Lightning Phenomenology Notes

Note 21

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A Simple Model of Repeating Lightning-Leader Pulses

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Abstract

This paper investigates some implications of observed repeating fast lightning-leader pulses (steps), utilizing both optical and electromagnetic-pulse data. Estimates of leader-step length, current, charge, and pulse width are combined to give estimates of the resistance presented to the continuing current between the pulses which recharges the leader tip.

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1. Introduction

Leader pulses associated with lightning are a complex phenomenon. Experimental data in the fast-time regime (tens of nanoseconds) are limited. However, it is in this time regime that important things are occurring. Figures 1.1 and 1.2 are taken from [2], showing such fast-time events. One can also find other examples in [2, 3, 11], e.g., in [3 (Section 10.2)]. The data in Figs. 1.1 and 1.2 are also discussed in [4] and are tabulated in [3 (Section 6.1)].

From this and other data in the above references we can summarize

$$
\begin{aligned}
t_2 &\simeq 0.05\ \mu s \text{ to } 0.6\ \mu s \text{ pulse width} \\
&\equiv \text{pulsewidth at half maximum of field pulses} \\
t_2 &\simeq 2\ \mu s \text{ to } 7\ \mu s \text{ average spacing between pulses} \\
|\vec{\Upsilon}| &\simeq \left|\sum_n I_n \mathrm{v}_n\right| \simeq 10^{11} \text{ to } 1.5 \times 10^{12} \text{ Am/s from field pulses and distance to source}
\end{aligned}
\tag{1.1}
$$

As discussed in [4] the leader pulse can be thought of as comprised of a forward-propagating pulse with speed v_f and a backward propagating pulse with speed v_b (both limited by c) with the same currents (for continuity), giving

$$
|\vec{\Upsilon}| \simeq |I|\left[\mathrm{v}_f + \mathrm{v}_b\right] \tag{1.2}
$$

Note, of course, that only the transverse (to the direction to the observer) part of the field vector is measured. In some of the data (not including Figs. 1.1 and 1.2) there were events from more than one location in the sky; these were sorted out by the techniques discussed in the references so that the pulse spacing was for data from individual sky locations.

Note that due to the fine time resolution of our measurements, these leader pulses have shown to have propagating speeds approaching c (3×10^8 m/s), which is quite different from the much slower average speed (by a factor of 100 or so [4]) over a group of such leader steps. It is the slower average speed that old optical measurements have typically recorded. These two speeds have been discussed by Schonland [5] who states:

> "No accurate measurement of V can be made owing to the short lengths of the steps and the very feeble luminosity of the streamers behind them but it has been shown to exceed 5×10^9 cm./sec. The effective velocity v ranges from 0.8 to 2.4×10^8 cm./sec. most of the observed values being close to 1.0×10^7 cm./sec."

