A Short Scientific Report on the STSM

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1. Purpose of the visit

This report presents results obtained at the University of Florida, Gainesville in June 2006 during a Short Term Scientific Mission. The main purpose of the visit to the University of Florida was lightning research, especially, lightning discharge modeling and analyze of the close electric field measurements made in 2000 at the International Center for Lightning Research and Testing (ICLRT) located at Camp Blanding, Florida [1]. Additionally, discussion on the application of the moving frame concept and the transmission-line type models formulated in the frequency domain was also planned. These specific purposes correspond with the main objectives of the Action P18 which are modeling of lightning discharge and of its effects on natural and man-made systems. Strengthening of collaboration in the field of lightning discharge modeling with the ICLRT was also one of the purposes of the STSM.

The ICLRT is operated by Electrical and Computer Engineering department of the University of Florida since 1994. The triggered-lightning experiments are conducted from May through September. The ICLRT includes a tower launcher 11 m in height and a relocateable SATTLIF (Sandia Transportable Triggered Lightning Instrumentation Facility). Apart from the launchers, ICLRT includes overhead power lines, pad mount transformers located in four instrumentation stations, a simulated house, other test objects and systems and various office and storage trailers.

1. Miki, M., V.A. Rakov, K.J. Rambo, G.H. Schnetzer, and M.A. Uman, (2002), Electric fields near triggered lightning channels measured with Pockels sensors, *J. Geophys. Res*., vol. 107, pp. D11-D16.

2. Description of the work carried out during the visit

A main issue of scientific work carried out during the visit to the University of Florida was analysis of different electric field zones within and outside of the lightning corona sheath . It was considered based on the measurements made by Miki in 2000 at the ICLRT at Camp Blanding, Florida, and theoretical papers on modeling of the lightning corona sheath.

<u>*Concept of electric field zones*</u>

Electric field waveform at horizontal distances from the triggered lightning channel attachment point ranging from 0.1 to 1.6 m have been measured with Pockels sensors at the ICLRT. Typical V-shape of electric field waveforms were recorded. The negative electric field measured during the leader stage often has been overcompensated by the electric field growing during the return-stroke stage. Interestingly, the maximum overcompensate values recorded for the horizontal electric field components were enough for starting of positive breakdowns.

Such phenomena can be explained based on the idea of the positive and negative charge distribution inside the lightning corona sheath which finally is established after the return stroke stage. *Maslowski and Rakov*, (2006)[2] based on the their consideration of the lightning corona sheath dynamics inferred about two zones around the lightning channel core. First zone close to the core, with net positive charge and the second zone with negative charge distributed on the boundary of the corona sheath. The net charge has been assumed zero for the observer situated outside of the corona sheath. The same type of regions has been considered by *Gorin*, (1985)[3]. He does not considered dynamics of the corona sheath but assumed an arbitrary distribution of the positive and negative charge inside the corona sheath in two instants of time: before and after the return stroke.

The idea of two different charged zones inside the corona sheath can be used to explain the measured waveshapes of the horizontal electric field components.

<u>*Leader channel just prior to the return stroke*</u>

The arbitrary negative charge distribution within the corona sheath can be assumed just

[2] G. Maslowski and V.A. Rakov, “A Study of the Lightning-Channel Corona Sheath,” *J. Geophys. Res*., (in print), 2006.
[3] Gorin, B.N., (1985), Mathematical modeling of the lightning return stroke, *Elektrichestvo* 4, pp. 10-16.

prior to the return stroke. Two possible volume charge density was shown in Fig. 1.

