Estimation of input energy in rocket-triggered lightning

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[1] Electric fields in the immediate vicinity (within 0.1 to 1.6 m) of the triggered-lightning channel were measured with Pockels sensors at the International Center for Lightning Research and Testing at Camp Blanding, Florida. These fields and the associated currents measured at the base of a 2-m strike object were used to compute the input power and energy, each per unit channel length and as a function of time, associated with return strokes in rocket-triggered lightning. In doing so, we assumed that the vertical component of the electric field at horizontal distances of 0.1 to 1.6 m from the lightning attachment point is not much different from the longitudinal electric field inside the channel (Borovsky, 1995). The estimated mean input energy over the first 50 μs or so is between 10^3 and 10^4 J/m, consistent with predictions of gas dynamic models, but one to two orders of magnitude smaller than Krider et al.'s (1968) estimate for a natural-lightning first stroke, based on the conversion of measured optical energy to total energy using energy ratios observed in laboratory long-spark experiments. The mean channel radius and resistance per unit channel length at the instance of peak power are estimated to be 0.32 cm and 7.5 Ω/m, respectively. **Citation:** Jayakumar, V., V. A. Rakov, M. Miki, M. A. Uman, G. H. Schnetzer, and K. J. Rambo (2006), Estimation of input energy in rocket-triggered lightning, *Geophys. Res. Lett.*, *33*, L05702, doi:10.1029/2005GL025141.

1. Introduction and Methodology

[2] A knowledge of lightning input energy is needed, for example, in determining the amount of NO and other trace gases produced by lightning and in the testing of proposed thunder generation mechanisms. There is presently no consensus on the value of energy associated with the lightning return stroke. Various estimates differ by one to two orders of magnitude, as discussed by *Rakov and Uman* [2003].

[3] In this paper, as schematically shown in Figure 1, we use measurements of the vertical electric field, E(t), in the immediate vicinity (within 0.1 to 1.6 m) of the lightning channel [*Miki et al.*, 2002] and measured current, I(t), at the channel base to estimate the input power per unit length, $P(t) = E(t) \cdot I(t)$, as a function of time to 50 μs or so. Integrating this power over time, we obtain the return-stroke input energy per unit channel length near the channel base. In the above, we assume that the vertical electric field measured within 0.1 to 1.6 m of the lightning channel is not much different from the longitudinal electric field inside the channel, the tangential component of electric field being continuous across the boundary. According to *Borovsky* [1995], the longitudinal electric field at radial distances up to 1.6 m from the channel axis differs from the field at the channel axis by less than 0.002%. Further, we neglect the possible influences of the presence of a grounded strike object in the vicinity of the electric field measuring device, electric field distortion by the measuring device, and lightning channel inclination and tortuosity. Difficulties in measuring electric fields in the immediate vicinity of the lightning channel are discussed by *Miki et al.* [2002]. We additionally estimate channel resistance per unit length and channel radius.

[4] The experimental data used in this study were acquired during Summer 2000 at the International Center for Lightning Research and Testing at Camp Blanding, Florida. Lightning was triggered using the classical rocket-and-wire technique [e.g., *Rakov*, 1999].

[5] The energy to be estimated is associated with the resistive heating of the lightning channel and can be viewed as the input energy for the return-stroke process, energy that is primarily spent in ionization of air, channel expansion, and the production of electromagnetic (including optical) and acoustic radiation from the channel.

2. Data

[6] Vertical electric fields at a distance of 0.1 to 1.6 m from the channel and associated channel-base currents were obtained for 36 strokes in nine triggered lightning flashes. For five strokes, although the current records were available, the corresponding electric field records were saturated. All the usable electric field signatures can be divided in three types: 1) "classical" V-shaped signatures having

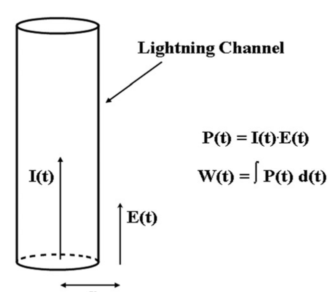

Figure 1. Illustration (not to scale) of the method used to estimate power, P(t), and energy, W(t), each per unit length, from measured lightning channel-base current, I(t), and vertical electric field, E(t), in the immediate vicinity of the channel.

