Lightning Phenomenology Notes

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Measurement of Closure Position Between Downward and Upward Leaders: Return-Stroke Initiation Position

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Abstract

In modeling, the lightning return stroke, one would like to have better knowledge of the closure position of the downward- and upward-propagating leaders. This paper discusses ways to measure this based on electromagnetic-field measurements.

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1. Introduction

An important feature of cloud-to-ground lightning concerns the upward propagating leader meeting the downward propagating leader at some location above the ground. This is the initiation point of the return stroke [5]. One would like to measure this point in space so as to be able to better model the return stroke.

This problem can be considered a special case of the lightning-locating electromagnetic techniques discussed in [3, 4, 6]. In the present case we are looking near the ground where the two leaders connect. The upward propagating leader may come from some field-enhanced region (blade of grass, etc.), or it may be near the tip of a rocket sent up to trigger the lightning [2]. In this latter case one may also have other measurement techniques (optical, etc.) to locate the connection point. One also has some prior knowledge (based on rocket trajectories) of the likely approximate connection point.

2. Vertical Channel on *z* Axis

The first case is a simple one as in Fig. 2.1. Let both upward and downward leaders be on the *z* axis (which is perpendicular to a flat ground surface on $z = 0$). We have coordinates (Cartesian and cylindrical)

$$x = \Psi \cos(\phi) \quad , \quad y = \Psi \sin(\phi)$$
$$z = z \tag{2.1}$$

With leader connection at $z = h$ the lightning-channel return stroke has a current $I(z, t)$ beginning at this connection point and propagation outward. With the observer at $(\Psi, \phi, 0)$ on the ground surface the initial wave arrives at an angle

$$\psi = \arctan\left(\frac{h}{\psi}\right) \tag{2.2}$$

with respect to the ground surface. The plane of incidence contains the *z* axis and the observation position. The initial fields at the observer include only the r^{-1} (radiation) term with

$$\begin{aligned} E_z &= E\cos(\psi) \\ E_\Psi &= E\sin(\psi) \\ H_\phi &= \frac{E}{Z_0} \\ Z_0 &= \left[\frac{\mu_0}{\varepsilon_0}\right]^{1/2} \simeq 377\ \Omega \end{aligned} \tag{2.3}$$

Concentrating on E_z and H_ϕ we have

$$\frac{E_z}{H_\phi} = Z_0 \cos(\psi) \tag{2.4}$$

which can be used to measure ψ, and thereby the leader-closure position. One can, of course, conveniently choose the observation point to lie on the positive *x* axis for which $\phi = 0$ and H_ϕ is H_y.

Note that there is a reflected wave at the ground surface, but it has the same property as in (2.4) so as not to change the measurement [1]. This assumes a uniform and isotropic soil medium. This last assumption can be avoided by use of a conducting ground plane on the local earth surface [3, 4, 6].

