The electrodynamic model of the return stroke processes involving a bipolar leader scheme

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Introduction

- Return stroke (RS) process initiates when a stepped leader connects to an upward propagating leader.

- There are four types of the RS models:
  the gas dynamic models,
  the distributed-circuit models,
  the “engineering” models,
  the electromagnetic models

- Electromagnetic model of the RS solves the full set of the Maxwell's equations

- The concept of a bidirectional leader was put forward by Kasemir (1960). The leader develops bidirectionally with a zero overall charge.

The model

- We solve the Maxwell's equations in terms of electric and magnetic potentials similar to [da Silva, Pasko, 2015].

$$
\begin{aligned}
U(z,t) &= U_{amb}(z) + \frac{1}{4\pi\epsilon}\int_{h_1}^{h_2} \frac{q(z',t')}{\rho(z,z')}dz' + \frac{1}{4\pi\epsilon}\int_{d_1}^{d_2} \frac{q(z'',t'')}{\rho(z,z'')}dz'', \\
A(z,t) &= \frac{\mu_0}{4\pi}\int_{h_1}^{h_2} \frac{I(z',t')}{\rho(z,z')}dz' + \frac{\mu_0}{4\pi}\int_{d_1}^{d_2} \frac{I(z'',t'')}{\rho(z,z'')}dz'', \\
\frac{\partial A}{\partial t} &+ \frac{\partial U}{\partial z} + \frac{I}{G} = 0, \\
\frac{dq}{dt} &+ \frac{dI}{dz} = 0.
\end{aligned}
$$

- The system of equations are numerically solved by the MOM combined with FDTD method.

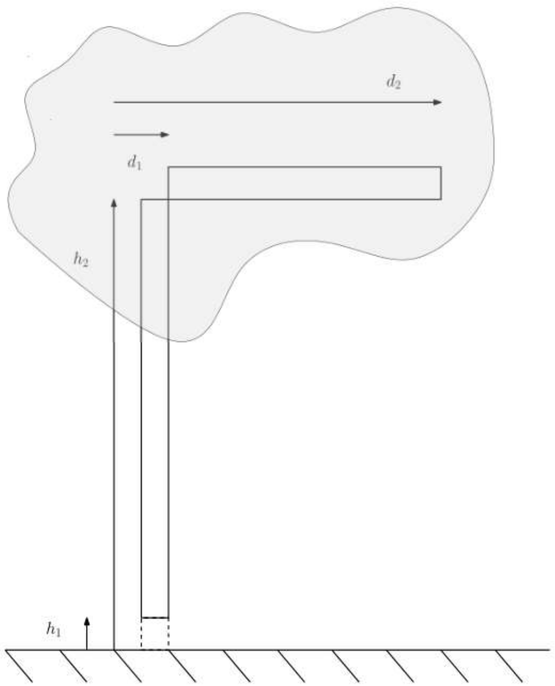
The model

- We put a zero potential element to the bottom part of the channel to model RS processes

- We use a nonlinear resistance model to evolve line conductivity

$$G(z,t) = \frac{\beta + \int_0^t I^{2/3} dt}{\alpha}$$

- We model the vertical RS channel connected to the horizontal in-cloud channel



The model

- We use the formula by [Uman et al., 1975] for computation of the electric and magnetic field for a given a current distribution

$$E_z(D,t) = \frac{1}{2\pi\epsilon_0}\int_{h_1}^{h_2}\frac{2-3\sin^2\theta}{R^3}\cdot\int_0^t I(z,\tau-R/c)d\tau dz$$
$$+ \quad \frac{1}{2\pi\epsilon_0}\int_{h_1}^{h_2}\frac{2-3\sin^2\theta}{cR^2}I(z,t-R/c)dz - \frac{1}{2\pi\epsilon_0}\int_{h_1}^{h_2}\frac{\sin^2\theta}{c^2R}\frac{\partial I(z,t-R/c)}{\partial t}dz,$$