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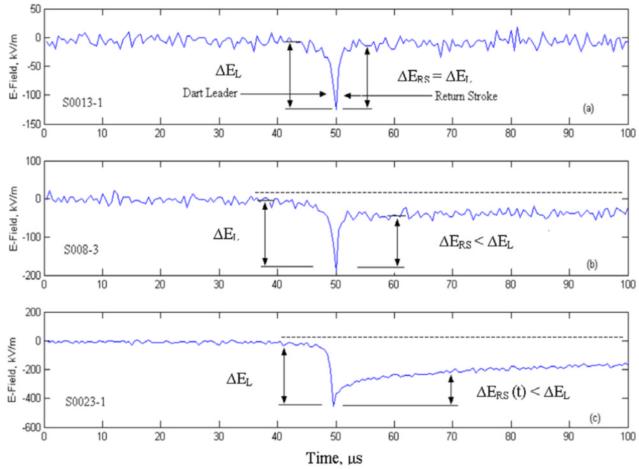

Figure 2. V-shaped electric field signatures with a) the return stroke field change, ΔE_{RS}, being equal to the leader field change, ΔE_L. b) $\Delta E_{RS} < \Delta E_L$, field flattening within 20 μs or so of the beginning of the return stroke (of the bottom of the V), c) ΔE_{RS} (t) < ΔE_L, no flattening within 20 μs.

return-stroke electric field changes ΔE_{RS} approximately equal to the leader electric field changes ΔE_L ($\Delta E_{RS} = \Delta E_L$); 2) V-shaped signature with ΔE_{RS} being appreciably smaller ΔE_L; 3) same as 2, but with the return stroke portion not exhibiting the flattening that typically occurs within 20 μs or so of the beginning of the return stroke [e.g., *Rakov*, 1999]. These three types of waveforms are illustrated in Figure 2. The reason for the "residual" electric field some tens of microseconds after the return stroke for Types 2 and 3 is apparently the fact that the return stroke fails to neutralize all the leader charge, as discussed by *Miki et al.* [2002]. Type 1 represents the "classical" leader/return stroke sequence, while Types 2 and 3 indicate the presence of an additional, slower process involved in the removal of charge from the channel (not all the electrostatic energy deposited along the channel by the leader is tapped by the return stroke). Only Type 1 events (a total of eight) are considered in this paper. They are characterized by geometric mean values of electric field change, $\Delta E_{RS} = \Delta E_L$, of 109 kV/m and of peak current 16 kA.

3. Analysis of Type 1 Events

[7] The product of channel-base current and the close longitudinal electric field, each as a function of time, yields the power per unit channel length vs. time. Since we have the current record for the return stroke only, the following results represent processes following the initiation of the return stroke (leader/return stroke transition). The energy per unit length is obtained by the integration of the power waveform over time.

3.1. Data Processing

[8] Electric field waveforms are typically noisy after the initial, fast-varying portion (see Figure 2) and hence some filtering (averaging) is desired in that part of the waveform. A moving-average window of 100 data points (50 μs), which acts as a low-pass filter, was used for this purpose. Averaging was started a suitable time interval after the beginning of the return stroke, so that the initial (fast-varying) portion of the return stroke was not modified. Electric field and current records were aligned manually using the bottom of the V-shaped electric field signature and the beginning of the current waveform.

3.2. Power and Input Energy

[9] Power as a function of time, obtained as the product of longitudinal electric field and strike-rod current, and energy, the time integral of the power, are shown in Figure 3, for Type 1 stroke S0013-1 having a V-shaped electric field signature with $\Delta E_{RS} = \Delta E_L$. The estimated peak power and energy values for all eight strokes of this type are given in Table 1.

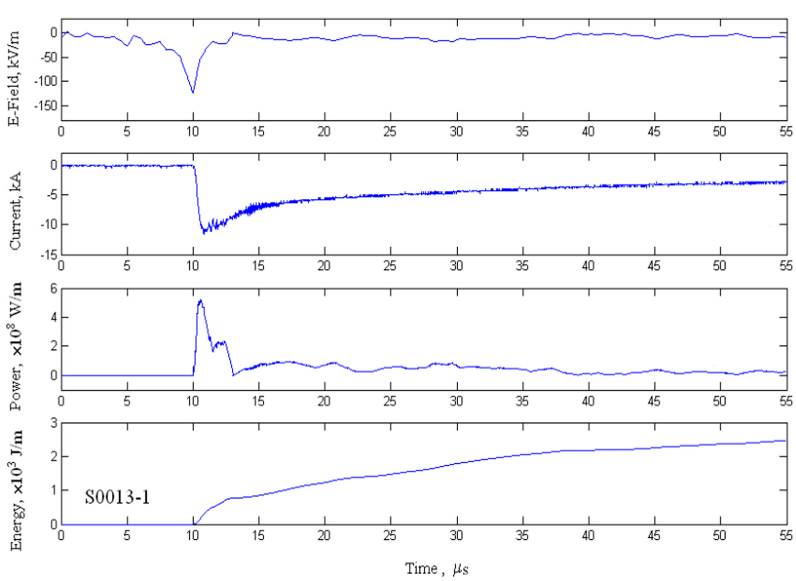

Figure 3. Time variation of, from top to bottom, vertical electric field, current, power, and energy for stroke S0013-1. Return stroke begins at t = 10 μs.

