An Examination of Lightning-Strike-Grounding Physics

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Introduction

Observations of the traces left on the surface of the ground after lightning has struck often show dendritic patterns of the type shown in Figure 1 which indicate that after striking the ground, rather than going into the Earth, these discharges propagated outward from the strike points on the earth surface.

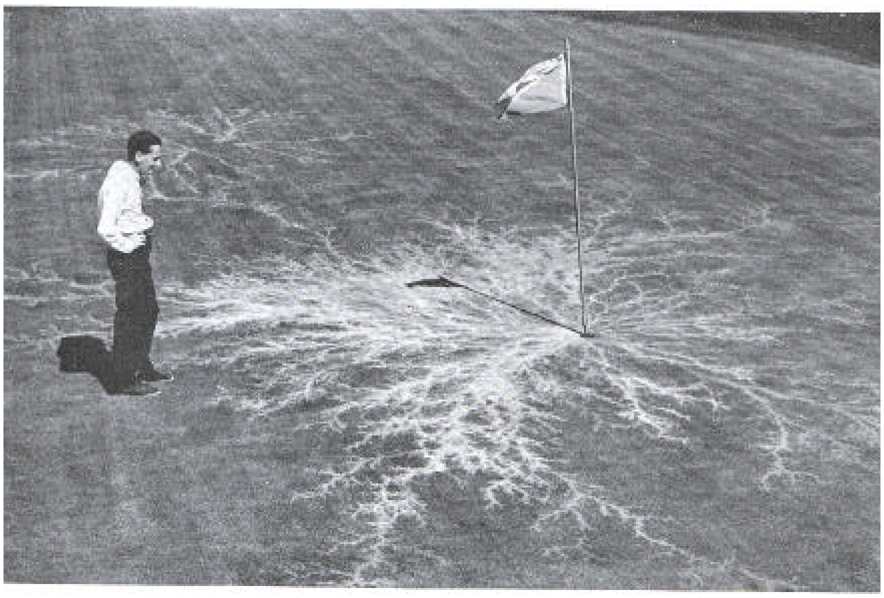

Figure 1. Scorched grass on a golf course near Chevy Chase Club, D. C. resulting from a lightning strike to the flagpole at the center of the dendritic pattern (Colton, 1950). Similar patterns have been photographed more recently in Arizona and in Florida..

Similar observations associated with measurements of lightning currents during some triggered-lightning experiments have been reported by Fisher et al. (1994) and by Schnetzer et al. (1996) They repeatedly initiated lightning with the use of rockets that towed aloft fine wires, the lower ends of which were attached to 8-foot-long ground rods driven into the earth at Fort McClellan, AL and at Camp Blanding, FL. Video cameras were used to record the lightning strikes to the ground rod. On analyzing their data, Fisher and Schnetzer found that electrical discharges and arcs sometimes developed radially outward from the ground rod, along the ground surface, whenever the strike's peak current exceeded 5 kA and 80% of the times when the peak stroke currents exceeded 15 kA. A photograph of one of these arcing discharges is shown in Figure 2.

While these reports of surfacing arcing are puzzling, some understanding of the phenomenon can be extracted from a photograph of a laboratory discharge to the surface of a pool of water that appeared in the August, 1969 issue of the National Geographic Magazine. This photograph, taken at the University of Colorado in Boulder and reproduced here as Figure 3, shows that the

