

# Lightning Direction-Finding Systems for Forest Fire Detection

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## Abstract

Extensive networks of magnetic direction-finding (DF) stations have been installed throughout the western United States and Alaska to facilitate early detection of lightning-caused fires. Each station contains a new wideband direction-finder that responds primarily to cloud-to-ground lightning and discriminates against cloud discharges and background noise. Good angle accuracy is obtained by measuring the lightning direction at just the time the return-stroke electromagnetic field reaches its initial peak. Lightning locations are calculated from the intersections of direction vectors and/or from the ratio of signal strengths recorded simultaneously at two, three, or four DF sites. The development of these systems has proved to be a significant aid in the detection of lightning-caused fires and in fire weather forecasting.

## 1. Introduction

Each year lightning starts approximately 10 000 wildland fires in the United States. The lightning fire hazard is particularly serious in remote, unpopulated areas because of the greater difficulty of early detection and suppression. Meteorological satellites and weather radars can identify convective cloud systems and precipitation, but not lightning. Since some clouds produce much precipitation but little lightning and others produce lightning but relatively little precipitation, a system that detects and locates the lightning directly is highly desirable. Here we briefly describe a new magnetic direction-finding (DF) system that has been developed to facilitate early detection of lightning-caused fires.

A lightning discharge or flash to ground contains several large current surges or strokes (see Uman, 1969, for a review of basic lightning phenomena). A typical flash begins with a faint *stepped leader*, which proceeds rather slowly from cloud to ground in a series of short, intermittent steps. When the stepped leader contacts ground,

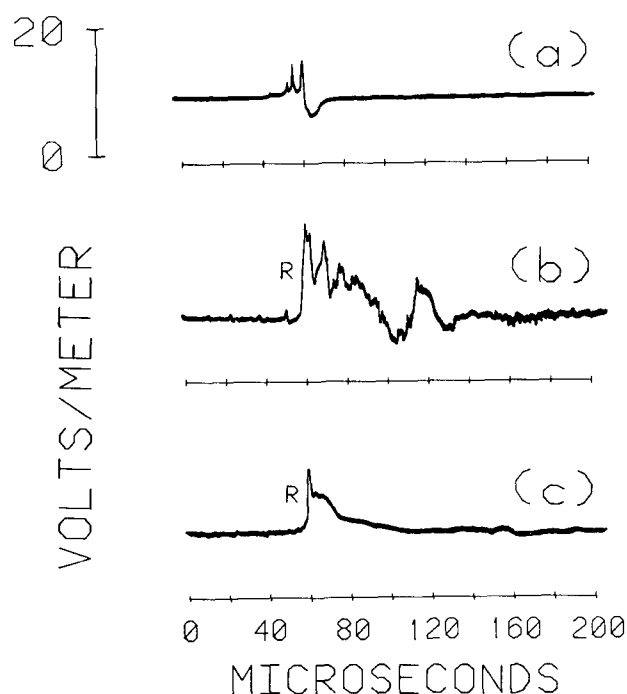


FIG. 1. The radiation field signatures produced by a typical lightning discharge to ground at a distance of about 60 km. The top trace (a) shows a cloud discharge impulse that preceded the first return stroke (b) and a subsequent return stroke (c).

a very energetic and bright *return stroke* propagates rapidly back up the ionized path established by the leader. After a pause of 30–50 ms, a *dart leader* often propagates down the previous channel and is followed by another bright return stroke propagating upward. A typical flash to ground contains three or four leader-return stroke combinations, which almost always transfer negative charge to ground. The currents in return strokes typically rise to peak values of 10–40 kA in 1–10  $\mu$ s or less.

