LUMINOSITY CHARACTERISTICS OF LIGHTNING DISCHARGE MODELS

Novaković Vladimir, Mijović Bogdan, Gligorijević Ivan, Stefanović Miloš, Jovan Cvetić
Faculty of Electrical Engineering, University of Belgrade, Belgrade

Abstract - A comparative analysis has been performed on the lightning channel-base current and the radiated light waveforms for different return stroke models. It is accepted that the lightning current along the channel and the emitted light signals exhibit a linear relationship (direct proportionality) in their rising portions. The strong influence of the velocity decay constant on the apparent return stroke velocity is analyzed. Two return stroke models of the traveling-current-source-type are chosen and compared: Diendorfer-Uman model and the modified Diendorfer-Uman model. It is concluded that the channel discharge constant has the decisive influence on the channel luminosity output. These findings support the idea of evaluating the variations of return stroke current along the lightning return stroke channel using light signals, provided that evaluation is limited to the rising portions of those signals and assuming that the light/current relationship observed at the bottom of the channel holds at other heights.

1. INTRODUCTION

Flowers [1], was the first to examine the relation between the intensity of emitted light and the lightning current. Unfortunately, due to the poor time resolution he could not examine the relation of the emitted light and the current of the individual return strokes. Simultaneous electrostatic field change records, Mackerras [2], that were correlated with the photometric observations of the light emitted by entire lightning channels have shown the correlation between the charge transferred or the energy dissipated by the lightning return stroke. Later investigations of the relation between the emitted light from either a section or the entire channel and the electric field patterns, Guo and Krider [3], Jordan and Uman [4], indicated that the intensity of visible light emitted by the return stroke and the peak value of the radiated electric field are related. Since the current is the source of the radiated electric field, the return stroke light and current are also related.

The linear correlation between the peak relative light intensity near ground and the stroke peak current performed on triggered lightning subsequent return strokes have been indicated through the measurements of Idone and Orville [5].

Particular interest has been devoted to the two-dimensional velocity of propagation of lightning return strokes, Boyle and Orville [6]. The range of observed velocities spans the interval of 2.9-24×10⁷ ms⁻¹ with the peak stroke current at approximately 10⁸ ms⁻¹. The rise time of the accepted channel-base current is \( \tau_p = 4.2 \mu s \).

3. THE INFLUENCE OF THE VELOCITY DECAY CONSTANT ON THE APPARENT RETURN STROKE VELOCITY

The geometry of the lightning channel and the observer is shown in Fig.1. The existence of straight vertical channel without tortuosity is assumed. According to the Fig.1, the return stroke wave-front at some instant of time is at height \( H_1 \), moving upwards with the real return stroke velocity \( v(H) \). The apparent height \( h_M \) of the channel can be expressed as [12]:

\[
\int_0^{h_M} d\xi / \sqrt{v(\xi)} = t - R_{RM}/c, \quad R_{RM} = [ (h_M - h)^2 + r^2 ]^{1/2}.
\]

In further consideration the observer’s time \( t_M \) instead of absolute time is used

\[
t_M = t - t_{min}, \quad t_{min} = \sqrt{r^2 + h_M^2 / c},
\]

If the real return stroke velocity profile is described with the exponential decrease (the most used approximation in literature, Bruce and Golde [13]):
where $v_0$ is the initial return stroke velocity at the ground level and $\lambda'$ represents the velocity decay constant. The solution of the integral equation Eq. (1) using the real return stroke velocity profiles given by the Eq. (3) is given in Figs. 2 and 3.

\[ v(z) = v_0 \exp(-\xi/\lambda') \]

\[ \text{(4)} \]

where $v_0$ is the initial return stroke velocity at the ground level and $\lambda'$ represents the velocity decay constant. The solution of the integral equation Eq. (1) using the real return stroke velocity profiles given by the Eq. (3) is given in Figs. 2 and 3.

Figure 1 The position of the lightning channel and the observer

In Fig. 2 the deviation of the average apparent return stroke velocities as a function of the apparent return stroke height are shown. The different values of the initial return stroke velocities (with the decay constant $\lambda = 2$ km) and the radial distances of the observer are used as parameters. For all radial distances and for all heights up to 2-3 km the relative deviation is negative rising up to more than 60%.

Figure 2 The deviation of the average apparent return stroke velocity as a function of the apparent return stroke height at $h=20$ m for different initial values and distances: a) $v_0=0.5c$, b) $v_0=0.42c$, c) $v_0=0.33c$, d) $v_0=0.25c$. The return stroke velocity decay constant is $\lambda = 2$ km.