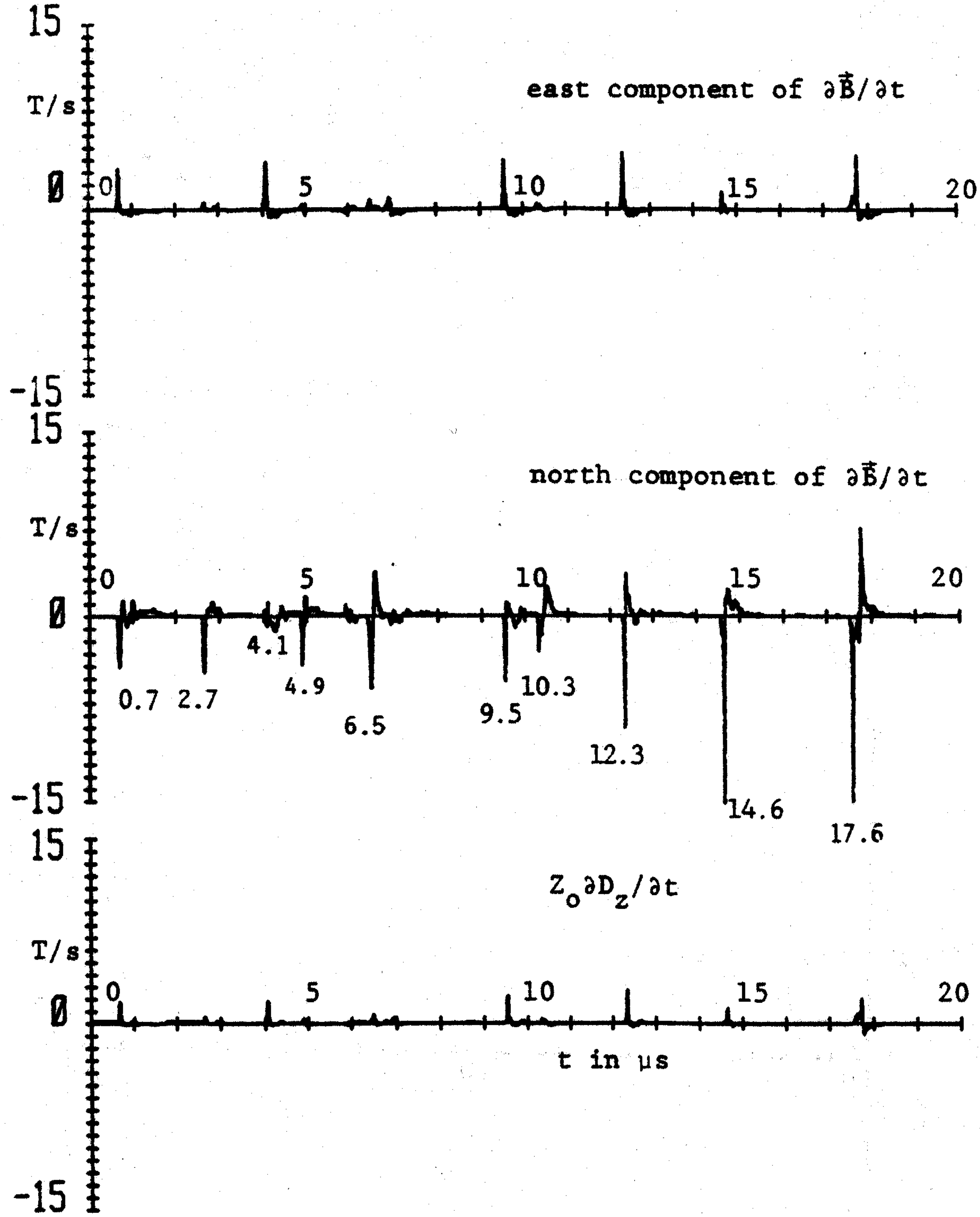

Fig. 1.1. Derivative Fields From Rocket-Triggered Lightning.