## 2. Direction-finding system

Each DF system senses the electromagnetic fields radiated by lightning on two orthogonal magnetic-loop an-

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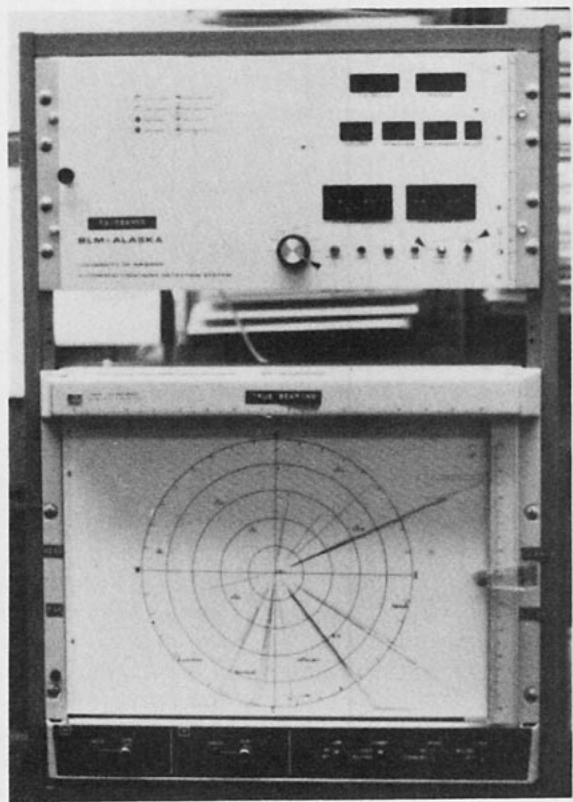


FIG. 2. The original lightning DF system developed for use in interior Alaska. The orthogonal magnetic-loop antennas are shown at the top, and the associated electronics and x-y plotter are below.

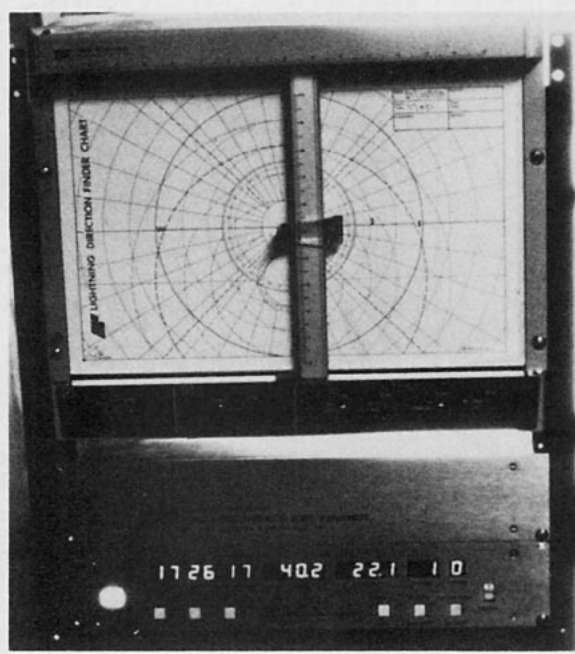
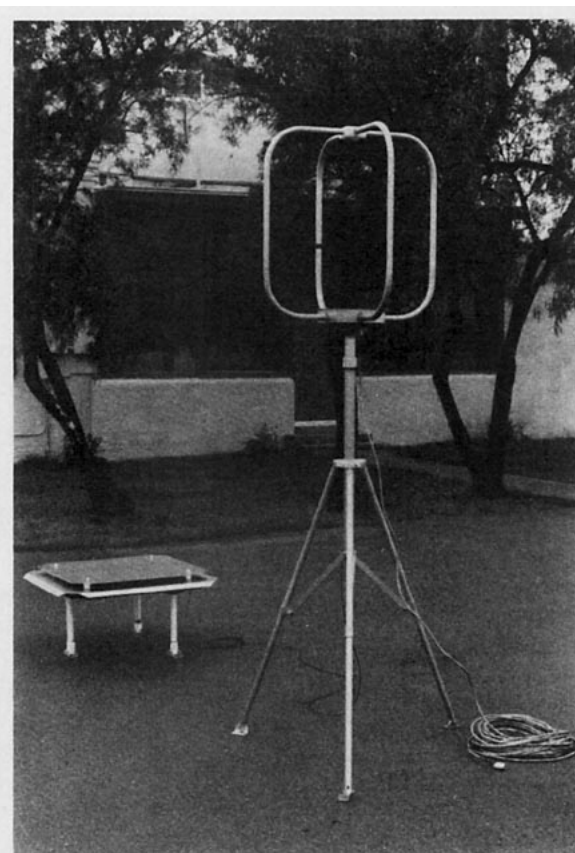