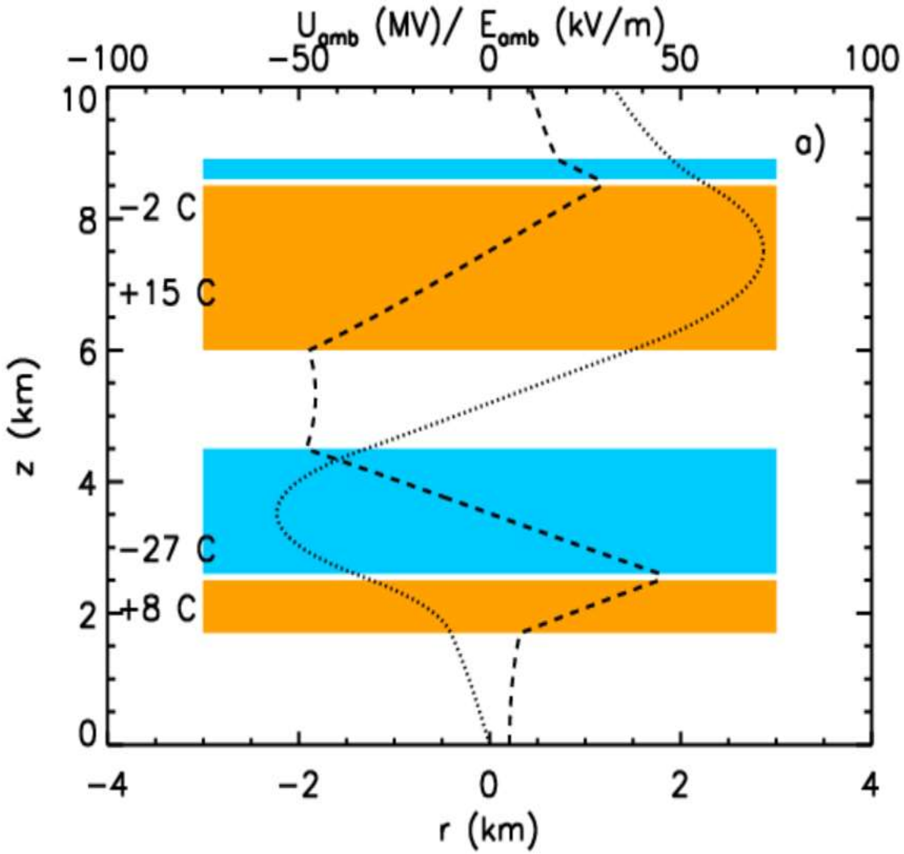
$$B_\phi(D,t) = \frac{\mu_0}{2\pi}\int_{h_1}^{h_2}\frac{\sin\theta}{R^2}I(z,t-R/c)dz + \frac{\mu_0}{2\pi}\int_{h_1}^{h_2}\frac{\sin\theta}{cR}\frac{\partial I(z,t-R/c)}{\partial t}dz.$$

- We assume the finite conductivity of a ground

The model

- We solve Poisson equation for a realistic thundercloud charge structure

$$\Delta U_{amb} = -\frac{\rho}{\epsilon}$$



The measurements

- The measurements were conducted at two different measurement sites in France

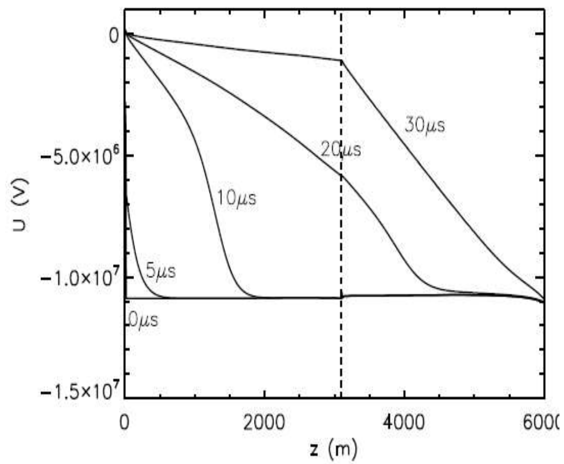
- Our instrumentation consists of a broadband HF analyzer BLESKA (Broadband Lightning Electro-magnetic Signal Keeper Analyzer); a clone of the IME-HF analyzer developed for the TARANIS spacecraft and the SLAVIA magnetic antenna

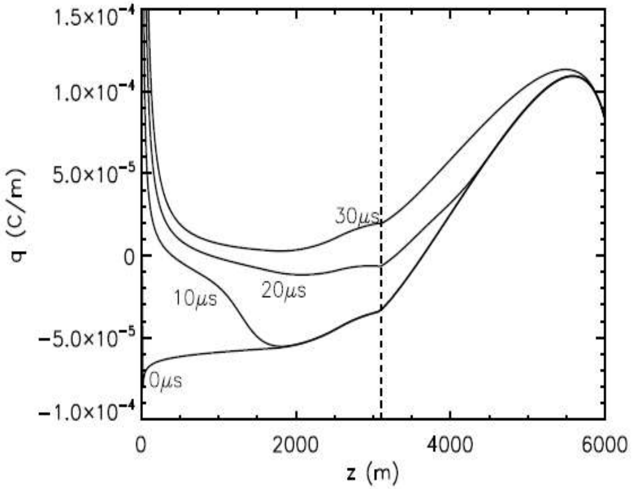
- A time derivative of a horizontal component of the magnetic field is sampled at a rate of 80 MHz and numerically integrated.

