (RT) of lightning current is assumed to be 5 μs ($5h/c$, a typical subsequent return stroke with relatively more high frequency (e.g., Qie et al., 2007, 2009, 2014; Wang et al., 2012; Yang et al., 2008, 2010; Zhang et al., 2009), the corresponding field attenuation along the finitely conducting ground is more (see Fig. 6(b)), because the presence of tall objects tends to further increase higher frequency contents, and the field propagation attenuation for lightning strike to tall objects mainly depends on the height of tall objects, the earth conductivity and the current RT. From the simulated results and observed data (Weidman et al., 1981; Leteinturier et al., 1990; Zhang et al., 2012a), the propagation effect of finitely conducting ground on the electromagnetic spectrum about over 1–2 MHz (the corresponding characteristic RT of current waveform is about less than 1 μs) has to be taken into account. However, when the lightning strikes the 300-m-tall object (see Fig. 6(c)), the RT is $5h/c$ (5 μs), which is a typical first return stroke with relatively less high frequency, the corresponding field attenuation is less.

In order to further investigate the difference between the traditional method and the case for strike to tall objects for finitely conducting earth, let us define the coefficient $B = H_{peak,peak}/H_{trad,peak}$, where, $H_{peak,peak}$ presents the case of strike to tall objects and $H_{trad,peak}$ presents the traditional method. As shown in Fig. 7, we note that, the coefficient $B$ is larger than 1 (see Fig. 7(a)), which means that the tall object increases the initial field peak, the taller objects result into a larger field peak and at the same time the corresponding field attenuation is less due to the larger RT. However, for the 50-m-tall object, the coefficient $B$ is less than 1 in some cases (see Fig. 7(b)), which means that although the 50-m-tall object increases the initial field peak, the propagation effect is more serious due to the less RT, and the lower conductivity will result into the more serious field attenuation. Therefore, when the lightning strikes the 300-m tall object, the lightning current peak from the measured magnetic field peak according to the traditional method is overestimated ranging from about +5% to +20% (positive means overestimation while negative means underestimation) and the derivation value is more within distances of 20 km because of the effect of induction magnetic field component. When the lightning strikes the 50-m-tall object, the predicted current peak according to the traditional method has an error ranging from about +5% to −15%.

Further analysis shows that the coefficient $B$ is the function of the observed distance $d$, conductivity $\sigma$, height of tall object $h$ and the current RT. For the typical RT ($5h/c$), we can derive the fitted coefficient $B$ for different tall heights from the computed field values as shown below:

$B(d) = 0.057 \exp\left(-8.066 \times 10^{-5}d\right) + 1.031 \exp\left(-2.600 \times 10^{-7}d\right)$

for $\sigma = 0.01$ S/m and $h = 50$ m

$B(d) = 0.114 \exp\left(-4.033 \times 10^{-5}d\right) + 0.957 \exp\left(-11.55 \times 10^{-7}d\right)$

for $\sigma = 0.001$ S/m and $h = 50$ m

$B(d) = 0.211 \exp\left(-9.826 \times 10^{-5}d\right) + 1.117 \exp\left(-2.990 \times 10^{-7}d\right)$

for $\sigma = 0.01$ S/m and $h = 300$ m

$B(d) = 0.218 \exp\left(-8.360 \times 10^{-5}d\right) + 1.094 \exp\left(-5.183 \times 10^{-7}d\right)$

for $\sigma = 0.001$ S/m and $h = 300$ m

Also, we found that the reflection coefficients of tall objects ranging from observed data presented by Bermudez et al. (2003) have not much effect on the far magnetic field, as shown in Fig. 8, and our fitted functions from Eqs. (13)–(16) nearly do not depend on the reflection coefficients of tall objects.

Therefore, for finitely conducting earth, we can revise the far-field–current relationship between the lightning current peak and...
value and the measured magnetic field peak for strike to electrically short objects as below

\[ H_{\phi}^{\text{peak}} = B(d) \frac{V}{2\pi cd} \]

(17)

where, \( B(d) \) is the coefficient as shown from Eqs. (13)–(16) for different cases, \( H_{\phi}^{\text{peak}} \) is the measured magnetic field peak on the finitely conducting ground and \( I_s^{\text{peak}} \) is the lightning stroke current peak that would be measured at an ideally grounded object with a negligible height.

Also, it is worth noting that from the traditional term (or the traditional method), the azimuthal magnetic field has the same waveform of the lightning current. Although this condition is valid for large distances from the stroke point (Uman et al., 1975), as can be seen in the general time-domain expression for the lightning magnetic field (Barbosa and Paulino, 2007), these waveforms may be identical also for the close range, provided that the return stroke speed is very close to the speed of light \( (v=c) \). From Figs. 9 and 10, stroke speeds have much effect on the far field and coefficient \( B \), our results in this paper, including Eqs. (10)–(17),

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are valid for the typical return stroke speed $v = 150$ m/s that is the most widely used in many references (e.g., Baba and Rakov, 2005a, 2007, Cooray, 2008, 2009, Li et al., 2013, 2014).

4. Conclusion and discussion

In this paper we have studied the accuracy of the general expressions presented by Bermudez et al. (2005, 2007) and have revisited them for perfectly and finitely conducting ground, respectively. For the perfectly conducting ground, the results show that when the rise time of lightning current (RT) is 5/h, the field peak values for strike to tall objects are about close to that strike to flat ground at distances of 10–100 km from the lightning channel, and the overestimation caused by the traditional method is within 10% beyond a distance of 20 km, and with the decrease of observed distance $d$, the error will increase due to the effect of induction field component. However, for the finite conductivity ranging from 0.01 S/m to 0.001 S/m, when the lightning strikes the 300 m-tall object, the lightning current peak from the measured magnetic field according to the traditional method is overestimated ranging from about +5% to +20% and the derivation value is more within distances of 20 km because of the effect of induction field component. When the lightning strikes the 50-m-tall object, the predicted current peak according to the traditional method has an error ranging from about +5% to −15% (positive means overestimation while negative means underestimation).

Above all, the estimation of the lightning current peak for strike to tall objects should consider the effect of the observed distance, earth conductivity, height of tall object, the RT of strike current waveform and stroke speed. Also, in this paper we do not consider the effect of attachment process between the downward leader and upward leader (e.g., Gao et al., 2014; Lu et al., 2008a, 2008b, 2009, 2012, 2013; Jiang et al., 2013) on the far magnetic field, and also we do not consider the effect of frequency dependent soil (e.g., Cavka et al., 2014; Portela, 1999; Visacro et al., 2011; Visacro and Alipio, 2012), which will be studied in future work.

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