Table 1. Power and Energy Estimates for Type 1 Strokes Having V-Shaped Electric Field Signatures With $\Delta E_L = \Delta E_{RS}$

Date	Flash ID (Number of Strokes)	Stroke Order	Termination Point	Peak Current, kA	ΔE_L, kV/m	Peak Power, $\times 10^8$ W/m	Energy, $\times 10^3$ J/m (at 46 μs)
6/13	S0006 (5 strokes)	4	Rod	14	53	2.4	1.8
6/17	S0008 (>8 strokes)	4	Ring	21	60	2.2	0.9
6/18	S0013 (6 strokes)	1	Rod	12	125	5.2	2.6
		4	Ring	12	123	8.6	1.3
6/23	S0015 (6 strokes)	2	Rod	19	105	9.9	6.4
		4	Rod	22	113	8.7	5.0
		6	Rod	20	93	15	1.3[a]
7/11	S0023 (3 strokes)	3	Ring	9.9	305	25	6.2

[a]At 10 μs, because for this stroke after 10 μs $\Delta E_{RS} > \Delta E_L$ causing the power waveform to change polarity (become negative), which is physically unreasonable.

[10] As seen from Table 1, the peak power varies from 2.2 $\times 10^8$ W/m to 25.1$\times 10^8$ W/m and input energy at 10 to 50 μs from 0.9 $\times 10^3$ J/m to 6.4 $\times 10^3$ J/m. The peak power values are consistent with 12 $\times 10^8$ W/m reported for a natural-lightning first stroke by *Krider et al.* [1968], and the energy values are in agreement with predictions (of the order of 10^3 J/m) of gas-dynamic models [e.g., *Rakov and Uman*, 2003]. The lightning channel could attach to either the "rod" the "ring" which the strike object (see Figure 3 of Miki et al. [2002]). The mean values of peak power and energy for strokes terminating on the rod (5 events) and on the ring (3 events) are not much different. For all eight strokes combined, the mean values of peak power and energy are 9.6 $\times 10^8$ W/m and 3.6 $\times$ 10^3 J/m, respectively.

[11] The zero-to-peak risetime of the power pulse ranges from 0.28 to 0.60 μs with a mean value of 0.43 μs. For comparison, the corresponding values for current pulses are 0.40, to 1.6, and a mean of 0.85 μs.

3.3. Channel Resistance and Radius

[12] The resistance per unit length of the return-stroke channel near its base as a function of time is given by the expression R(t) = E(t)/I(t). The evolution of the channel radius can be estimated (neglecting the electromagnetic skin effect) from the channel resistance using the expression, $r(t) = [\sigma \pi R(t)]^{-0.5}$, where σ is the electrical conductivity of the channel. We assume that $\sigma = 10^4$ S/m. In reality, σ increases with time (as the channel temperature increases), but this variation is rather weak for the expected temperatures (≥20,000°K or so) and pressures ranging from 1 to 10 atm [e.g., *Yos*, 1963; *Plooster*, 1971]. The assumption of σ = const is equivalent to the assumption that R(t) decreases only due to expansion of the channel, that is due to an increase in r(t).

[13] The evolution of resistance and channel radius along with corresponding electric field, current, and power profiles, for Type 1 stroke S0013-1 for the time interval when the electric field magnitude is greater than 20 kV/m is shown in Figure 4. Table 2 summarizes the values of resistance and channel radius at the instant of peak power for eight strokes of Type 1.