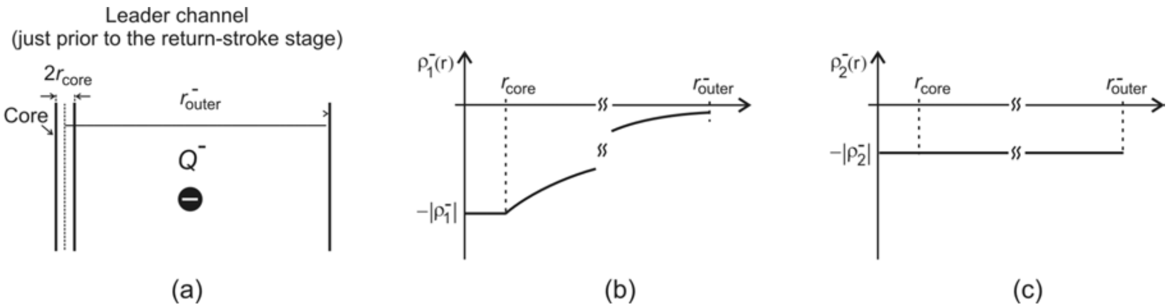

Figure 1. Leader channel (a) with negative charge distributed inside the channel core and within the corona sheath, (b) uniform charge density inside the core and inversely proportional to radius within the corona sheath from r_{core} to outer radius r_{outer}^{-}, (c) uniform charge density inside the core and corona sheath.

The horizontal (radial) electric field can be calculated close to the lightning channel assuming the cylindrical symmetry of charge distribution. Then, the horizontal field component in the cylindrical coordination should satisfied the differential Gauss' law,

$$\frac{1}{r}\frac{d}{dr}\left[rE(r,t_1)\right]=\frac{\rho(r,t_1)}{\varepsilon_0} \tag{1}$$

Note that t_1 will be neglected for simplicity in further consideration. Using (1) and volume charge density described in Figure 1b, that is,

$$\rho_1^-(r)=\begin{cases} -\left|\rho_1^-\right| & \text{for} \quad 0\le r\le r_{core} \\ -\dfrac{\left|\rho_1^-\right| r_{core}}{r} & \text{for} \quad r_{core}\le r\le r_{outer}^- \\ 0 & \text{for} \quad r>r_{outer}^- \end{cases} \tag{2}$$

one can derive the radial electric field as,

$$E_1^-(r)=\begin{cases}-\dfrac{\left|\rho_1^-\right|}{2\varepsilon_0}r & \text{for } 0\le r\le r_{core}\\ -\dfrac{\left|\rho_1^-\right|r_{core}}{\varepsilon_0}+\dfrac{\left|\rho_1^-\right|}{\varepsilon_0}\dfrac{r_{core}^2}{r} & \text{for } r_{core}\le r\le r_{outer}^-\\ -\dfrac{\left|\rho_1^-\right|r_{core}}{\varepsilon_0}\dfrac{r_{outer}^-}{r}+\dfrac{\left|\rho_1^-\right|}{2\varepsilon_0}\dfrac{r_{core}^2}{r} & \text{for } r\ge r_{outer}^-\end{cases} \tag{3}$$

For uniform charge distribution described by

$$\rho_2^-(r)=\begin{cases}-\left|\rho_2^-\right| & \text{for} \quad 0\le r\le r_{outer}^-\\ 0 & \text{for} \quad r> r_{outer}^-\end{cases} \tag{4}$$

one can derive in the same manner the following solution of (1)

$$E_2^-(r)=\begin{cases}-\dfrac{\left|\rho_2^-\right|}{2\varepsilon_0}r & \text{for } 0\le r\le r_{outer}^-\\ -\dfrac{\left|\rho_2^-\right|}{2\varepsilon_0}\dfrac{(r_{outer}^-)^2}{r} & \text{for } r\ge r_{outer}^-\end{cases} \tag{5}$$