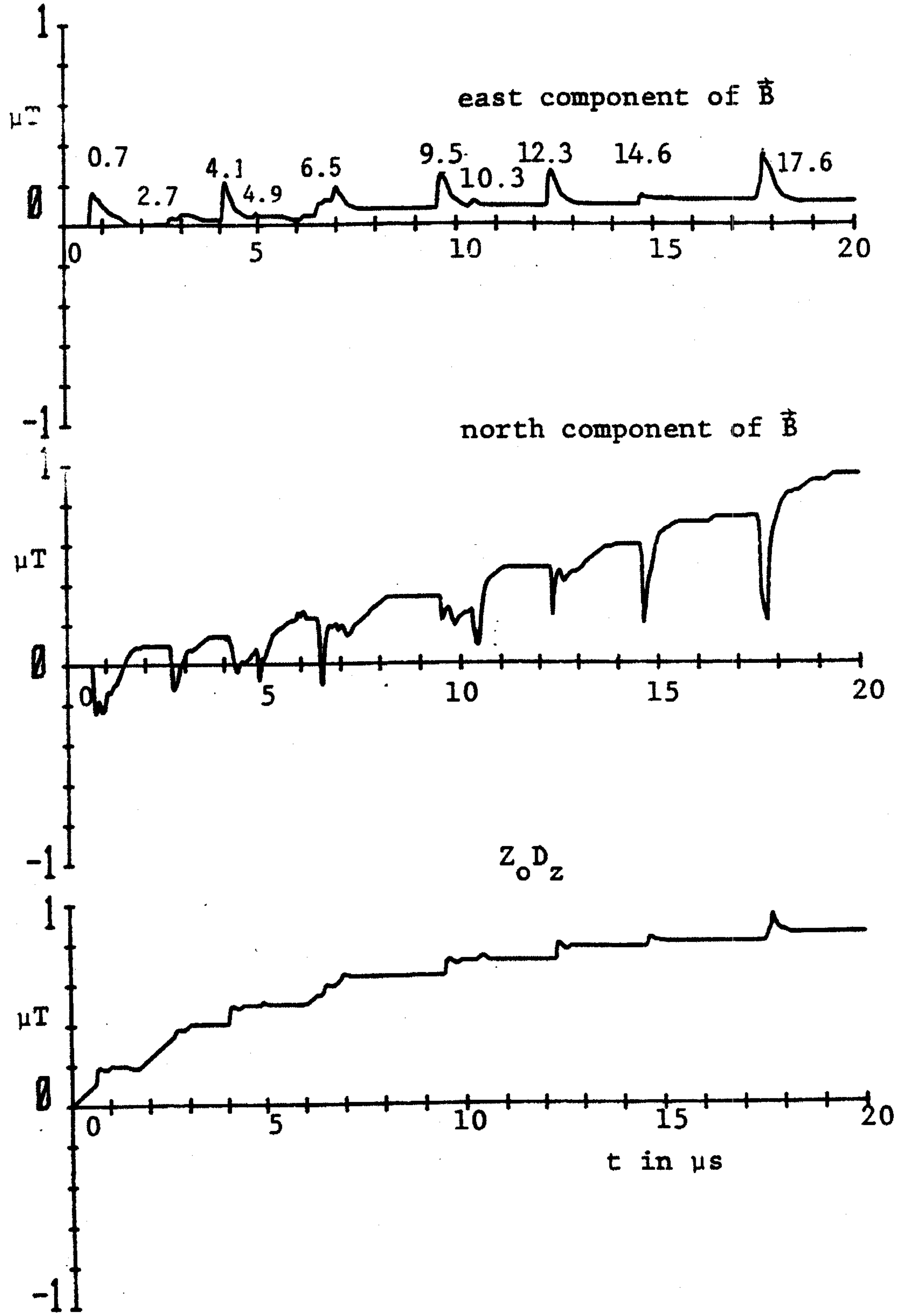

Fig. 1.2. Fields From Rocket-Triggered Lightning.

Our measurements, of course, use more modern instruments, but it is interesting to note that fast speeds of the order of 10^8 m/s (or even more) implied by our data are consistent with the Schonland citation.

We can also consider the length (meters) of the steps. The cited numbers in [5] of 10 to 200 m correspond to the lower effective velocity v cited above, and so may apply to a group of these fast steps as in Figs. 1.1 and 1.2. Similar step lengths (corresponding to the slow effective velocity) are also reported in [6]. So one may expect the step lengths for the fast steps to be somewhat less than the numbers above. A recent paper [10] gives optical measurements of dart-stepped leaders with average temporal spacing of 4.6 μs (consistent with our electromagnetic data). From the effective velocity v of 2.5 x 10^6 m/s we obtain 11.5 m as an estimate of the average step length. So

$$\begin{aligned} \ell_f &\simeq \text{10 to 20 m} \\ &\equiv \text{length of forward propagation of leader} \end{aligned} \tag{1.3}$$

seems an appropriate value from the optical data. Additional optical measurements [7] also support an ℓ_f of about 10 m.

2. Physical Model

Now let us introduce a model which may be useful for interpreting these data. As in Fig. 2.1, let the steps be spaced a time t_2 which is large compared to t_1, the temporal duration of the fast steps. Furthermore let each of the fast steps advance (in the $-z_s$ direction) a distance ℓ_f (f for forward). Refer to [4] for some of the notation and diagrams.