4. Discussion and Summary

[14] As noted above, there is presently no consensus on the energy associated with the lightning return stroke [*Rakov and Uman*, 2003]. According to the gas-dynamic

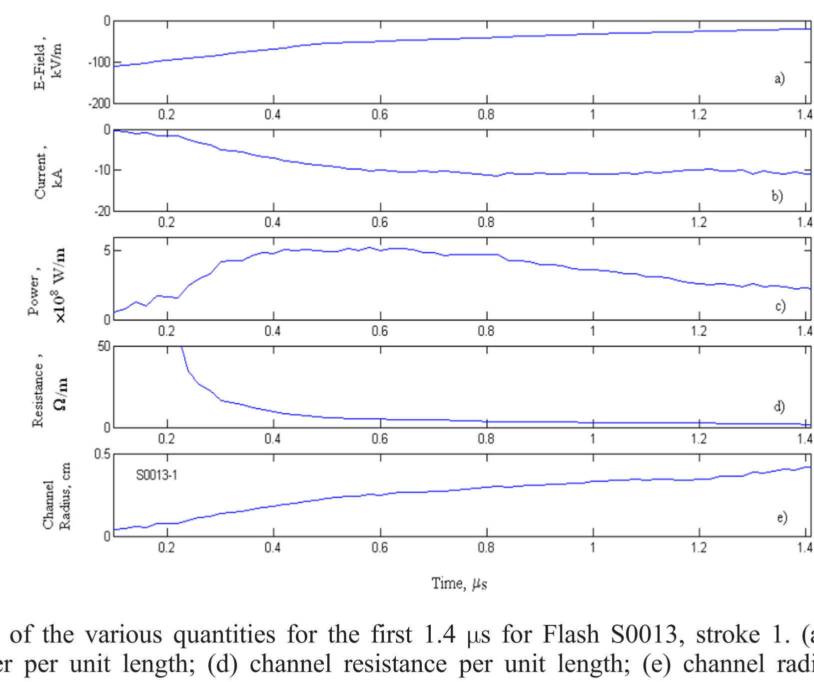

Figure 4. Evolution of the various quantities for the first 1.4 μs for Flash S0013, stroke 1. (a) Vertical electric field; (b) current; (c) power per unit length; (d) channel resistance per unit length; (e) channel radius.

Table 2. Resistance and Channel Radius at the Time of Peak Power for Type 1 Strokes Having V-Shaped Electric Field Signatures With $\Delta E_{RS} = \Delta E_L$ ($\sigma = 10^4$ S/m)

Flash ID	Stroke Order	Resistance, Ω/m	Channel Radius, cm
S006	4	0.67	0.69
S008	4	1.3	0.49
S0013	1	5.1	0.25
	4	8.0	0.22
S0015	2	4.5	0.31
	4	5.1	0.25
	6	4.3	0.27
S0023	3	31	0.10
Mean value		7.5	0.32

models of *Hill* [1971, 1977], *Plooster* [1971], *Paxton et al.* [1986], and *Dubovoy et al.* [1991], the energy per unit length dissipated in the channel core is of the order of 10^3 J/m. Based on electrostatic consideration, *Borovsky* [1998] predicted that this energy should be between $2 \times 10^2 – 1 \times 10^4$ J/m, and *Krider et al.* [1968] calculated a value of 2.3×10^5 J/m for a single-stroke natural flash, using field and laboratory experimental data. From electrostatic consideration, *Uman* [1987] obtained a possible range of values between 10^5 and 10^6 J/m. Note that the energy estimates obtained by *Krider et al.* [1968] and *Uman* [1987] probably include the energy dissipated during both the stepped leader and first return-stroke processes, and, hence, may not be directly comparable to other estimates based on the models that describe only the return-stroke process.

[15] The mean input energy for return strokes in triggered lightning over the first 50 μs or so estimated in this study, 10^3 to 10^4 J/m, is consistent with predictions of gas dynamic models. Only "classical" Type 1 strokes are analyzed in this paper, because strokes of Types 2 and 3 apparently involve an additional, slower (other than return stroke) process that removes leader charge from the channel. Energy estimates are relatively insensitive to the uncertainties in data and methodology used here, with the energy variation not exceeding 30%. Uncertainties in estimated peak power are larger, up to about 70%. The mean channel radius and resistance per unit channel length estimate for Type 1 strokes at the instant of peak power (which occurs at around 0.4 μs) are 0.32 cm and 7.5 Ω/m, respectively. For comparison, *Rakov* [1998], using the lossy transmission line approach, estimated these parameters to be 0.3 cm and 3.5 Ω/m ahead of the return-stroke front and 3 cm and 0.035 Ω/m behind the return-stroke front. Optical measurements typically yield return-stroke channel radii of the order of a few centimeters [e.g., *Orville et al.*, 1974; *Idone*, 1992]. It appears that at the time of peak power the properties of the lightning channel are similar to those expected for the leader stage, presumably due to insufficient time (0.4 μs or so) for creation of a fully-conditioned return-stroke channel, which, according to gas-dynamic models, takes several microseconds or more [e.g., *Paxton et al.*, 1986].

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