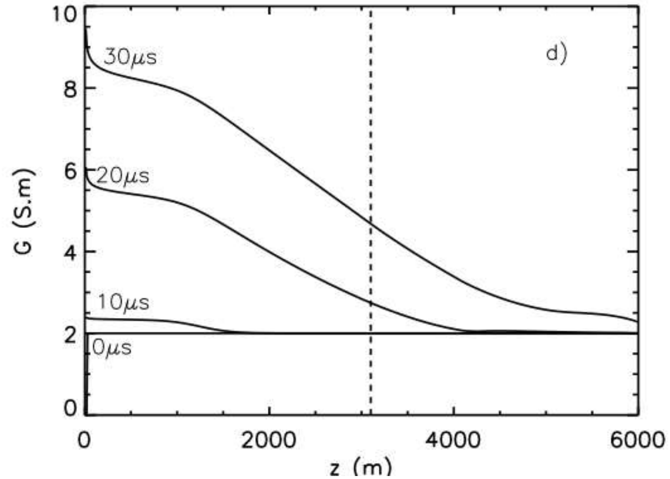
- We use the measurements in order to compare radiation part of the magnetic field waveform with our model

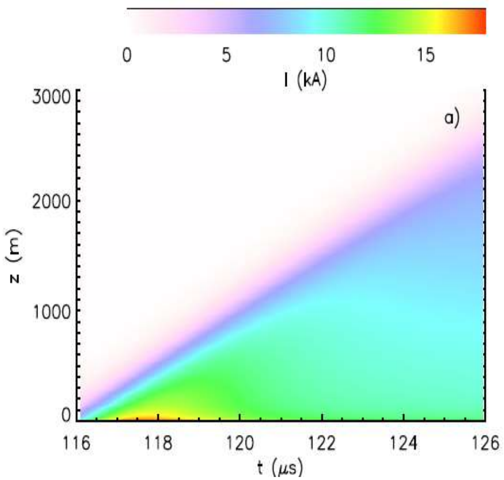
Results

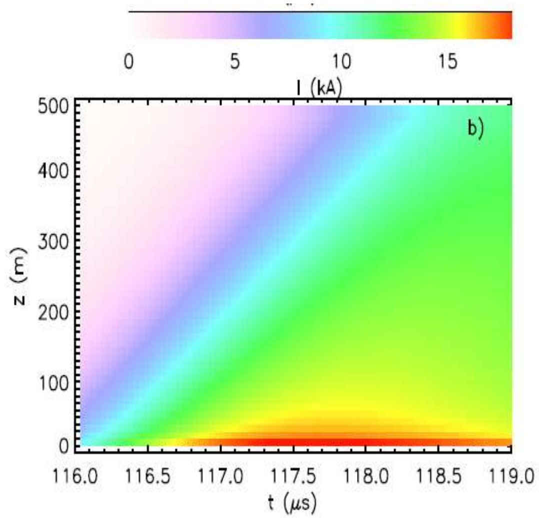
- Leader potential for different times since the beginning of the RS process, the total charges along the lightning core, values of the line conductivity distributed along the lightning channel
- The current pulse evolution for different heights above the ground level.