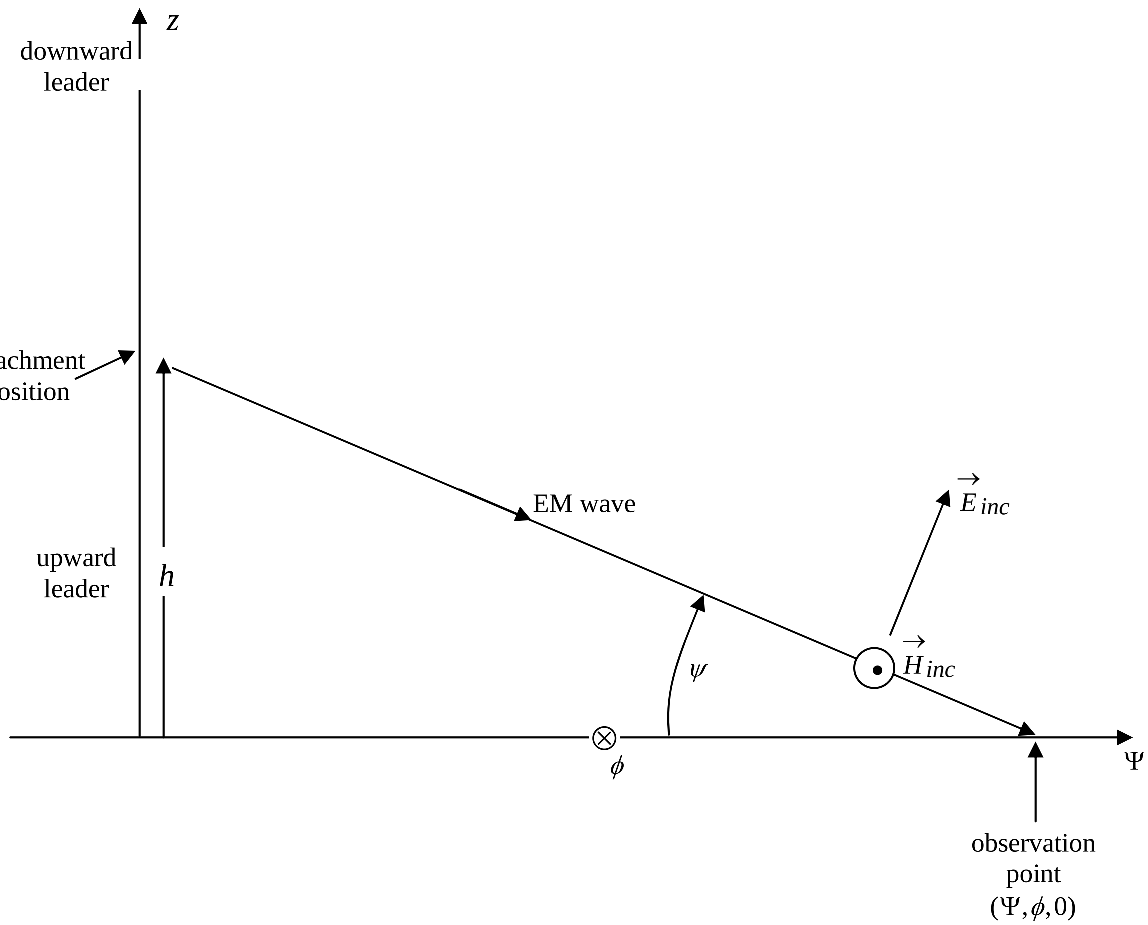

Fig. 2.1 Leader on *z* Axis.

One should use this for early-time measurements for which the characteristic times have

$$\Delta t \ll \frac{r}{c}$$

$$r = \left[\Psi^2 + z^2\right] = \text{distance to source} \tag{2.5}$$

$$c = \left[\mu_0 \varepsilon_0\right]^{-1/2} = \text{speed of light}$$

3. Vertical Channel Off z Axis

Now suppose that the lightning channel near the attachment position is displaced, but still vertically oriented (parallel to $\vec{1}_z$), at least locally. Then the magnetic field at our measurement location is oriented perpendicular to the direction of propagation from the source (lightning closure) point. Let us have the closure point at

$$\vec{r}_0 = (x_0,\ y_0,\ z_0) \tag{3.1}$$

while the observation point (taken on the x axis) is at

$$\vec{r}_1 = (x_1,\ 0,\ 0) \tag{3.2}$$

Then the elevation angle is

$$\psi_0 = \arctan\left(\frac{z_0}{\left[\left[x_1 - x_0\right]^2 + y_0^2\right]^{1/2}}\right) \tag{3.3}$$

The source angle away from the x axis is

$$\phi_0 = \arctan\left(\frac{y_0}{x_1 - x_0}\right) \tag{3.4}$$

The magnetic field at the observer (early time) is oriented at an angle of ϕ_0 away from the y axis. By measuring both H_x and H_y (or their time derivatives) at the observation point we have

$$\begin{aligned} \phi_0 &= \arctan\left(\frac{H_x}{H_0}\right) \\ H_0 &= \left[H_x^2 + H_y^2\right]^{1/2} \end{aligned} \tag{3.5}$$

From this we can find ψ_0 from

$$\frac{E_z}{H_0} = Z_0 \cos(\psi_0) \tag{3.6}$$

The distance to the source $|\vec{r}_1 = \vec{r}_0|$ is found from other data, such as photographs of the channel. With the knowledge of ψ_0 and ϕ_0 one can see what coordinates on the lightning channel correspond (at least approximately) to these angles.

