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978-1-107-07223-7 — Fundamentals of Lightning
Vladimir A. Rakov
Excerpt
More Information

1 Types of lightning discharges and lightning terminology

Lightning can be defined as a transient, high-current (typically tens of kiloamperes) electric discharge in air whose length is measured in kilometers. As for any discharge in air, the lightning channel is composed of ionized gas – that is, of plasma – whose peak temperature is typically 30,000 K—about five times higher than the temperature of the surface of the Sun. Lightning was present on Earth long before human life evolved, and it may even have played a crucial role in the evolution of life on our planet. The global lightning flash rate is some tens per second to 100 per second. Each year, some 25 million cloud-to-ground lightning discharges occur in the United States, and this number is expected to increase by about 50 percent due to global warming over the twenty-first century (Romps et al., 2014). Lightning initiates many forest fires, and over 30 percent of all electric power line failures are lightning related. Each commercial aircraft is struck by lightning on average once a year. A lightning strike to an unprotected object or system can be catastrophic.

1.1 Overview

The lightning discharge in its entirety, whether it strikes the ground or not, is usually termed a “lightning flash” or just a “flash.” A lightning discharge that involves an object on the ground or in the atmosphere is referred to as a “lightning strike.” A commonly used non-technical term for a lightning discharge is a “lightning bolt.” About three quarters of lightning discharges do not involve the ground. They include intracloud, intercloud, and cloud-to-air discharges and are collectively referred to as cloud flashes (see Fig. 1.1) and sometimes as ICs. Lightning discharges between cloud and earth are termed cloud-to-ground (or just ground) discharges and sometimes referred to as CGs. The latter constitute about 25 percent of global lightning activity. About 90 percent or more of global cloud-to-ground lightning is accounted for by negative downward lightning, in which negative charge is effectively transported to the ground, and the initial process begins in the cloud and develops in the downward direction. The term “effectively” is used to indicate that individual charges are not transported all the way from the cloud to the ground during the lightning processes; rather, the flow of electrons (the primary charge carriers) in one part of the lightning channel results in the flow of other electrons in other parts of the channel. Other types of cloud-to-ground lightning include positive downward, negative upward, and positive upward discharges (see Fig. 1.2). Downward flashes exhibit downward branching, while upward flashes are branched upward. Upward lightning discharges (types (b) and (d) in Fig. 1.2) are thought to occur only from tall objects (higher than 100 m or so) or from

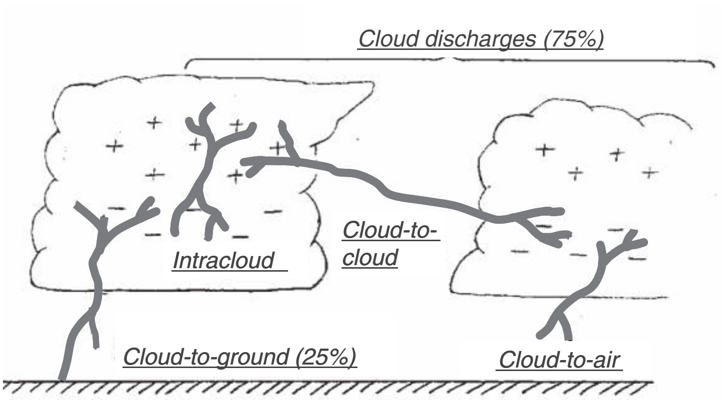

Fig. 1.1 General classification of lightning discharges from thunderstorm clouds. Cloud discharges constitute 75 percent and cloud-to-ground discharges 25 percent of global lightning activity.

objects of moderate height located on mountain tops. There are also bipolar lightning discharges sequentially transferring both positive and negative charges during the same flash. Bipolar lightning discharges are usually initiated from tall objects (that is, are of the upward type). Downward bipolar lightning discharges do occur, but appear to be rare.