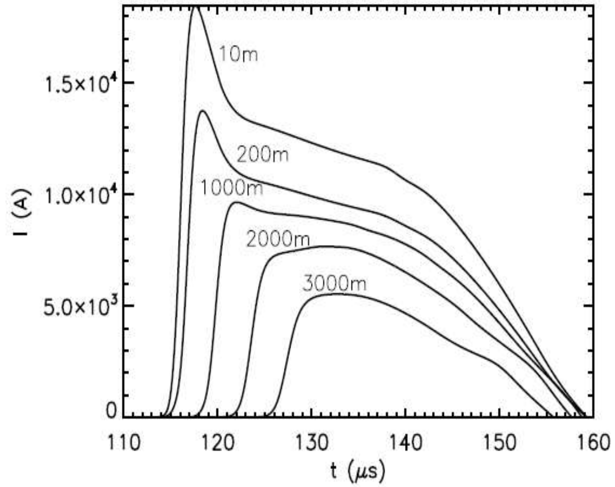






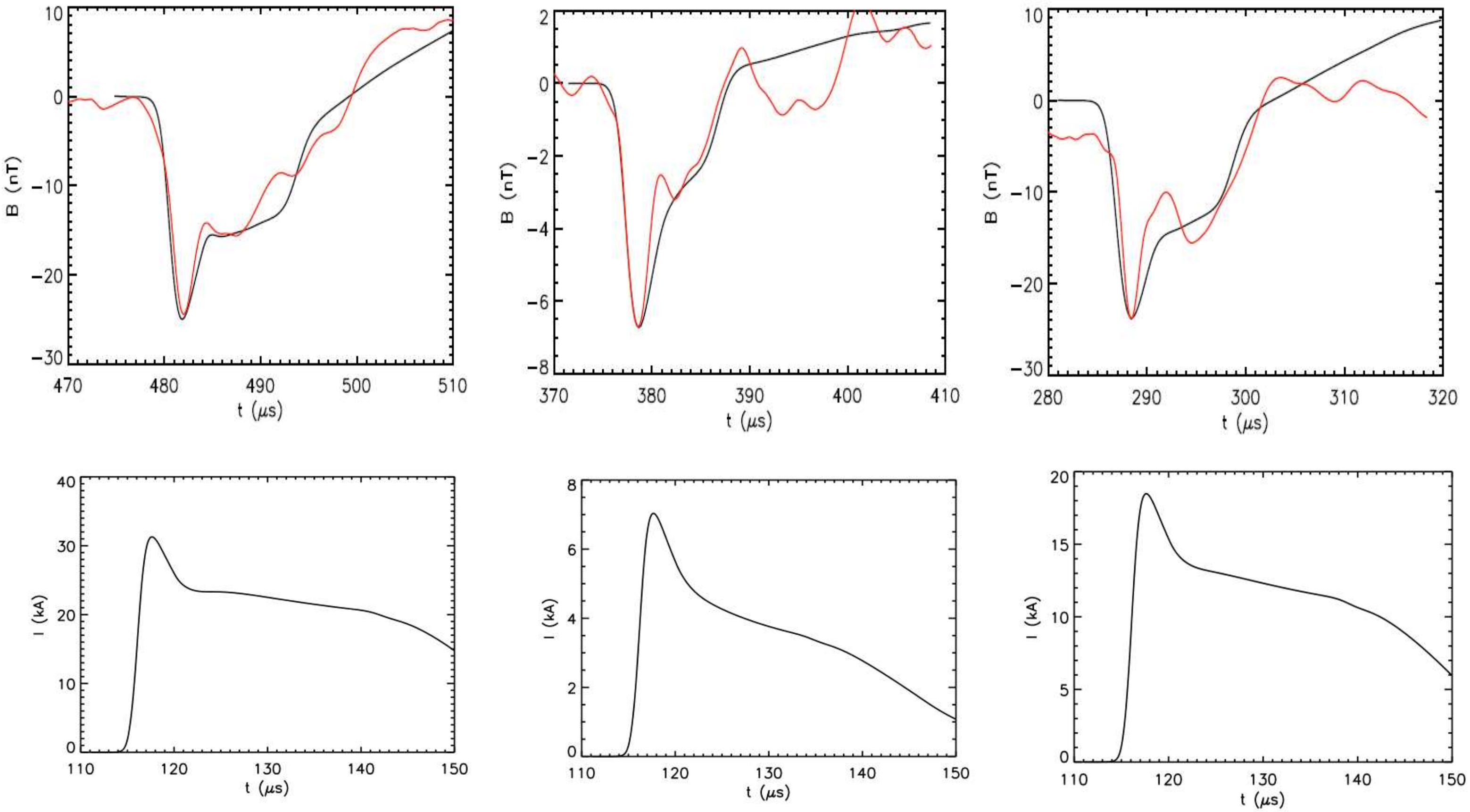






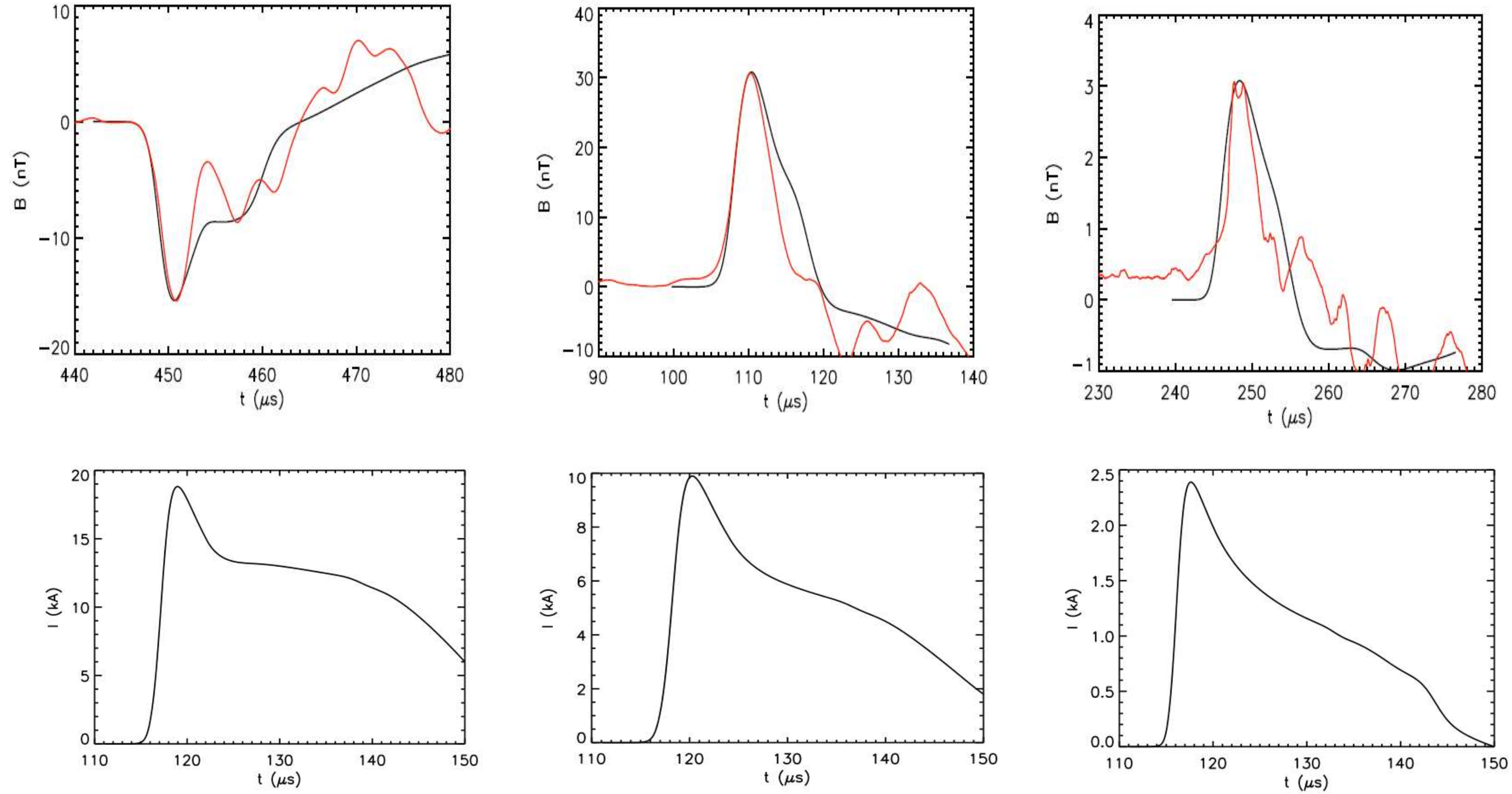
Results

- The measurement was conducted at the distances of tens of km from a lightning discharge
- Red line denotes the measurements, black line denotes the modeled waveform



- At the bottom there is a channel-base current derived from the model

Results



- Modeled magnetic field waveforms together with simulated channel-base current

Results

It was found (Lin et al., 1979) that the electromagnetic waveforms radiated by the RS processes occurring at different geographical and seasonal conditions possess following characteristic features (see the next slide for the modeled waveform):

1. Characteristic increase and subsequent flattening of the electric field waveforms at the close distances of about 1 km.

