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Research Paper

Optical emission and peak electromagnetic power radiated by negative return strokes in rocket-triggered lightning

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ABSTRACT

Calibrated measurements of the optical radiation produced by negative return strokes in rocket-triggered lightning (RTL) have been made in the visible and near infrared (VNIR) spectral region in correlation with currents measured at the channel base. Using a simple transmission-line model, the currents have been used to estimate the peak electromagnetic (EM) fields and Poynting power that are radiated in the time-domain (i.e. from about 1 kHz to 3 MHz). The results show that the optical power radiated by RTL at the time of the peak current has a mean and standard deviation of 130 ± 120 MW, a value that is only about 5% of the Poynting power that is radiated into the upper half-space at that time. These results are in good agreement with similar measurements made on the subsequent return strokes in natural lightning that remain in a pre-existing channel. Our methods and assumptions are similar to those of (Guo and Krider, 1983; Krider and Guo, 1983; Quick and Krider, 2013).

1. Introduction

Today most investigators view a return stroke in cloud-to-ground (CG) lightning as an energetic wave of ionization that propagates rapidly up (i.e. in a retrograde fashion) a partially-ionized leader channel. The bulk of the power and energy that go into this process likely originate in the space charge that the leader has deposited in a local volume surrounding a main current-carrying core (Uman, 1969, Chapter 7; Uman, 1987, Chapters 7 and 15; Rakov and Uman, 2003, Chapter 12). Understanding the mechanisms by which the electric power and energy are dissipated, and the relative importance of these processes as a function of time, are of fundamental importance in lightning physics. Prior investigators who have made significant contributions to our understanding of these topics include (Plooster, 1971; Paxton et al., 1986, 1987; Cooray, 2014; Liang et al., 2014; Ripoll et al., 2014a,b; Carvahlo et al., 2014; Koshak et al., 2015) and others. Of particular interest here will be the magnitude of the optical power that is radiated in the visible and near infrared spectral band, or VNIR (0.4–1.1 μm), at the time of the initial peak current, and the broadband (1 kHz to 3 MHz) electromagnetic (*EM*) or Poynting power that is radiated at that time.

Optical signatures have been used for many years to study the leaders, return strokes, and other processes in CG lightning as well as relationships between light and current at the channel base (Wang et al., 2005; 2013; Qie et al., 2011; Zhou et al., 2014; Carvahlo et al., 2014). Unfortunately, only a few of the optical measurements have been calibrated. The Poynting vector is a quantity that describes the *EM* power per unit area that is radiated by the acceleration of free charge, and a distant surface integral of that quantity over the upper half-space, above perfectly conducting ground, will be termed the total *EM* or Poynting power (Krider and Guo, 1983)

In 1982, Guo and Krider (1982) made calibrated measurements of the broadband optical radiation produced by natural lightning in the VNIR spectral region that were time-correlated with broadband electric fields to determine the type of discharge process that produced the radiation and in 1983, Krider and Guo (1983a,b) estimated the optical and Poynting powers at the time of the peak fields. Here we extend those measurements to the return strokes in rocket-triggered lightning (RTL). The estimates of Poynting power will be computed using measured peak currents at the channel base, assuming the current satisfies a simple transmission line (TL) model at early times.

2. Experiments and methods

All measurements of RTL were carried out at the International Center for Lightning Research and Testing (ICLRT) which is operated by the Lightning Laboratory at the University of Florida (see

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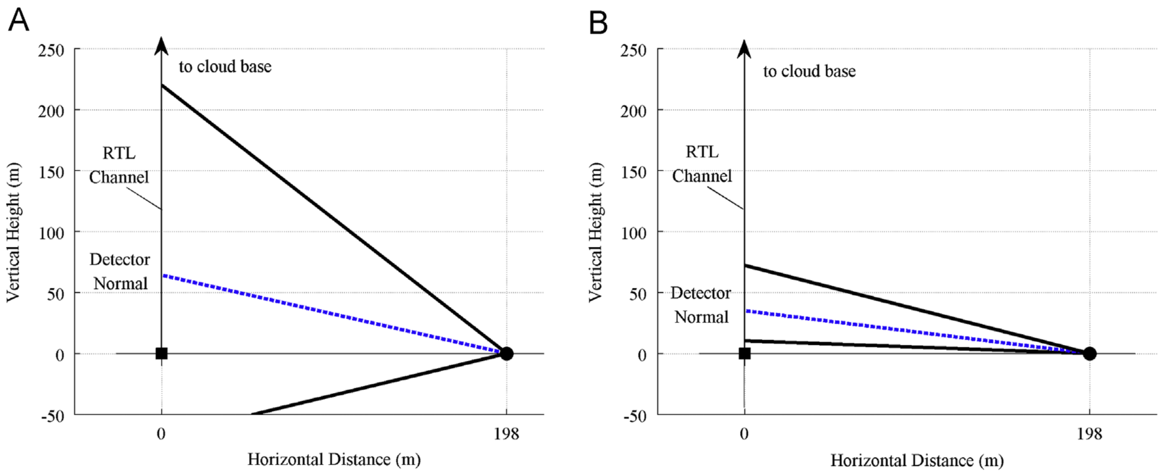

Fig. 1. The vertical lines represent ideal vertical RTL channels between the rocket launcher and cloud base, shown together with the sensor FOVs. Sketch (A) shows the viewing geometry in 2011 when the sensor viewed a channel segment from 0 to about 220 m; the looking angle was 18°. Sketch (B) shows the viewing geometry used in 2012 when the sensor viewed a channel segment from 10 to 72 m; the looking angle was 10°.