Cloud flashes are most likely to begin near the upper and lower boundaries of the main negative charge region, and in the former case often bridge the main negative and main positive charge regions in the cloud (see chapter 3). Other scenarios are possible. There is a special type of cloud lightning that is thought to be the most intense natural producer of HF–VHF (3–300 MHz) radiation on Earth. It is referred to as compact intracloud discharge (CID). CIDs received their name due to their relatively small (hundreds of meters) spatial extent. They tend to occur at high altitudes (mostly above 10 km), appear to be associated with strong convection (however, even the strongest convection does not always produce CIDs), and tend to produce less light than other types of lightning discharges. Additional information on CIDs is given in Appendix 4.

Lightning occurrence is not limited to the Earth's atmosphere. There exists convincing evidence for lightning or lightning-like discharges on Jupiter and Saturn. Currents in Jovian lightning are expected to be one to two orders of magnitude larger than in Earth lightning. A review of extraterrestrial lightning is given by Rakov and Uman (2003, Ch. 16).

1.2 Downward negative lightning

We first introduce, referring to Figs. 1.3a and b, the basic elements of the negative downward lightning discharge, termed "component strokes" or just "strokes." Each flash typically contains three to five strokes, the observed range being one to 26.

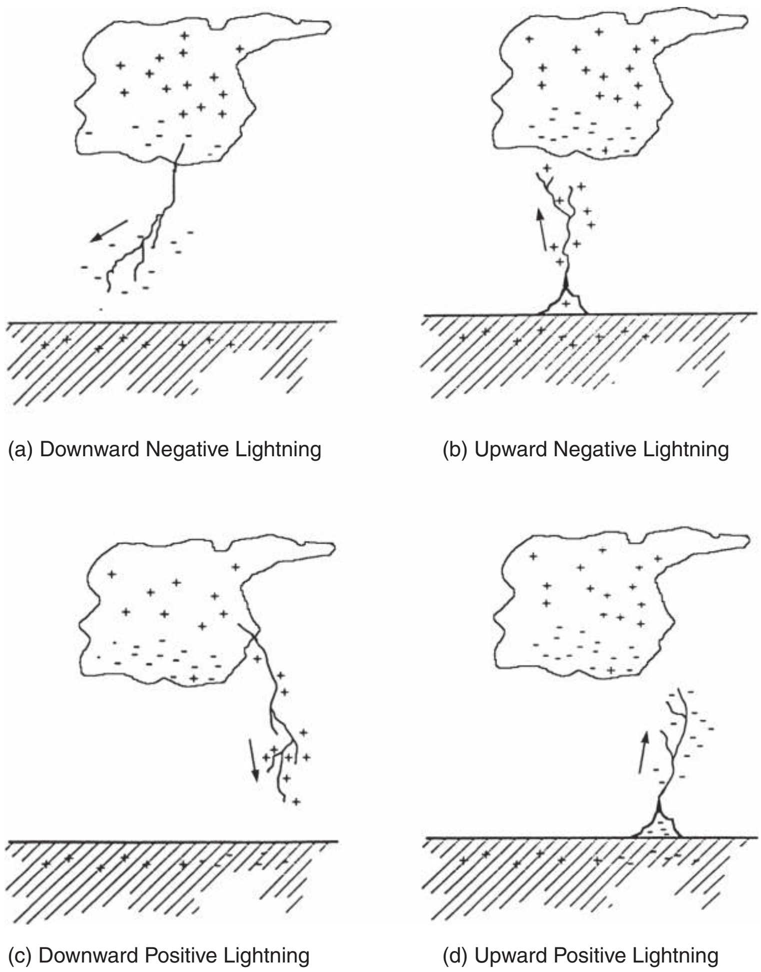

Fig. 1.2 Four types of lightning effectively lowering cloud charge to the ground. Only the initial leader is shown for each type. For each lightning-type name given below the sketch, direction (downward or upward) indicates the direction of propagation of the initial leader and polarity (negative or positive) refers to the polarity of the cloud charge effectively lowered to the ground. In (a) and (c), the polarity of charge lowered to the ground is the same as the leader polarity, while in (b) and (d) those polarities are opposite. Not shown in this figure are upward (object-initiated) and downward bipolar lightning flashes. © Vladimir A. Rakov and Martin A. Uman 2003, published by Cambridge University Press, reprinted with permission.