Using the optical estimate of ℓ_f with the electromagnetic estimate of the pulse width t_1 (full width, half maximum) we have

$$v_f \; \frac{\ell_f}{t_1} \simeq 0.17\times 10^8 \text{ to } 2\times 10^8 \text{ m/s} \tag{2.1}$$

for the forward leader speed. While this seems reasonable, let us note that one would like to have both optical and electromagnetic data for the same leader pulse to narrow this down. More precisely, one could attempt to calculate

$$\ell_f = \int v_f(t)\,dt \tag{2.2}$$

However, this assumes a straight leader path. Furthermore, the electromagnetic data includes only transverse (to observer) components and includes signals from both the downward and upward propagating currents.

For forward propagating leaders we can estimate the current and charge based on the corona model [1] using an assumed breakdown electric field E_b of about 2 MV/m.

$$\begin{aligned} \Psi_c &\simeq 1.1\text{ m (corona radius)} \\ Q' &\simeq 150\ \mu\text{C/m (charge per unit length)} \\ I_{max} &\simeq 15\text{ kA} \\ |\Upsilon|_{max} &\simeq 1.5\text{ TA m/s} \\ v_f &\simeq 10^8\text{ m/s} \end{aligned} \tag{2.3}$$

Based on the considerations in [4] involving both forward and backward propagating currents, we may wish to lower I_{max} (say a factor of 2 or so). In [9] there are experimental results giving currents of a few kA for dart-stepped leaders, consistent with the above. In [7] similar values of Q' are found.