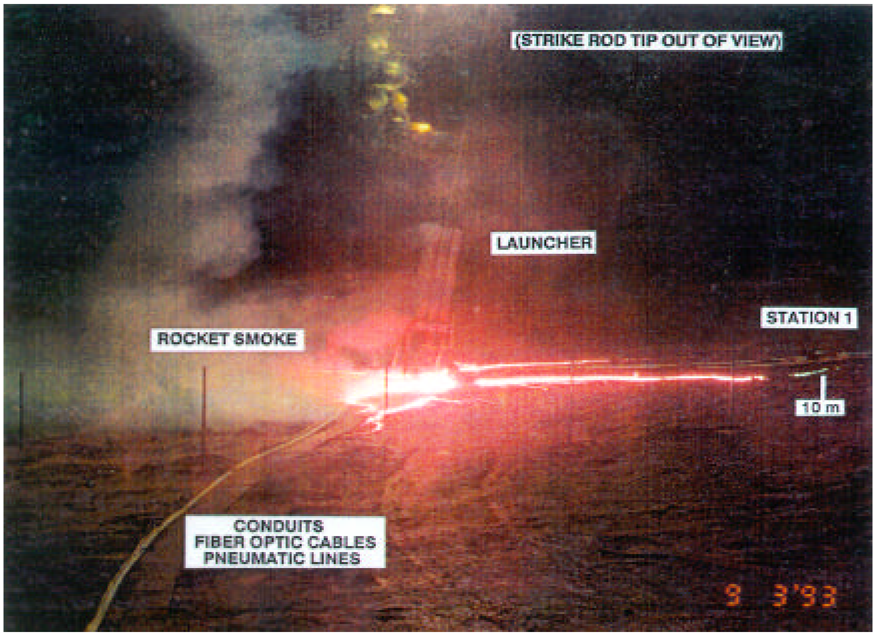

Figure 2. Photograph of the surface arcs emanating from the ground rod conducting a 29.6 kA rocket-triggered lightning strike to ground at Fort McClellan, AL. (Fisher and Schnetzer, 1994)

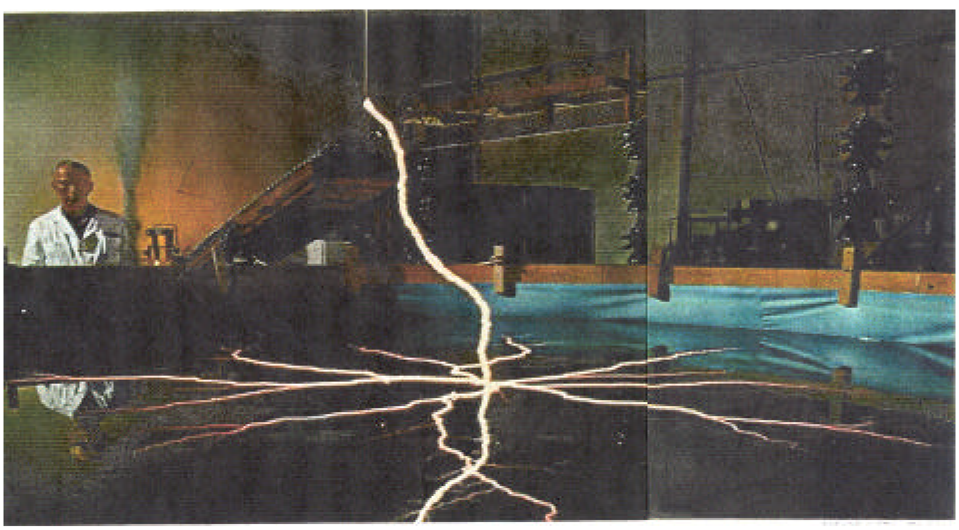

Figure 3. Photograph of a discharge to a pool of water at the University of Colorado, Boulder. (This photograph appeared in the August, 1969 issue of The National Geographic Magazine.)

discharge did not penetrate the body of water but, instead, created dendritic discharge patterns out over the water surface. The details of this experiment are not yet available but, from anecdotal reports, it appears that many of these experiments were made with water from the Boulder City water supply; apparently, no effort was made to use highly purified, low conductivity water in these studies.

An investigation into the physics of surface arcing.

The photograph in Figure 3 allows some insight into the process involved in a discharge arcing over the surface of the target. Following is our analysis of the processes that occur when a non-metallic but weakly-conducting target receives a discharge on an exposed surface. Our model is that in which a concentrated negative charge, Q, is brought above a plane surface of a target having an volume electrical conductivity, λ. During the period prior to the onset of any discharge, the electric fields, E, created by this charge will polarize the target, acting to repel electrons, leaving positive charges on the surface of the target. This electron-repulsion process will continue until the concentration, σ, of positive charges on the target surface divided by the *permittivity*, ε_0, of the air, 8.854 pico farads/meter equals the strength of the electric field applied to the surface, thus canceling that electric field at all points below the surface.