Roughly half of all lightning discharges to earth strike the ground at more than one point, with the spatial separation between the channel terminations being up to many kilometers. Then we will introduce, referring to Figs. 1.4a and b, the two major lightning processes comprising a stroke, the "leader" and the "return stroke," which occur as a sequence with the leader preceding the return stroke. We will also briefly review lightning parameters, with more details being found in Rakov and Uman (2003) and references therein.

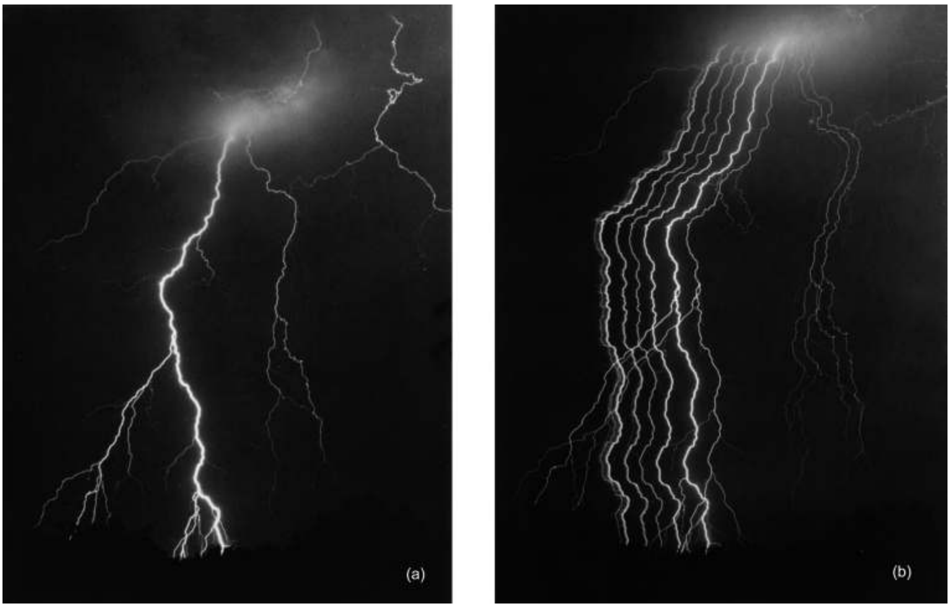

Fig. 1.3 Lightning flash which appears to have at least seven (perhaps as many as ten) separate ground strike points: (a) still-camera photograph, (b) moving-camera photograph. Some of the strike points are associated with the same stroke, having separate branches touching the ground, while others are associated with different strokes taking different paths to the ground. Adapted from Hendry (1993).

