EFFECT OF HEAT TRANSFER ON THE PROPAGATION OF A LIGHTNING RETURN STROKE CURRENT WAVEFORM

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ABSTRACT

Lightning return stroke currents propagate along the channel left by leader processes and the characteristics of that channel govern how the channel current propagates and emits radiation. Those channel characteristics can be thought of in terms of a transmission line where the circuit elements per unit length are functions of the conductivity and geometry of the channel. This paper will describe how various physical processes in the channel control the equivalent circuit elements in a nonlinear model.

INTRODUCTION

Lightning return stroke currents generate large electromagnetic fields that can interfere with or damage electronic circuits. To properly protect those circuits, we must know the sources and characteristics of the lightning currents. Models of the lightning return stroke often consider the channel as uniform and lossless when the plasma making up the channel is resisitive as is the surrounding plasma. As the current propagates it loses high frequency content. The high frequency transmissions are therefore from near the base of the channel. The rate of loss is then due to the time varying capacitance, inductance, resistance, and conductance per unit length of the channel. This model calculates the evolution of those parameters based on the hydrodynamic evolution of the channel.

THE MODEL

When a lightning leader nears the ground an upward going leader leaves sharps objects on the ground and joins the downward going leader. At the point of joining the return stroke begins [Lightning Electromagnetics, R. L. Gardner, ed., Taylor and Francis, 1990]. The closing of that switch allows a current waveform to begin which lower charge to the ground and that current waveform travels back along the channel formed by the leader. The return stroke current can then be modeled as a current on a transmission line. Since the plasma initially formed by the leader and subsequently developed by the return stroke current is lossy, the transmission line model must be complete. That is, it should have conductance and resistance terms in addition to the inductance and capacitance terms normally associated with simple current propagation models. Further, the channel develops in time as the current flows through the channel, so the model should be nonlinear in the sense that the elements of the transmission line should be functions of the current that has flowed through that particular section of the return stroke.

Electromagnetic fields radiated from the lightning return stroke are often used as a diagnostic for the currents on the channel as well as pose a threat to electronics and other systems. Simple models are used to interpret the current-field relation so that the current and radiation field waveforms are often assumed to be the same. Use of the lossy transmission line model also affects the way one interprets these current-field relations. When a current waveform is injected onto a lossy transmission line the high frequencies are preferentially attenuated by the resistance and conductance terms so that the current waveform becomes less sharp and smaller in magnitude as it propagates up the channel. Behavior of this type has been observed [Wang, et al, JGR, 104, No. D12, Pg. 14,369, 27 Jun 99]. The loss of high frequencies in the channel current with height means that the highest frequencies that are radiated as lightning electromagnetic fields are radiated from near the base of the channel and are further attenuated with channel height. High frequencies radiated near the ground and observed near the ground are more likely to show the effects of "ground-wave" propagation.

The first step in developing a model that qualitatively shows the flattening of the waveforms shown in the Wang, et al. paper is a standard transmission line model with a constant resistance per unit length. Such a model has been applied to the lightning return stroke and to the case of the Wang, et al data and compared well in a qualitative sense. An effort was made to improve the fit with a nonlinear model patterned after that of Strawe [Private Communication]. Strawe's model uses a simple analytical form for the evolution of the radius of the channel originally developed by Braginskii. This model is nonlinear in the sense that the radius of the channel increases and therefore the channel resistance decreases as a function of the history of the current that has flowed through the channel element. This model, however, did not significantly improve the fit compared to that of the constant resistance model.

In this paper, we will extend the nonlinear features of the model to better model the channel conductivity, temperature and radius. This should improve the fit for the resistance per unit length. Further, predictions will be made of the radiation and sound energy given off by the channel that allow better comparison with experiment. The model will include simple models of the channel radiation, conduction, and hydrodynamic expansion. An analytic equation of state is used that considers dissociation and ionization. Fig. 1 shows the interior channel characteristics. The center is hot, reaching temperatures of 1-3ev. These high temperatures allow the air to be conducting, but also trigger prompt cooling mechanisms including radiation. Energy balance is very complex with all of the competing processes.

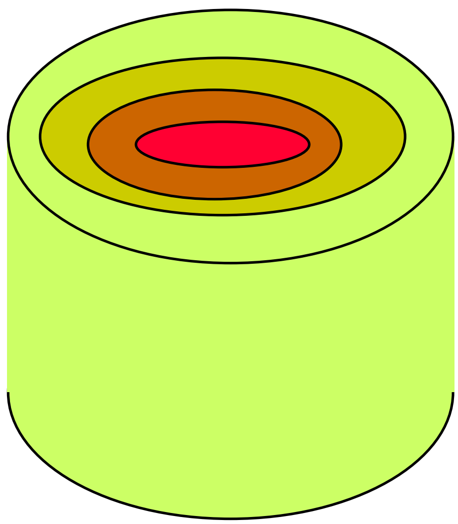

Figure 1: Conductivity profile of lightning return stroke