The rate at which positive charges are induced on the surface can be calculated from Ohm's law: The density, j, of the electric current in the target material is determined by the conductivity, λ, of the material times the strength, E, of the electric field *in* the material. This Ohm's law relation can be expressed as:

$$\mathbf{j} = \lambda \mathbf{E} \qquad \text{Eq. 1}$$

where j equals $d\sigma/dt$, the time rate of change for the surface density of charge. The field strength inside the material causing the current flow equals the surface density of charge divided by the permittivity of the material, which is given by the permittvity of space, ε_0, times the dielectric constant of the material, k_d. With these definitions, Eq. 1 can be written as:

$$\frac{d\sigma}{dt} = -\lambda \frac{\sigma}{k_d \, \varepsilon_0} \; . \qquad \text{Eq. 2}$$

Integration of Eq. 2 yields the value for the density of the field-induced charge on the surface of the conductor as a function of time, τ, after onset of the electric field:

$$\sigma(t) = \varepsilon_0 \, E_0 \left(1 - e^{-\frac{t}{\tau}}\right) \qquad \text{Eq. 3}$$

where τ, the time constant for σ to change from the initial value to all but 1/e (i. e., all but about 36.8%) of the final value is defined by

$$\tau = \frac{k_d \, \varepsilon_0}{\lambda} . \qquad \text{Eq. 4}$$

The measured conductivity of rain and of non-purified city water is of the order of 10^{-4} per ohm meter, depending on the dissolved salts. (Pure water has a conductivity of about 5×10^{-6} per ohm meter.) Since the dielectric constant of water substance is 81, the permittivity of water is 717 picofarads per meter. Use of these values in Eq. 4 indicates that the time required (to form 63.2% of the induced layer charges on the water surface beneath the electrode by ionic conduction processes) would be of the order of 7 microseconds after application of a voltage to the electrode whereas, 95% of the induced surface charges would be in place after another two τ, about 21 microseconds after the electrode. was energized.

As a result, at the time that the discharge commenced, there was a layer of *induced* charges on the surface of water below the electrode that were opposite in polarity but almost equal in magnitude to the charges carried by the spark. A calculation for the locations of these charges follows.

Distribution of the induced charges on the water surface

The strength of the vertical component of the electric field at the surface of the water pool at a distance, x, from the point directly beneath a charge, Q, at a height, h, is

$$E_{\text{vertical}} = \frac{2\,Q}{4\,\pi\,\varepsilon_0} \times \frac{h}{\left(h^2 + x^2\right)^{3/2}} \,. \qquad \text{Eq. 5}$$

The charge, q, induced on the water surface within the horizontal radius, R, by the charge, Q, above it, is:

$$q = \left(\frac{Q}{2\,\pi\,\varepsilon_0}\right) \times \int_0^R \left[\frac{\varepsilon_0\, h \times (2\pi\, x\, dx)}{\left(h^2 + x^2\right)^{3/2}}\right] \qquad \text{Eq. 6}$$

which gives

$$\left|\frac{q}{Q}\right| = 1 - \frac{h}{\left(h^2 + R^2\right)^{1/2}} \qquad \text{Eq. 7}$$

Solving for the radius, R, within which a given fraction, q/Q, of the induced charge lies, yields

$$R = h\left[\left(1 - \frac{q}{Q}\right)^{-2} - 1\right]^{1/2} . \qquad \text{Eq. 8}$$

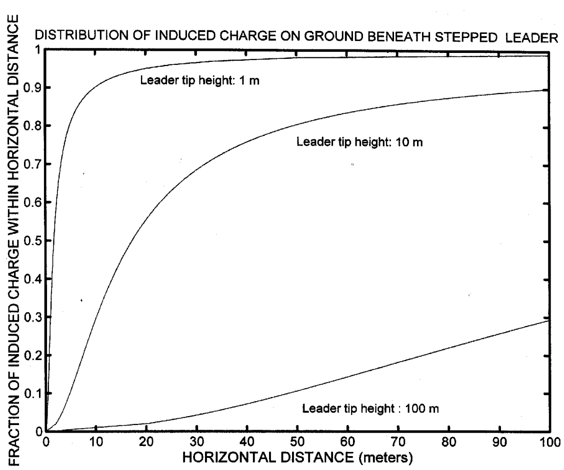

Figure 4. A plot of the distribution of induced charge on a conducting surface beneath a point charge.