FIG. 3. The present lightning DF system, consisting of wideband electric and magnetic field antennas (top) and associated electronics and x-y plotter (bottom).

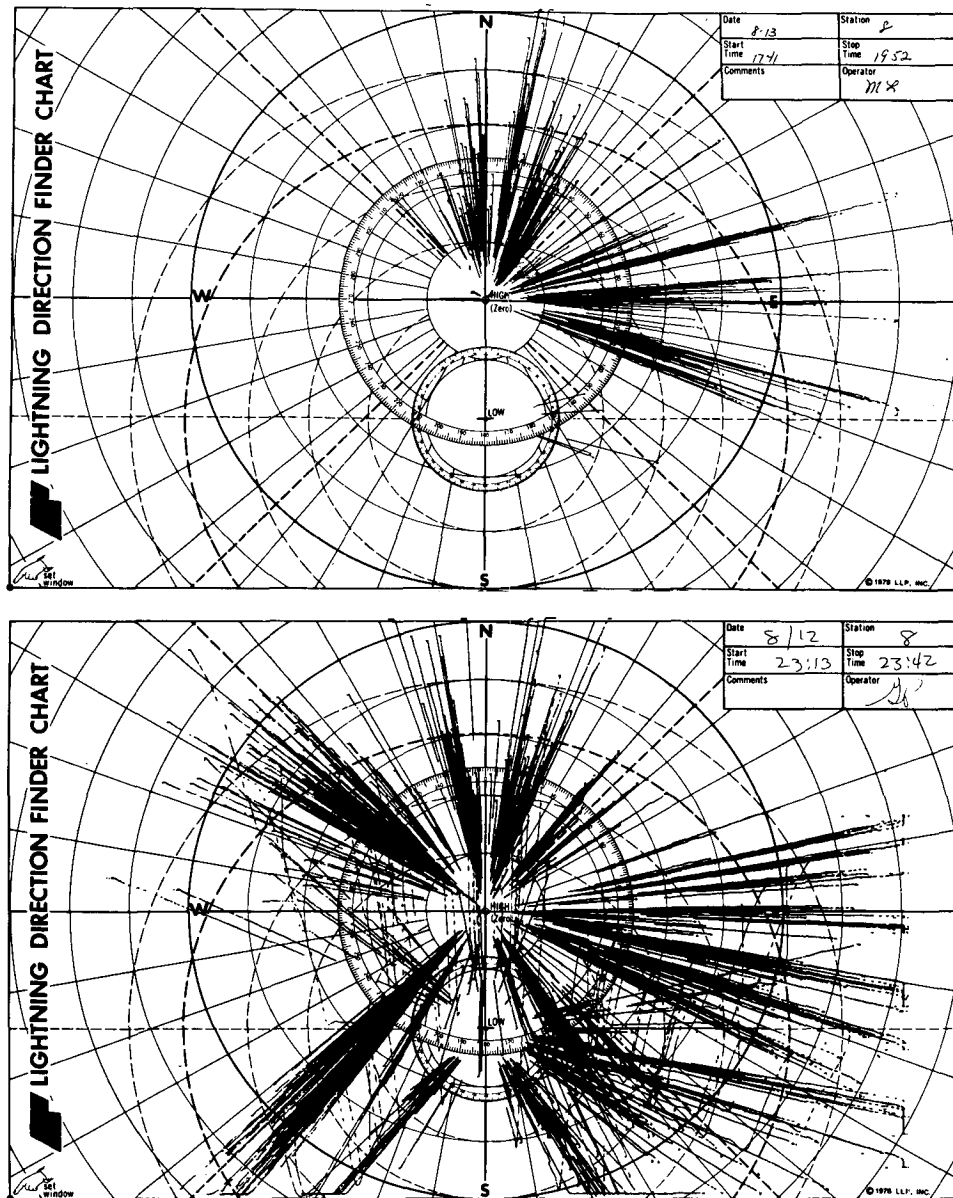


FIG. 4. Examples of lightning direction vectors recorded at Las Vegas, Nev. The top chart shows 131 min of moderate activity on 13 August 1978, and the lower record shows 29 min of heavy, close activity on 12 August 1978.

tennas and on a flat-plate electric antenna. The bandwidths of the antenna systems are wide (approximately 1 kHz–1 MHz) so that the shapes and polarities of the lightning field waveforms are preserved. The voltage produced by the electronics associated with each magnetic loop is proportional to the lightning magnetic field multiplied by the cosine of the angle between the plane of the loop and the direction of propagation of the incoming field. The direction of a lightning flash can, therefore, be determined from the ratio of the signals on the two orthogonal loops, a standard technique in radio direction-finding.

In order to optimize accuracy and eliminate background noise, the DF electronics are designed to respond

to only those field waveforms that are characteristic of return strokes in cloud-to-ground flashes. As we shall see, the shapes and polarities of return-stroke fields are quite distinctive and are different from those radiated by cloud discharges and most types of background noise. To illustrate this, note in Fig. 1b the electric field radiated by the first return stroke in a typical cloud-to-ground flash, and note in Fig. 1a the field due to a large cloud impulse that preceded this return stroke. These signatures were recorded at a distance of about 60 km using a broadband antenna and waveform recording system similar to that described by Krider *et al.* (1977). The waveform produced by a return stroke subsequent to the first is shown in Fig. 1c.