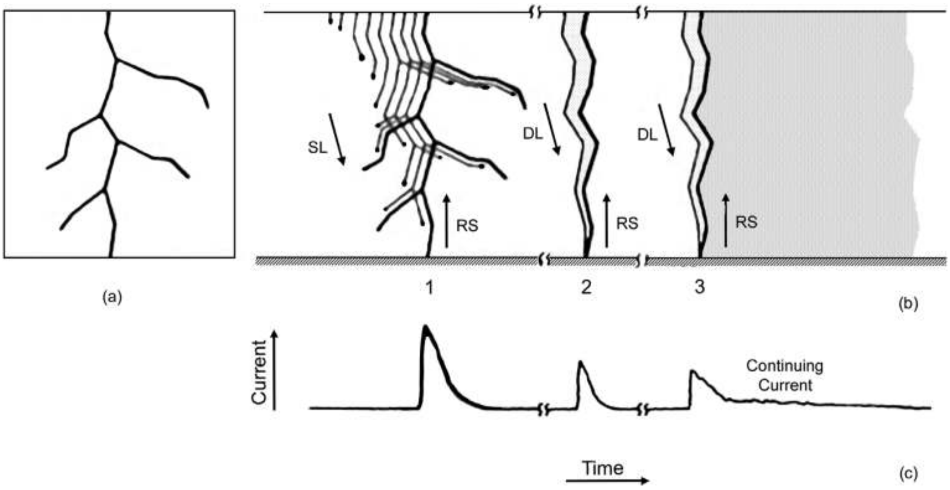

Fig. 1.4 Schematic diagram showing the luminosity of a three-stroke downward negative flash and the corresponding current at the channel base: (a) still-camera image, (b) streak-camera image, and (c) channel-base current. © Vladimir A. Rakov and Martin A. Uman 2003, published by Cambridge University Press, reprinted with permission.

Two photographs of a negative cloud-to-ground discharge are shown in Figs. 1.3a and b. The image in Fig. 1.3a was obtained using a stationary camera, while the image in Fig. 1.3b was captured with a separate camera that was moved horizontally during the time of the flash. As a result, the latter image is time-resolved, showing several distinct luminous channels between the cloud and the ground separated by dark gaps. The distinct channels are associated with individual strokes, and the time intervals corresponding to the dark gaps are typically of the order of tens of milliseconds. These dark time intervals between strokes explain why lightning often appears to the human eye to "flicker." In Fig. 1.3b, time advances from right to left, so that the first stroke is on the far right. The first two strokes are branched, and the downward direction of branches indicates that this is a downward lightning flash.

Now we consider sketches of still and time-resolved images of the three-stroke lightning flash shown in Figs. 1.4a and b, respectively. A sketch of the corresponding current at the channel base is shown in Fig. 1.4c. In Fig. 1.4b, time advances from left to right, and the timescale is not continuous. Each of the three strokes in Fig. 1.4b, represented by its luminosity as a function of height above ground and time, is composed of a downward-moving process, termed a "leader," and an upward-moving process, termed a "return stroke (RS)." Transition from the leader to the return stroke is referred to as the "attachment process," which is not shown in Fig. 1.4b. The leader creates a conducting path between the cloud charge source region and the ground and distributes negative charge from the cloud source region along this path, and the return stroke traverses that path moving from the ground toward the cloud charge source region and neutralizes the negative leader charge. Thus, both leader and return stroke processes serve to effectively transport negative charge from the cloud to the ground. As seen in Fig. 1.4b, the leader initiating the first return stroke differs from the leaders initiating the two subsequent strokes (all strokes other than first are termed "subsequent strokes"). In particular, the first-stroke leader appears optically to be an intermittent process – hence the term "stepped leader (SL)" – while the tip of a subsequent-stroke leader appears to move continuously. The continuously moving subsequent-stroke leader tip appears on streak photographs as a downward-moving "dart," hence the term "dart leader (DL)." The apparent difference between the two types of leaders is related to the fact that the stepped leader develops in virgin air, while the dart leader follows the "pre-conditioned" path of the preceding stroke or strokes. Sometimes, a subsequent leader exhibits stepping while propagating along a previously formed channel; it is referred to as "dart-stepped leader." There are also so-called "chaotic" subsequent-stroke leaders.

The electric potential difference between a downward-moving stepped-leader tip and the ground is probably some tens of megavolts, comparable to or a considerable fraction of that between the cloud charge source and the ground. The magnitude of the potential difference between two points, one at the cloud charge source and the other on the ground, is the line integral of electric field intensity between those points. The upper and lower limits for the potential difference between the lower boundary of the main negative charge region and the ground can be estimated by multiplying, respectively, the typical observed electric field in the cloud, 10^5 V m^{-1}, and the expected electric field at the ground under a thundercloud immediately prior to the initiation of lightning, 10^4 V m^{-1}, by the height of the lower boundary of the negative charge region above ground. The resultant range is 50–500 MV, if the height is assumed to be 5 km.