For q/Q equal to 0.5, R equals 1.73 h; for q/Q equal to 0.75, R equals 3.87 h; and 95 % of the induced charge is on the surface within a distance, 20 h, of the strike point. A plot of the relation in Eq. 8 is shown in Figure 4.

The import of Equation 8 is that much of the charge, induced on a conducting surface by another charge above the surface, is concentrated in a disc-shaped region beneath the inducing charge.

An explanation for the discharge patterns shown in Figure 3.

Our explanation for the dendritic channels shown in this figure is that when a discharge occurs from the elevated charge to the surface, it propagates most readily where the electric fields are the strongest, which is toward the surface charges.

As the potential of the electrode shown above the water was caused to increase toward breakdown levels, the resulting electric fields acting on the water induced charges on the water surface such that the electric fields *inside* the pool of water did not increase. This induction process followed closely the potential increase, requiring a time interval of less than about 30 microseconds to complete. When the electric fields around the tip of the elevated electrode exceeded the "breakdown" level, a discharge from its tip developed and propagated toward and through the induced charges *on* the water surface. The earlier migration of charges to the surface has weakened any fields within the material so there are no strong driving forces and few, if any, induced charges there to act on the developing discharge. Accordingly, the spark discharge does not propagate into the water volume.

The question then arises: "What would have happened if the tip of a 'ground rod', immersed in the water, had protruded above the water surface directly below the high voltage discharge electrode such that it was the 'strike receptor'?"

The surge impedance of a ground rod.

Bazelyan and Raiser, in their recent book, *Lightning Physics and Lightning Protection*, (Institute of Physics Publishing, Bristol and Philadelphia, 2000) define the inductance per unit length, L', of an isolated conductor of radius, r_c and length, H >> r_c as

$$L' \approx \frac{\mu_0}{2\pi} \ln\left(\frac{H}{r_c}\right) = 0.2 \ln\left(\frac{H}{r_c}\right) \text{microhenry/meter} \qquad \text{Eq. 9}$$

where μ_0 is $4\pi \times 10^{-7}$ henries/meter, the permeability of space.

According to this relation, the inductance of an 8-foot long, 5/8-inch diameter ground rod is about 2.4 microhenries which would present a significance impedance to an impulsive discharge On strike contact to the top of the rod, the potential of the charge at the tip of the negative leader, would create a radial electric field in excess of several hundred kilovolts/m. Under such an electric field, radial streamers develop and propagate outward, connecting the strike to the surrounding induced charges on the ground surface. The primary destination of the strike is the induced charge on the ground surrounding the strike point. It follows that a vertical ground rod is much less effective in connecting a cloud-to-ground lightning strike to Earth than would be several buried conductors that extend radially outward from the top of the ground rod.

How far should radial ground conductors extend outward ?

A rough measure for the extent of the region in which the destination charges lie can be obtained by estimating the height of the approaching stepped leader at a time that is several surface-conduction time constants, τ, before the strike. Just prior to a strike above a moist surface, when the height of a descending stepped leader is about 2 meters, about 75% of the induced charge on the ground surface might lie within 8 meters of the strike point. It would follow from these estimates that buried radial ground conductors with lengths of about 8 meters could provide discharge paths for most of the charges carried by the strike whereas arcing out along the surface probably would occur during strong strikes to a single, vertical ground rod.

Conclusion

An essential component of a lightning protection system is the means by which the lightning discharge is conducted to the Earth. While the traditional ground rods that Benjamin Franklin invented are often effective, they sometimes fail in that discharges do not always follow the rods into the ground; discharges out along the surface of the ground are commonly observed. These surface discharges can be hazardous to persons and to animals in the vicinity of a strike.

The significance of this paper is that grounding of lightning can be improved by the use of radial conductors buried just below the ground surface and extending for distances of about 8 or 10 meters from the bottoms of the downconductors.

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