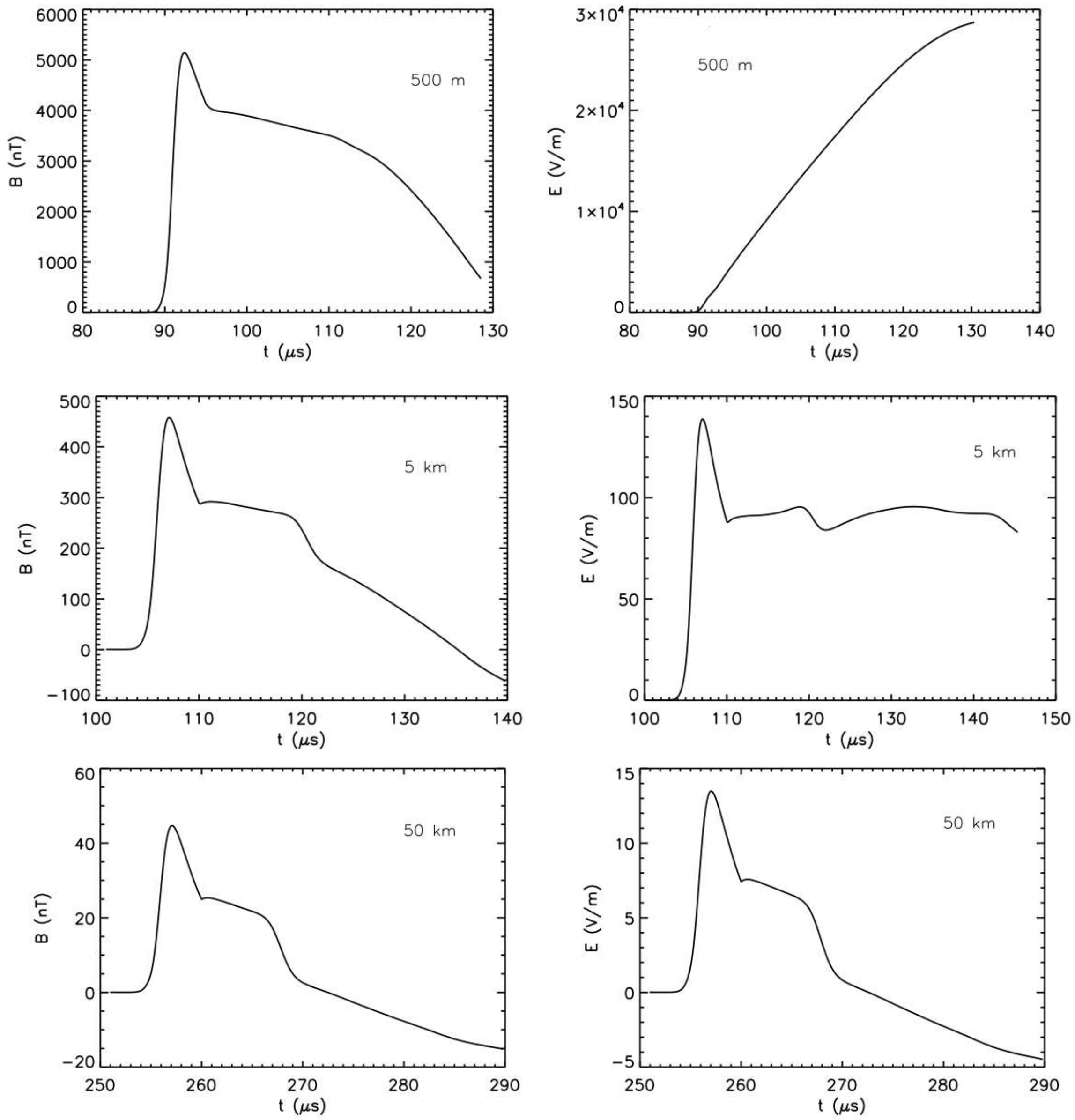
2. Characteristic hump in the magnetic field waveforms at the close distances of about several km.

3. An initial peak at the beginning of the electric and magnetic field waveforms at the distances from several km to tens of km.

4. A characteristic ramp following initial peak in the electric field waveforms at the distances of about 2 to 15 km.

5. A zero crossing for both electric and magnetic field at further distances such as 50 km.

Results



Simulated electric and magnetic field waveforms at the various distances from the lightning discharge

Conclusions

- We have developed a new return stroke model based on a bidirectional leader concept.
- The model does not require a current pulse injected at the bottom of the channel, but the RS process initiates by attachment of the zero potential element
- A decrease of current amplitudes and increase of current risetimes with height is in accordance with luminosity observations
- We obtain good correspondence of the RS modeled magnetic field waveforms both with measured data