When the descending stepped leader attaches to the ground, the first return stroke begins. The first-return-stroke current measured at the ground rises to an initial peak of about 30 kA in some microseconds and decays to half-peak value in some tens of microseconds. The return stroke effectively lowers to the ground the several coulombs of charge originally deposited on the stepped-leader channel, including all the branches. Once the bottom of the dart leader channel is connected to the ground, the second (or any subsequent) return-stroke wave is launched upward, which again serves to neutralize the leader charge. The subsequent return-stroke current at the ground typically rises to a peak value of 10–15 kA in less than a microsecond and decays to half-peak value in a few tens of microseconds.

The high-current return-stroke wave rapidly heats the channel to a peak temperature near or above 30,000 K and creates a channel pressure of 10 atm (1 megapascal) or more, resulting in channel expansion, intense optical radiation, and an outward propagating shock wave that eventually becomes the thunder (sound wave) we hear at a distance. Each cloud-to-ground lightning flash involves an energy of roughly 10^9 to 10^{10} J (1–10 gigajoules). Lightning energy is approximately equal to the energy required to operate five 100 W light bulbs continuously for one month. Note that not all the lightning energy is available at the strike point; only 10^{-2}–10^{-3} of the total energy, since most of the energy is expended in producing thunder, hot air, light, and radio waves.

The impulsive component of the current in a return stroke is often followed by a continuing current, which has a magnitude of tens to hundreds of amperes and a duration of up to hundreds of milliseconds. Continuing currents with a duration in excess of 40 ms are traditionally termed "long continuing currents." Between 30 and 50 percent of all negative cloud-to-ground flashes contain long continuing currents. Current pulses superimposed on continuing currents, as well as the corresponding enhancements in luminosity of the lightning channel, are referred to as M-components.

1.3 Downward positive lightning

Positive lightning discharges are relatively rare (about 10 percent of global cloud-to-ground lightning activity), but there are five situations that appear to be conducive to the more frequent occurrence of positive lightning. These situations include: (1) the dissipating stage of an individual thunderstorm; (2) winter (cold-season) thunderstorms; (3) trailing stratiform regions of mesoscale convective systems; (4) some severe storms; and (5) thunderclouds formed over forest fires or contaminated by smoke. Positive flashes are usually composed of a single stroke, in contrast with negative flashes, about 80 percent of which contain two or more strokes, with three to five being typical. Multiple-stroke positive flashes do occur but are relatively rare. Positive lightning is typically more energetic and potentially more destructive than negative lightning.

The gross charge structure of a "normal" thundercloud is often viewed as a vertical tripole consisting of three charge regions with the main positive at the top, main negative in the middle, and an additional (typically smaller) positive below the main negative (see chapter 3). Such a charge structure appears to be not conducive to the production of positive