The abrupt field transition labeled *R* in Fig. 1b is typical of first strokes and was produced by the onset of the return-stroke current just after the stepped leader contacted ground (Krider *et al.*, 1977; Weidman and Krider, 1978). The small pulses preceding *R* are due to the last few steps of the stepped leader (Krider and Radda, 1975; Krider *et al.*, 1977), and the subsidiary peaks following *R* are caused by the effects of branches and channel tortuosity (Weidman and Krider, 1978). Cloud discharges usually occur about twice as often as discharges to ground and, of course, all ground flashes also have intracloud components. Cloud pulses similar to Fig. 1a may occur individually or as part of a rapid sequence (Weidman and Krider, 1979) and must be rejected by any system designed to detect just return strokes. Note that the initial portion of the pulse in Fig. 1a contains several peaks and that the time to the largest peak is longer than the time to the *R* peak in Fig. 1b. The width of the first half-cycle in Fig. 1a is less than that of the first half-cycle in Fig. 1b, and the bipolar overshoot following the initial peak is more pronounced.

Basically, the DF electronics require the lightning field to have a rise time, width, and subsidiary peak structure characteristic of a return stroke. The field of the first return stroke in a flash must rise to peak within about 20  $\mu$ s, and no subsidiary peak can exceed the value of the first peak by more than 15%. The electric field must have a positive initial polarity (the polarity produced when negative charge is lowered toward ground) at the time of the first peak and must remain positive for at least 15  $\mu$ s after the first peak. Any pulses, such as stepped-leader pulses, that precede the first return stroke must have only a positive polarity, and the field overshoot following the initial peak must not exceed a preset fraction (typically  $-100\%$ ) of the first peak. The rise time and bipolar shape requirements also serve to eliminate very distant ( $>400$  km) lightning signals because the effects of propagation tend to increase the field rise times (Uman *et al.*, 1976) and distant ionospheric reflections are often large and inverted with respect to the initial ground wave (Taylor, 1963).