4. Slanted Channel Near *z* Axis

Another situation one might encounter has the connection point on or near the *z* axis, but with the channel slanted (i.e., not parallel to $\vec{1}_z$ near the connection point). In this case we have a situation similar to that in Section 2.

With $\phi_0 \simeq 0$, we can decompose the fields incident into two parts: E (or TM) and H (or TE). The H wave (due to the current component in the y direction) has an incident electric field in the y direction which we can ignore (especially given a highly conducting ground plane). The magnetic field has an *x* component which we can neglect. The E wave (due to *x* and *z* components of the current) has E_z and H_y components which we can measure and use as in (2.3)

5. Slanted Channel Off *z*-Axis

Now we go on to the general case. This is treated in [3, 4, 6]. There it is shown how to locate lightning based on the variation of the orientation of the leader pulses from one pulse to the next. Here our problem is slightly different in that the spatial difference between successive pulses is of the order of or larger than the distance that we would like to resolve due to the closeness of the attachment position to the ground.

To simplify this process, one can use optical measurements to locate the lightning channel and use this to *define* the z axis. For an approximately straight vertical channel, this can be done unambiguously. In this case the results of Section 2 apply for simply ascertaining the angle ψ to the attachment position. Together with optical channel location (2 photographs from different locations) we can locate the attachment position.

If the lightning channel in the region of interest is not vertical, then more elaborate computations can be pursued. One can start with some guess of the attachment height (and range from optical data). If the channel is approximately vertical there, then the technique in Section 3 applies. Does the estimate of ψ_0 so obtained agree with the estimated attachment height? If the channel at the position of interest is not vertical then the technique of Section 4 is applicable. By adjusting the z axis through this position one can use the E_z and H_y components to estimate ψ_0 and see if this agrees with the estimated attachment height. Continue this process until best approximate agreement of ψ_0 with the selected attachment position is obtained.

At this point one can also use time-of-arrival techniques to determine the angles from the observation position to the fast signal from leader closure [4]. This takes at least three field-measurement locations scattered around the observation position with sufficient separation (in time) compared to characteristic times in the closure signal (or its time derivative) which we can measure.

6. Concluding Remarks

There are thus several electromagnetic measurement techniques which can locate the initiation position of the lightning return stroke. Depending on the location of the lightning stroke and its orientation near the closure position, the complexity of the data interpretation can vary considerably. Experience with such measurements will be required to better understand their complexity and accuracy.

References

1. C. E. Baum, "The Reflection of Pulsed Waves From the Surface of a Conducting Dielectric", Theoretical Note 25, February 1967.

2. C. B. Moore, D. L. Hall, L. J. Caylor, T. F. Stueber, B. Cason, and D. Patrick, "Characteristics of American Rockets Used for Triggering Lightning, Part 1: Rockets from Flight Systems Inc., Burns Flat, Oklahoma", Measurement Note 29, February 1984.

3. C. E. Baum, E. L. Breen, J. P. O'Neill, C. B. Moore, and D. L. Hall, "Measurements of Electromagnetic Properties of lightning with 10 Nanosecond Resolution", Lightning Phenomenology Note 3, February 1982.

4. C. E. Baum, J. P. O'Neill, E. L. Breen, D. L. Hall, and C. B. Moore, "Location of Lightning Electromagnetic Sources by Time of Arrival Compared to Inference from Electromagnetic Fields, Thunder Acoustics, and Videotape Photographs", Lightning Phenomenology Note 11, October 1983.

5. C. E. Baum, "Return-Stroke Initiation", Lightning Phenomenology Note 19, October 1986; Proc. EMC Symposium, Zurich, March 1989, pp. 383-388.

6. C. E. Baum, J. P. O'Neill, E. L. Breen, D. L. Hall, and C. B. Moore, "Electromagnetic measurement and Location of Lightning", ch. 18, pp. 319-346, in R. L. Gardner (ed.), *Lightning Electromagnetics*, Taylor & Francis, 1990.