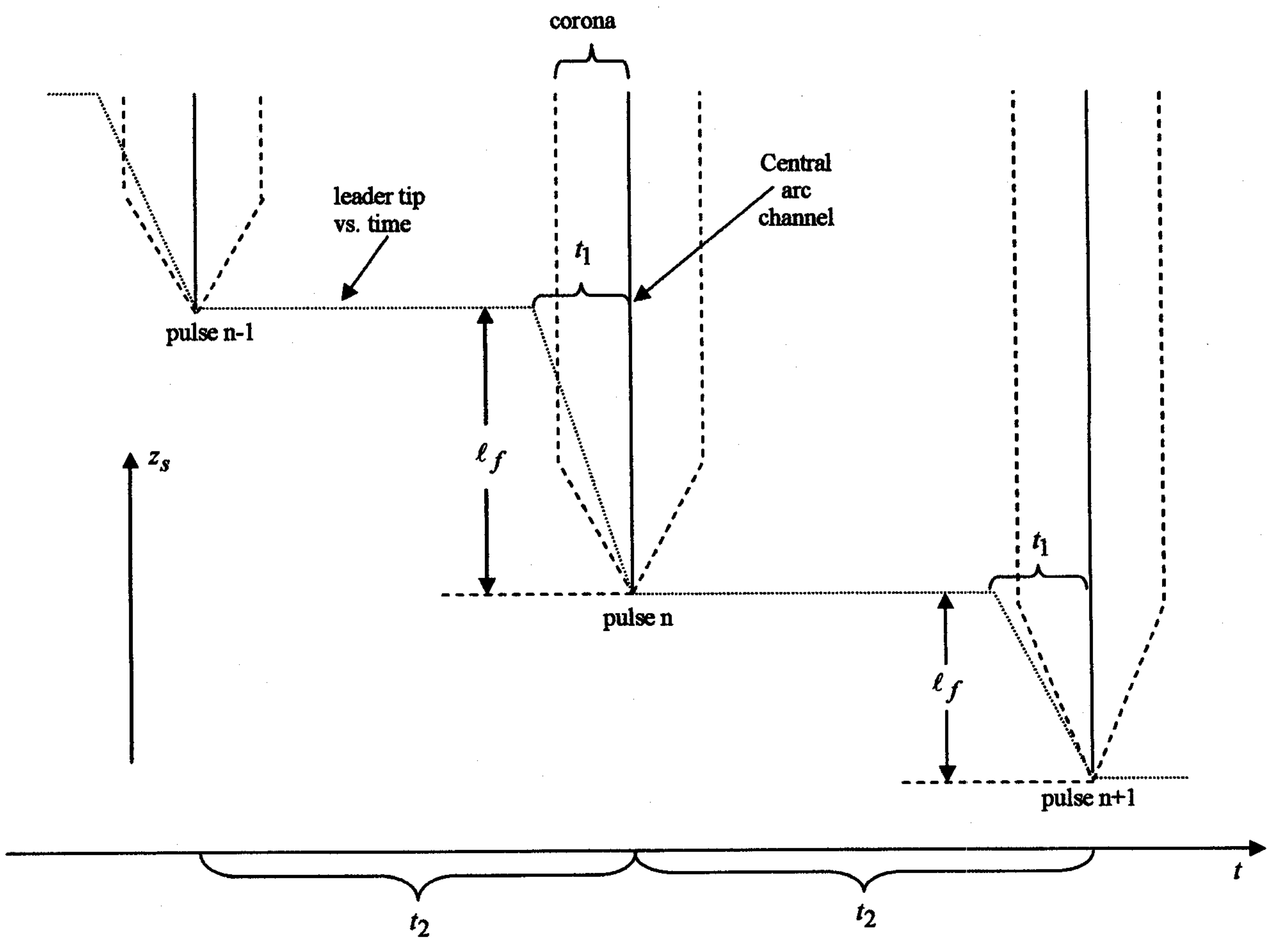

Fig. 2.1. Physical Model for Time Between Pulses.

We can estimate the capacitance associated with the forward part of the step leader as

$$C \simeq \frac{2\pi\varepsilon_0 \ell_f}{\ell n\left(\frac{\ell_f}{\Psi_c}\right)} \simeq 0.1 \text{ to } 0.2nF$$
$$Q \simeq Q'\ell_f \simeq 1.5 \text{ to } 3\,mC \tag{2.4}$$

This charge is in agreement with the experimental results for dart-stepped leaders (a few mC) cited in [9]. This corresponds to a voltage V of about 15 MV (reasonable for distances of 10 to 20 m in air). This is also in agreement with [7]. Note that this capacitance is an extra capacitance added onto that of the arc (including corona) above. There is also a smaller decrease in the capacitance above this forward step due to the backward propagating current. The average electric field along the leader is then

$$E_{\text{arg}} \simeq \frac{V}{\ell_f} \simeq 0.75 \text{ to } 1.5\,\text{MV/m} \tag{2.5}$$

In order to sustain the lightning streamer by recharging the lower portion of the leader there needs to be a continuing current

$$I_{avg} = I\frac{t_1}{t_2} \simeq 150\text{ A}$$
$$\frac{t_2}{t_1} \simeq 100 \qquad \text{(from [4])} \tag{2.6}$$

Retaining the field value in (2.6) for the time between the leader pulses gives an effective resistance per unit length

$$R'_{avg} = \frac{E_{avg}}{I_{avg}} \simeq 5 \text{ to } 10\,\text{k}\Omega/\text{m} \tag{2.7}$$

Note that this resistance estimate applies to the time between the leader pulses during which the comparatively small continuing current I_{avg} is recharging the leader tip to get ready for the next pulse. During the short time t_1 of the leader pulse we expect the resistance per unit length to be much less.

It is interesting to note that [8] gives some estimates of resistance per unit length based on quite different considerations. Ahead of the dart-leader front a few 10s of kΩ/m is found. This seems to be in rough agreement with (2.7).

3. Concluding Remarks

Another way to view the leader-step phenomenon is by a circuit analogy to a relaxation oscillator in which a capacitor is charged at some rate, and suddenly discharged when a critical voltage has been reached, the cycle then repeating.

The present calculations are truly of the back-of-the envelope form. However, one needs to start somewhere. Perhaps future data will lead to a refinement of this model.

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