The electric field predicted by (3) for $r_{core}\le r\le r_{outer}^-$ is practically constant. On the lateral surface of the corona sheath ($r_{outer}^-\gg r_{core}$) the negative electric field approaches to value $-\left|\rho_1^-\right|r_{core}/\varepsilon_0$ which can be assumed as a negative breakdowns value $-\left|E_r^-\right|$. The field predicted by (5) linearly decreases within the corona sheath up to value $-\left|\rho_2^-\right|r_{outer}^-/2\varepsilon_0$ which also can be assumed as a breakdowns value $-\left|E_r^-\right|$. Note that these assumptions enable to calculate ρ_1^- and ρ_2^- when the radii of channel core and negative corona sheath are known. The radius of lightning channel core is usually adopted in order of 10^{-2} m, and the radius of the negative corona sheath can be calculated from the following equation (*Maslowski and Rakov*, 2006),

$$r_{outer}^-=\frac{\rho_{leader}(z')}{2\pi\varepsilon_0\left|E_r^-\right|} \tag{6}$$

where $\rho_{leader}(z')$ is a line leader charge density. This charge density can be determined using transmission line type models. For the MTLL, MTLP, and MTLE models one can write $\rho_{leader}(z')$ as,

$$\rho_{leader}(z') = \begin{cases} -\dfrac{1}{H} Q^{+}_{total} & \text{for the MTLL model} \quad (7a) \\ -\dfrac{2(1 - z'/H)}{H} Q^{+}_{total} & \text{for the MTLP model} \quad (7b) \\ -\dfrac{e^{-z'/\lambda}}{\lambda} Q^{+}_{total} & \text{for the MTLE model} \quad (7c) \end{cases}$$

where Q^{+}_{total} is the total positive charge which is transferred by the longitudinal current. Note that we assume that the total negative charge deposited by leader Q^{-}_{total} is equal to Q^{+}_{total}.

Lightning channel after the return stroke

Due to enough strong radial electric field on the core surface occurring during the return stroke stage a part of the negative charge distributed close to this core is neutralized by positive charge. A strong positive electric field can overcompensate the negative leader electric field and then positive breakdowns can start inside the first zone of the corona sheath. The zone with net positive charge is stretched up to radius r^{+}_{outer} for which the positive electric field decreases below the assumed breakdown value and the total positive charge Q^{+}_{total} is equal to total negative charge Q^{-}_{total} (see Figure 2).

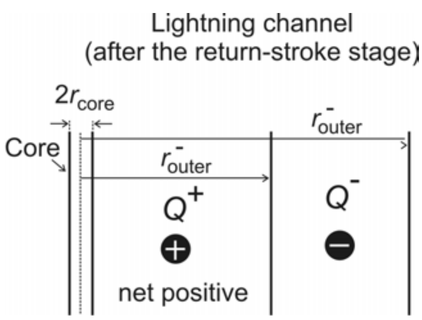

Figure 2. Lightning return stroke channel after the return stroke with two different charged zones.

We limit our further consideration to the following different positive charge distribution,

$$\rho_1^+(r) = \begin{cases} \left|\rho_1^-\right| + \rho_1^+ & 0 \le r \le r_{core} \\ \dfrac{\left|\rho_1^-\right| r_{core}}{r} + \dfrac{\rho_1^+ r_{core}}{r} & r_{core} \le r \le r_{outer}^+ \\ 0 & r > r_{outer}^+ \end{cases} \tag{8}$$

$$\rho_2^+(r) = \begin{cases} \left|\rho_2^-\right| + \rho_2^+ & 0 \le r \le r_{core} \\ \left|\rho_2^-\right| + \dfrac{\rho_2^+ r_{core}}{r} & r_{core} \le r \le r_{outer}^+ \\ 0 & r > r_{outer}^+ \end{cases} \tag{9}$$

$$\rho_3^+(r) = \begin{cases} \left|\rho_3^-\right| + \rho_3^+ & 0 \le r \le r_{outer}^+ \\ 0 & r > r_{outer}^+ \end{cases} \tag{10}$$