Hill et al. (2012a,b, 2013); Carvahlo et al. (2014)). During the summers of 2011 and 2012, two optical measurement campaigns were conducted at the ICLRT. A detailed description of those experiments is currently being prepared for publication (Quick and Krider, 2015), but a brief description will be given here.

The optical sensors and their fields-of-view (FOVs) differed somewhat in each year. In 2011, the radiometer had a rather large FOV, and in 2012 the FOV was smaller, as shown in Fig. 1. The horizontal FOV in both years was 45°, and detailed measurements of the vertical FOVs in both years are shown in Fig. 2. The FOV limits shown in Fig. 1 correspond to the 20% angular response levels in Fig. 2. Each radiometer consisted of a silicon PIN photodiode with an active area of 1.0 cm^2 that viewed the RTL directly through a geometric aperture with minimal internal reflections. Each photodiode was equipped with a blue filter to obtain a nearly flat spectral response so that the dependence of the measurements on the source spectrum was minimized. Calibrations of the sensor-filter responses in each year are shown in Fig. 3. The output voltages were AC coupled, using a time constant of about 1 s, to eliminate any variations in the background light. The ICLRT measured the RTL current directly at the channel base using a low-inductance resistive shunt, and all signals were recorded together on the same 8-channel digital storage oscilloscope (DSO), Yokogawa Model DL750, that sampled at a frequency of 10 MHz with 12-bit resolution. The DSO was triggered on the current waveform, and 2.0 s of data were stored for each event using a pre-trigger delay of 0.4 s. Each DSO channel had a cutoff frequency of 3 MHz to avoid aliasing.

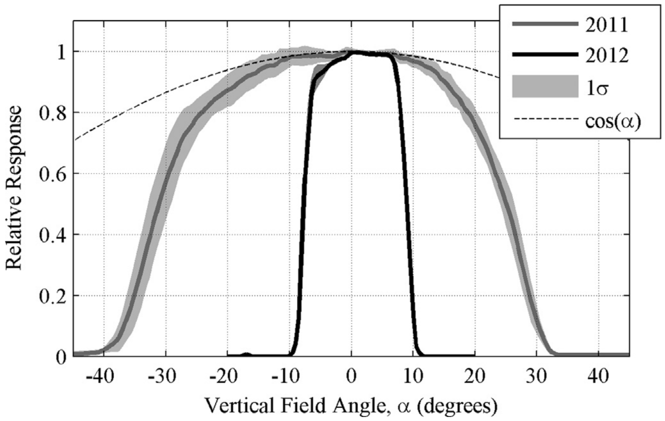

Fig. 2. Measured angular responses of the optical sensors used in 2011 and 2012. The 2011 sensor had a 67° vertical FOV (−37° to +30°), and in 2012 the vertical FOV was only 17° (−7° to +10°). The angular limits of the FOVs are assumed to be at the 20% response angles. One sigma standard measurement uncertainty in shown in the shaded region.

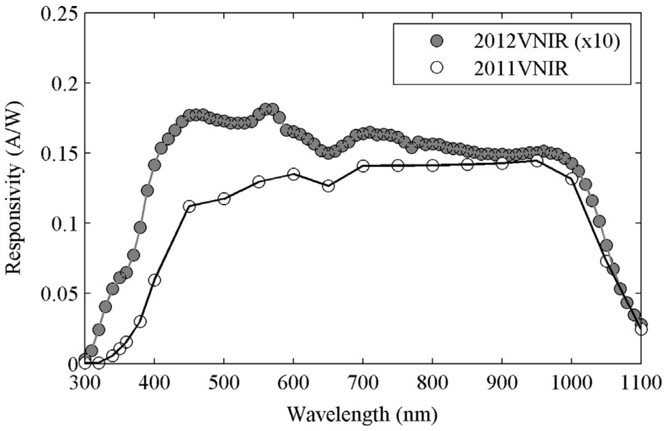

Fig. 3. The spectral responsivities of the optical sensors that were used to measure the VNIR emissions of RTL strokes. The response in 2011 is shown on the proper scale, but in 2012, the sensor included a 10% transmission neutral density filter. The combined responsivity of the detector and filter in 2012 has been multiplied by a factor of 10 to facilitate a comparison with the sensor used in 2011.

3. Theory and calculations

In order to determine the total optical power that RTL radiates at the time of the peak current, I_p, the measured irradiance, L, at that time was multiplied by the geometric factors shown in equation (1),

$$P_{opt} = 4\pi R^2 L \tag{1}$$

where R is the distance from the radiometer to the RTL launcher (198 m). This method assumes that early in the stroke, the channel is short and radiates isotropically.

The electric and magnetic fields that are radiated by lightning return strokes have been discussed by Krider and Noggle (1975), Weidman and Krider (1978) and many others (see for example, Chapter 4 in Rakov and Uman, 2003). A number of models have been developed that describe how the current propagates in a return stroke channel and that are consistent with the observed