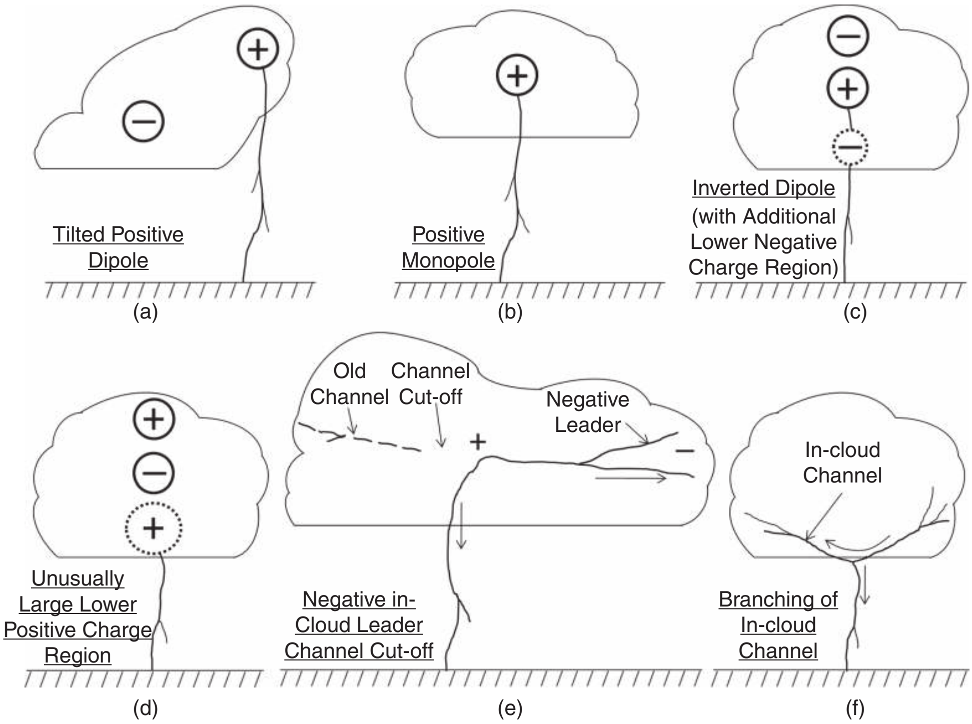

Fig. 1.5 Conceptual cloud charge configurations and scenarios leading to production of downward positive lightning. Adapted from Nag and Rakov (2012).

cloud-to-ground lightning. Figure 1.5 illustrates six conceptual cloud charge configurations and scenarios that were observed or hypothesized to give rise to positive lightning. For four of them, tilted positive dipole, positive monopole, inverted dipole, and unusually large lower positive charge region (Figs. 1.5a–1.5d, respectively), the primary source of charge is a charged cloud region, while for the other two, negative in-cloud leader channel cutoff and branching of in-cloud channel (Figs. 1.5e and 1.5f, respectively), the primary source of charge is an in-cloud lightning channel formed prior to the positive discharge to the ground.

1.4 Artificially initiated lightning

Lightning can be initiated artificially (triggered) by launching a small rocket trailing a thin grounded or ungrounded wire toward a charged cloud overhead. In the former case, the triggered lightning is referred to as "classical" and in the latter case as "altitude." The sequence of processes (except for the transition from leader to return stroke stage that is referred to as the "attachment process") in classical triggered lightning is schematically

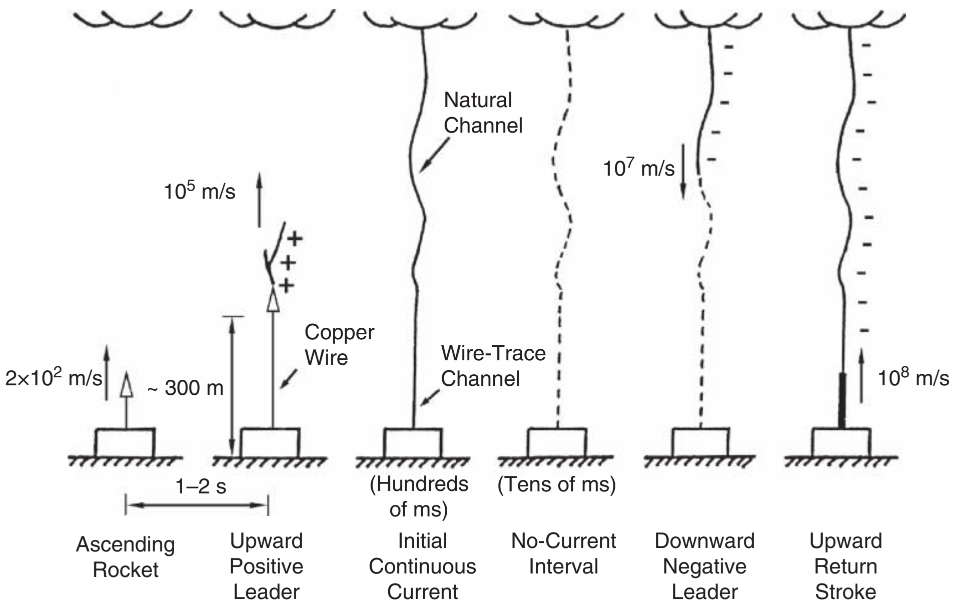

Fig. 1.6 Sequence of events (except for the attachment process) in classical triggered lightning. The upward positive leader and initial continuous current constitute the initial stage of a classical triggered flash. Adapted from Rakov et al. (1998).