Using (8) one can derive from (1) the electric field which is generated by positive charge in absence of negative charge,

$$E_1^+(r) = \begin{cases} \dfrac{\left|\rho_1^-\right| + \rho_1^+}{2\varepsilon_0} r & \text{for } 0 \le r \le r_{core} \\ \dfrac{\left(\left|\rho_1^-\right| + \rho_1^+\right) r_{core}}{\varepsilon_0} - \dfrac{\left(\left|\rho_1^-\right| + \rho_1^+\right)}{2\varepsilon_0} \dfrac{r_{core}^2}{r} & \text{for } r_{core} \le r \le r_{outer}^+ \\ \dfrac{\left(\left|\rho_1^-\right| + \rho_1^+\right) r_{core}}{\varepsilon_0} \dfrac{r_{outer}^+}{r} - \dfrac{\left(\left|\rho_1^-\right| + \rho_1^+\right)}{2\varepsilon_0} \dfrac{r_{core}^2}{r} & \text{for } r \ge r_{outer}^+ \end{cases} \tag{11}$$

Using charge distribution described by (9) one can determine from (1) the following field generated by positive charge,

$$E_2^+(r)=\begin{cases}\dfrac{\left|\rho_2^-\right|+\rho_2^+}{2\varepsilon_0}r & 0\le r\le r_{core}\\ \dfrac{\left|\rho_2^-\right|}{2\varepsilon_0}\dfrac{r^2-(r_{core})^2}{r}+\dfrac{\rho_2^+ r_{core}}{\varepsilon_0}\dfrac{r-r_{core}}{r}+\dfrac{(\left|\rho_2^-\right|+\rho_2^+)}{2\varepsilon_0}\dfrac{r_{core}^2}{r} & r_{core}\le r\le r_{outer}^+\\ \dfrac{\left|\rho_2^-\right|}{2\varepsilon_0}\dfrac{(r_{outer}^+)^2-(r_{core})^2}{r}+\dfrac{\rho_2^+ r_{core}}{\varepsilon_0}\dfrac{r_{outer}^+-r_{core}}{r}+\dfrac{(\left|\rho_2^-\right|+\rho_2^+)}{2\varepsilon_0}\dfrac{r_{core}^2}{r} & r\ge r_{outer}^+\end{cases}\qquad(12)$$

Using charge distribution described by (10) one can determine from (1) the following field generated by positive charge,

$$E_3^+=\begin{cases}\dfrac{\left|\rho_3^-\right|+\rho_3^+}{2\varepsilon_0}r & 0\le r\le r_{outer}^+\\ \dfrac{\left(\left|\rho_3^-\right|+\rho_3^+\right)}{2\varepsilon_0}\dfrac{\left(r_{outer}^+\right)^2}{r} & r\ge r_{outer}^+\end{cases}\qquad(13)$$

The electric field predicted by (11) for $r_{core}\le r\le r_{outer}^+$ is practically constant. On the lateral surface of the positive corona sheath zone $(r_{outer}^+ \gg r_{core})$ the positive electric field approaches to value $(\left|\rho_1^-\right|+\rho_1^+)r_{core}/\varepsilon_0$ which can be assumed as a sum of absolute values of the negative and positive electric field breakdowns $\left|E_r^-\right|+E_r^+$. Hence we have $E_r^+=\rho_1^+ r_{core}/\varepsilon_0$. From (12) one can deduce in the same manner that the $E_r^+=\rho_2^+ r_{core}/\varepsilon_0$, then, $\rho_1^+=\rho_2^+$. For case of uniform negative and positive charge distribution the horizontal electric field increases linearly within the core and corona sheath.

Note that assuming $Q_{total}^-=Q_{total}^+$ we can calculate the radius r_{outer}^+ as

$$\rho_{leader}dz=\left[\int_0^{r_{outer}^+}2\pi\rho^+(r)rdr\right]dz\qquad(14)$$

for different transmission-line type return stroke models.

3. Description of the main results obtained

Below, the spatial profiles of the positive, negative, and total electric fields for assumed charge distributions within the corona sheath both just prior to the return stroke and after the return stroke are shown. It was assumed an uniform charge distribution along the lightning channel as for the MTLL model.