In order to provide an optimum detection efficiency over a wide dynamic range, the DF contains both high- and low-gain circuits that operate in parallel. The rise time and pulse width intervals are longer in the high-gain section than in the low-gain to allow for the effects of propagation and because the shapes of near and distant lightning signals are somewhat different (Lin *et al.*, 1979; Uman *et al.*, 1976). Since the shapes of first and subsequent return strokes are also different, the rise time and width criteria are reduced to values appropriate for subsequent return strokes after the first stroke in a flash is detected.

When a return-stroke field is detected, the magnetic direction is determined at just the time the stroke field reaches its initial peak. At this time, the stroke current is still within about 100 m of the ground, so that any errors in magnetic direction due to horizontal channel

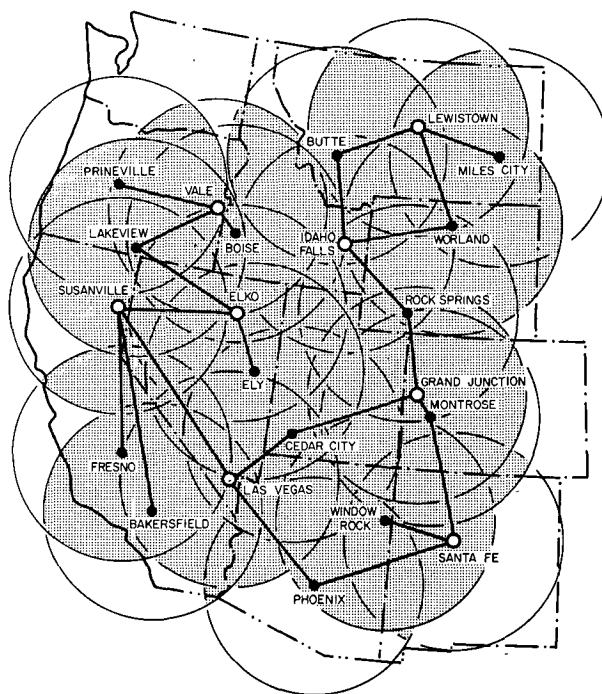


FIG. 5. The locations of lightning DF stations in the western United States. Stations that also contain position-analyzing computers are shown as open circles. The nominal range of each DF is shown as a circle with a radius of about 400 km. The shaded area of overlapping coverage totals about 600 million acres.

sections and branch currents are minimized (Krider *et al.*, 1976; Herrman *et al.*, 1976; Uman *et al.*, 1980) and errors due to ionospheric reflections (Horner, 1957) are eliminated. Also, by sampling at this time, the magnetic direction points toward the location of the ground contact point rather than some elevated portion of the channel. The angular accuracy of a DF system is typically 1–2° or better (Krider *et al.*, 1976), a value that is usually more than adequate to resolve individual cells of electrical activity within larger cloud systems.

Photographs of the DF antennas and associated electronics are shown in Figs. 2 and 3. The original system (Fig. 2) was designed and constructed in 1976 by The University of Arizona for use by the United States Department of the Interior (USDI) Bureau of Land Management in Alaska. Fig. 3 shows a more recent commercial version<sup>4</sup> that is now operating throughout the United States and several foreign countries.

Each DF station is designed to operate either as a stand-alone system, often in conjunction with a weather radar, or as part of a larger network that contains an automatic position-analyzing computer. In the former case, the lightning directions can be plotted on an analog x-y recorder as shown in Fig. 4. Each discharge is

<sup>4</sup> Manufactured by Lightning Location and Protection, Inc., Tucson, Ariz.

shown as a straight-line segment or vector on a compass grid, with the length of the vector being proportional to the peak amplitude of the first stroke field. Clusters of vectors indicate the directions and angular extent of individual storm cells. If weather radar data are available, clusters such as these are used to identify which clouds are producing lightning and which clouds are not. With some experience, the operator of a single DF system can often estimate an approximate range to a cell using an average of the lightning signal strengths within a cluster.