The small positive deviation of the average apparent velocity is the result of the approaching of the return stroke wave-front at the beginning of the discharge caused by the position ($h=20$ m) of the observer above ground. The greatest deviation is observed closest to the striking point for $r=0.1$ km. In that case the decreasing of the apparent speed more than 40% is calculated below 1 km of the channel regardless of the initial return stroke speed.

In Fig. 3 we examined the influence of the return stroke velocity decay constant on the average apparent velocity. As it is expected, the decay constant changes a lot the apparent return stroke profile. Even in the case (d) where this constant is infinite, the deviation of the apparent velocity is more than 20% regarding on the radial distance of the observer and the apparent height of the channel. The deviation increases with the increasing of the value of the velocity decay constant rising up to more than 80% for $\lambda = 4$ km. It is interesting to note in Figs. 2 and 3 that for the limiting case $t_M \rightarrow \infty$ the deviation does not depend on the radial distance.

4. MODELING OF LIGHTNING PROCESSES

The most used engineering models can be grouped in two categories: transmission-line-type models and traveling-current-source-type models. In the traveling-current-source-type models, the return stroke current may be viewed as being generated at the upward moving return stroke wave-front and then propagating downward.

In the DU model the current turns on gradually (exponentially with a time constant $\tau_D$). If $\tau_D = 0$ the DU model reduces to the TCS model. In the DU model two components of

**Figure 3** The deviation of the average apparent return stroke velocity as a function of the apparent return stroke height at $h=20$ m for different distances. The return stroke velocity decay constant is chosen as a parameter: a) $\lambda = 1$ km, b) $\lambda = 2$ km, c) $\lambda = 4$ km, d) $\lambda \rightarrow \infty$. The initial real return stroke velocity is $v_0=c/3$.
where \( \bar{\nu} \) is the average reduced return stroke velocity. The current distribution along the channel is given by:

\[
i(\xi, t) = \left\{ i_0(t - \frac{\xi}{c}) - i_0(\xi/\nu) \exp\left[-\left(t - \frac{\xi}{\bar{\nu}}/v_{av}\right)\right] \right\} u(t - \xi/\bar{\nu}),
\]

(5)

where \( \nu = v - c \nu - c \) is the so-called reduced return stroke velocity, \( i_0 \) is the current at the channel-base and \( u(t) \) is the Heaviside unit function.

Thottappilli et al. [15] mathematically generalized the DU model to include a variable upward front velocity and a variable downward current-wave velocity, both separate arbitrary functions of height. They introduced the average return stroke velocity:

\[
v_{av} = \int_0^\infty d\xi / \nu(\xi).
\]

(6)

The current distribution along the channel is given by:

\[
i(\xi, t) = \left\{ i_0(t - \frac{\xi}{c}) - i_0(\xi/\nu_{av}) \exp\left[-\left(t - \frac{\xi}{\bar{\nu}_{av}}/v_{av}\right)\right] \right\} u(t - \xi/\bar{\nu}_{av}).
\]

(7)

where \( \nu_{av} = \frac{\nu}{\bar{\nu}} \) is the average reduced return stroke velocity. Using the Eq.(4), from the Eq.(6) the average reduced return stroke velocity can be expressed as:

\[
v_{av}(z) = \frac{\lambda}{v_0} \left( \exp(z/\lambda) - 1 \right) / v_0.
\]

(8)

### 5. The Total Luminosity of the Channel According to the DU and the MDU Models

The expression for the total light intensity is given in [11] and [12]. According to Fig.1 its magnitude observed at the observer’s point M will be:

\[
\Psi_M(t_M) = \int_0^{h_M} \left( r/R_M^3 \right) i_M(\xi, t_M) \, d\xi.
\]

(9)

where

\[
i_M(\xi, t_M) = i(\xi, t - R_M/c) = i(\xi, t_M - t_{min} - R_M/c)
\]

(10)

is the current observed along the channel from the observer’s point.

In Fig.4 the graphs of the relative total light intensity \( \Psi^* = \Psi_M/\Psi_{Mmax} \), emitted from the channel during the rise time of the channel-base current for close distance \( r=0.1 \text{km} \), according to the DU model are depicted. We analysed the influence of the different real return stroke velocities on a channel light output. For the comparison analysis the graph of the channel-base current is depicted in function of the observer’s time. First, the current at the channel-base and the graphs of the channel luminosity pattern are similar, there are no light signal delay as it is observed in the transmission-line-type models [12]. Moreover, if the real return stroke velocity is equal to the half of the light speed both graphs are almost identical. Secondly, the decreasing of the real return stroke velocity produces the similar percentage decreasing in the channel light output.

In Fig.6 the graphs of the relative total light intensity according to the MDU model are depicted. Although the real return stroke velocity decreases exponentially there are no visible differences in the graphs compared with those of the DU model in Fig.5.
REFERENCES