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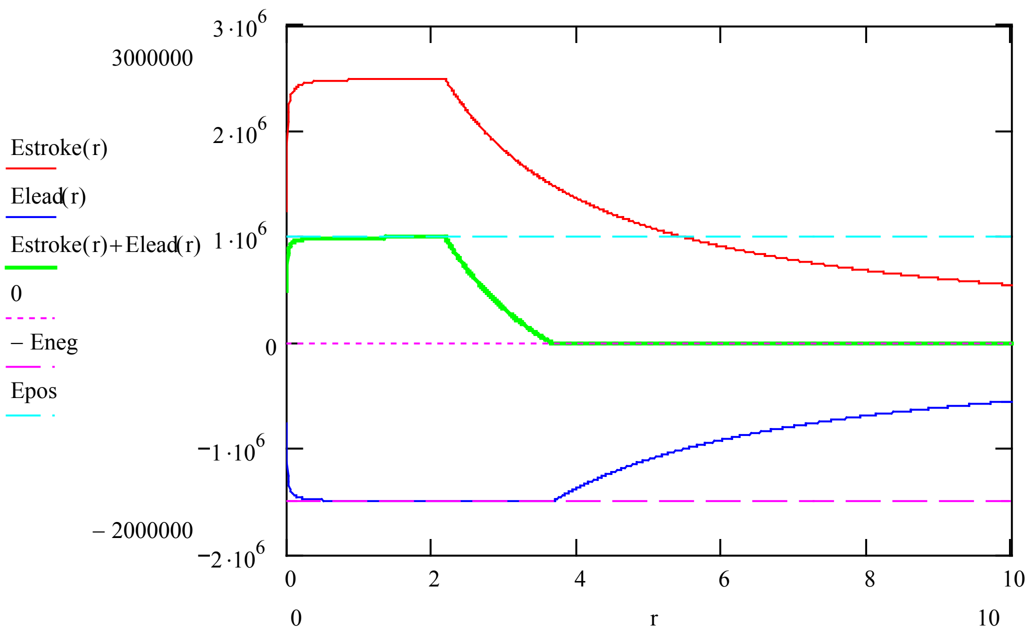
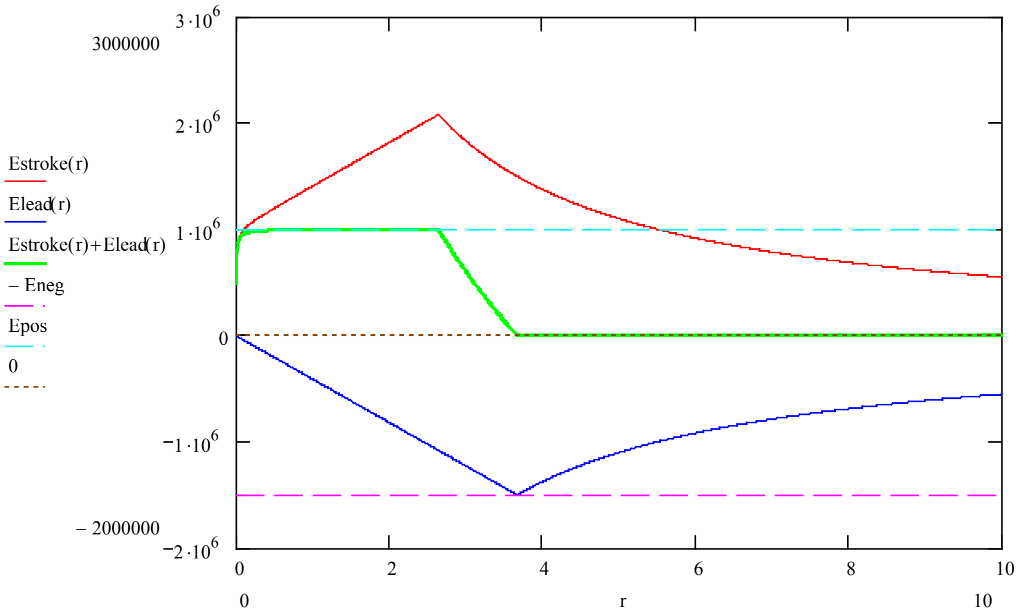
Negative charge distribution just prior to the return stroke - Equation (2)
Positive charge distribution after the return stroke - Equation (8)