A microcomputer subsystem built into each DF digitizes and stores the signals for up to eight return strokes in each flash to ground, computes the angles to each stroke, and stores the results in a buffer memory for subsequent output. The time, angle, signal amplitude, and number of return strokes for the most recent flash are shown on a front panel light-emitting diode (LED) display and are typed on a local data terminal. Under most conditions, the amplitude of the field at a given range and the multiplicity of strokes are good indicators of the severity of the discharge. The total number of flashes that are detected each hour, or for an

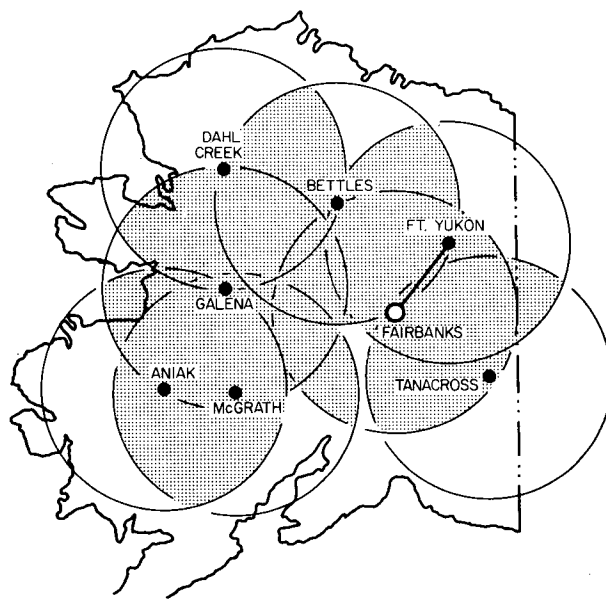


FIG. 6. The locations of lightning DF stations in Alaska. The total area of overlapping coverage is about 300 million acres (see also the caption to Fig. 5).