shown in Fig. 1.6. When the rocket, ascending at about 150–200 m s^{-1}, is about 200–300 m high, the field enhancement near the rocket tip launches a positively charged leader that propagates upward toward the cloud. This upward positive leader vaporizes the trailing wire, bridges the gap between the cloud and the ground, and establishes an initial continuous current with a duration of some hundreds of milliseconds that transports negative charge from the cloud charge source region to the triggering facility. After the cessation of the initial continuous current, one or more downward dart-leader/upward return-stroke sequences may traverse the same path to the triggering facility. The dart leaders and the following return strokes in triggered lightning are similar to dart-leader/return-stroke sequences in natural lightning, although the initial processes in natural downward and triggered lightning are distinctly different. To date, well over 1,000 lightning flashes have been triggered by researchers in different countries using the rocket-and-wire technique, with over 450 of them at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. The ICLRT was established in 1993 and, since 2004, also includes the Lightning Observatory in Gainesville (LOG), located 45 km from the Camp Blanding facility. Photographs of two classical rocket-and-wire triggered-lightning flashes from Camp Blanding are shown in Fig. 1.7.

The results of triggered-lightning experiments have provided considerable insight into natural lightning processes that would not have been possible from studies of natural lightning due to its random occurrence in space and time. As an example, Fig. 1.8 shows a photograph of surface arcing during a triggered-lightning flash from

Fig. 1.7 Photographs of lightning flashes triggered using the rocket-and-wire technique at Camp Blanding, Florida. Top – a distant view of a strike to the test runway; bottom – a close-up view of a strike to the test power system. © Vladimir A. Rakov and Martin A. Uman 2003, published by Cambridge University Press, reprinted with permission.

experiments at Fort McClellan, Alabama. The soil was red clay and a 0.3 or 1.3 m steel vertical rod was used for grounding the rocket launcher. The surface arcing appears to be random in direction and often leaves little if any evidence on the ground. Even within the same flash, individual strokes can produce arcs developing in different directions. In one case, it was possible to estimate the current carried by one arc branch which contacted the instrumentation. That current was approximately 1 kA, or 5 percent of the total current peak in that stroke. The observed horizontal

Fig. 1.8 Photograph of surface arcing associated with the second stroke (current peak of 30 kA) of flash 9312 triggered at Fort McClellan, Alabama. Lightning channel is outside the field of view. One of the surface arcs approached the right edge of the photograph, a distance of 10 m from the rocket launcher. Adapted from Fisher et al. (1994).

extent of surface arcs was up to 20 m, which was the limit of the photographic coverage during the Fort McClellan experiments. These results suggest that the uniform ionization of soil, usually postulated in studies of the behavior of grounding electrodes subjected to lightning surges, may not be an adequate assumption.

1.5 Upward lightning

The phenomenology of upward negative lightning, illustrated in Fig. 1.9 by the sketches of still and time-resolved photographic records and of the corresponding current record, is similar to that of negative lightning triggered using the classical rocket-and-wire technique (Section 1.4). In the latter case, the thin triggering wire plays the role of the grounded object, one that is rapidly erected and then replaced by the plasma channel of the upward leader. Downward leader/upward return stroke sequences in upward lightning (Fig. 1.9), and their counterparts in rocket-triggered lightning (Fig. 1.6), are similar to subsequent strokes in natural downward lightning (Fig. 1.4). For this reason, leader/return stroke sequences in upward (object-initiated) lightning and in rocket-triggered lightning are sometimes referred to as "subsequent strokes." Interestingly, only 20 to 50 percent of object-initiated flashes contain subsequent strokes, while over 70 percent of rocket-and-wire triggered flashes in Florida do so. Upward flashes can be negative, positive, or bipolar. A photograph of an upward flash (note upward branching) initiated from a 70 m tower on a 640 m mountain is shown in Fig. 1.10.