$E_r^- = 1.5$ MV/m, $E_r^+ = 1.0$ MV/m, $r_{outer}^+ = 2.21$m, $r_{outer}^- = 3.67$m, $Q_{total}^- = Q_{total}^+ = 2.3$C



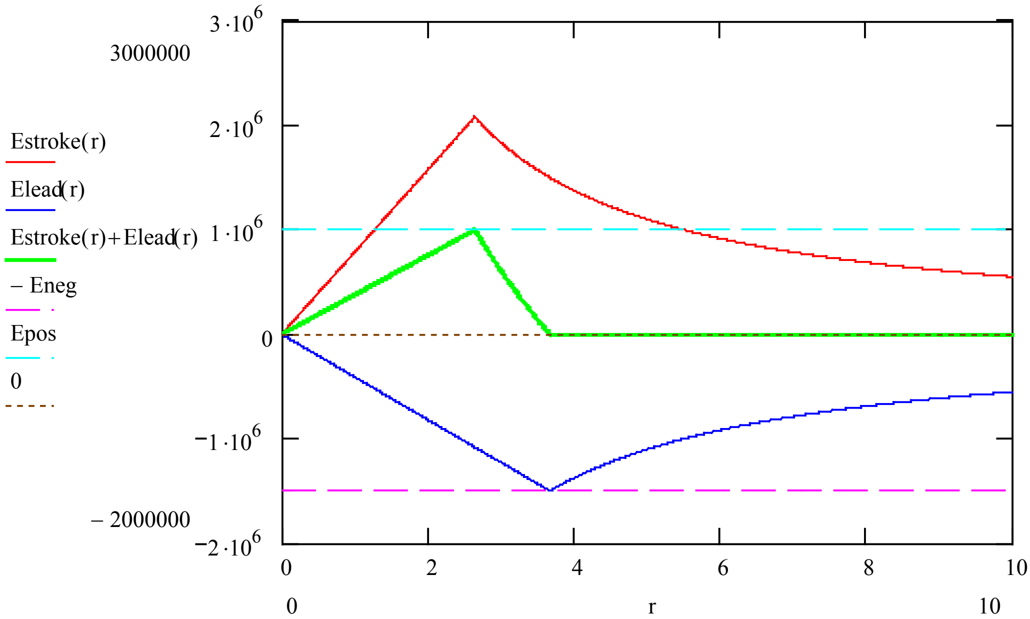
Negative charge distribution just prior to the return stroke - Equation (4)
Positive charge distribution after the return stroke - Equation (9)

$E_r^- = 1.5$ MV/m, $E_r^+ = 1.0$ MV/m, $r_{outer}^+ = 2.65$m, $r_{outer}^- = 3.67$m, $Q_{total}^- = Q_{total}^+ = 2.3$C



Negative charge distribution just prior to the return stroke - Equation (4)
Positive charge distribution after the return stroke - Equation (10)

$E_r^- = 1.5$ MV/m, $E_r^+ = 1.0$ MV/m, $r_{outer}^+ = 2.65$m, $r_{outer}^- = 3.67$m, $Q_{total}^- = Q_{total}^+ = 2.3$C



4. Future collaboration with host institution

Future collaboration with host institution is planned. Investigation of different electric field zones within the lightning corona sheath will be developed. Especially, theoretical consideration will be compared with the close electric field measurements made in 2000 at the International Center for Lightning Research and Testing (ICLRT) located at Camp Blanding, Florida.

Additionally, description of the transmission-line type models in a moving frame discussed during the STSM will be considered. Also, application of transmission line type models formulated in the frequency domain will be verified for the different configuration of lightning protection system of structures.

5. Projected publications/articles resulting or to result from the STSM

Two publication are planned which results from the STSM. First publication will be connected with the electric field zones issue, and the second will describe transmission line type models in the stationary and moving frame.