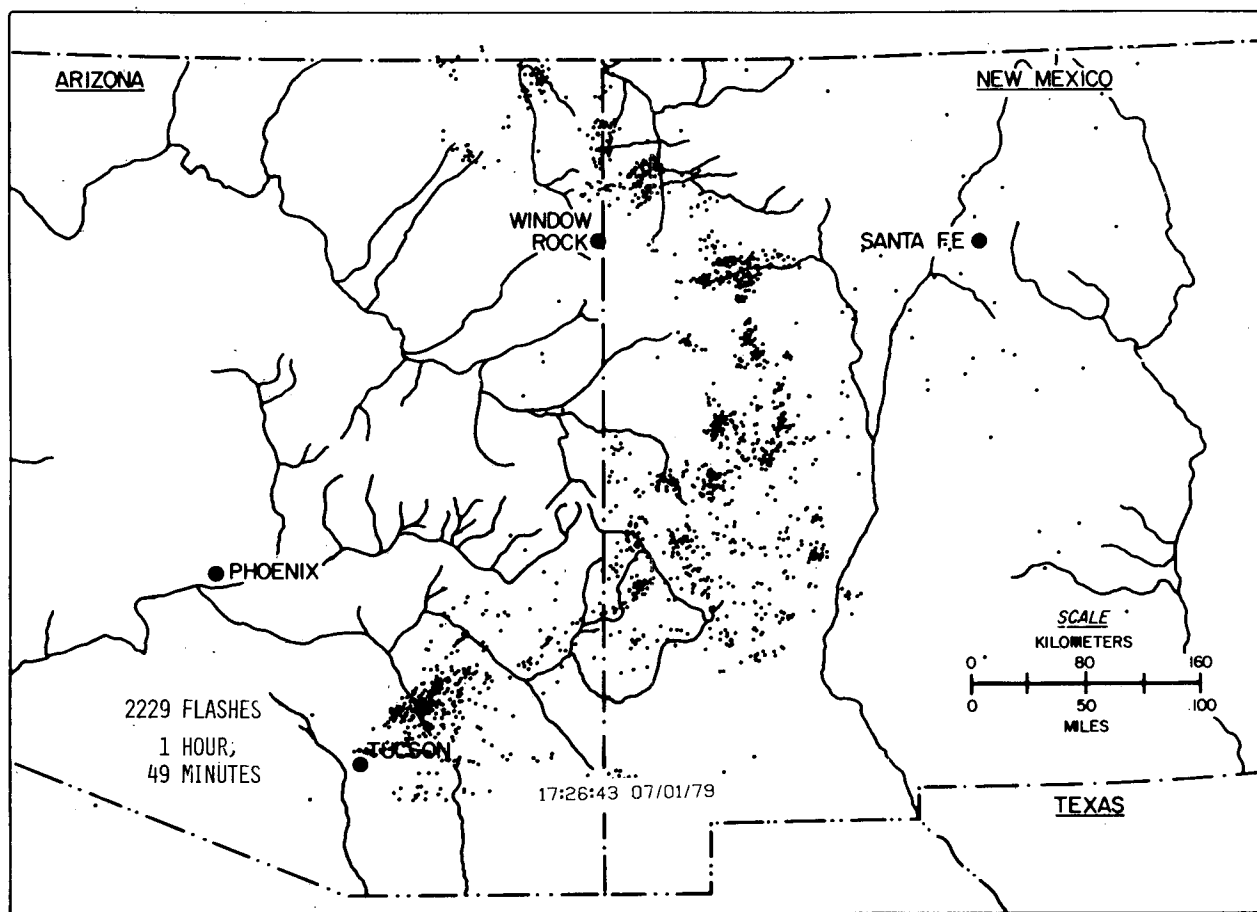


FIG. 7. A map of lightning locations recorded by a position analyzer at Tucson, Ariz., on 1 July 1979. The location of each flash is plotted as a dot. The DF stations were located at Tucson, Phoenix, Window Rock, and Santa Fe.

operator-determined time interval, are available for display or for typing on command. The microcomputer can also transmit the angle and signal-strength data for each discharge to a remote station where individual lightning locations are computed automatically.

### 3. Detection networks

The USDI Bureau of Land Management (BLM) has been operating lightning DF stations in the western United States and Alaska since 1976. At the present time, the BLM stations are located at the sites shown in Figs. 5 and 6. Similar DF stations are also operating in the Northwest Territories, Ontario, Saskatchewan, British Columbia, Quebec, and Alberta for forest-fire detection. In Figs. 5 and 6, the nominal range of each DF is shown as a circle with a radius of about 400 km, although large lightning signals can often be detected at much greater distances. Based on numerous visual observations, it is estimated that each DF station detects at least 80–90% of all cloud-to-ground flashes that occur within the nominal range. Flashes are not detected if there are unusual fluctuations in the return-

stroke field shapes, if the signal amplitudes are below the system threshold, or if the flashes lower positive charge to ground. Analyses of the shapes of fields that trigger DF systems suggest that the number of non-lightning triggers is negligible and that only 1–2% of all triggers are due to cloud discharges.

The solid lines in Figs. 5 and 6 show the communications lines that are used to connect individual DF stations to a central position-analyzing computer, where the locations of individual flashes are computed automatically. Each position analyzer accepts two, three, or four simultaneous DF inputs and computes, records, and maps the location of each cloud-to-ground flash in real time. Under most conditions, the locations are computed by triangulation using the lightning angles measured at the DF stations; however, if a strike occurs close to the baseline connecting two stations, the position may be computed using the field amplitudes as well as the angles. Two examples of lightning position maps obtained during 1979 are shown in Figs. 7 and 8.

The total overlapping area covered by the networks in the western United States and Alaska is currently about 900 million acres or about 38% of the total land area of the United States. To the best of our knowledge, these networks represent the largest and the

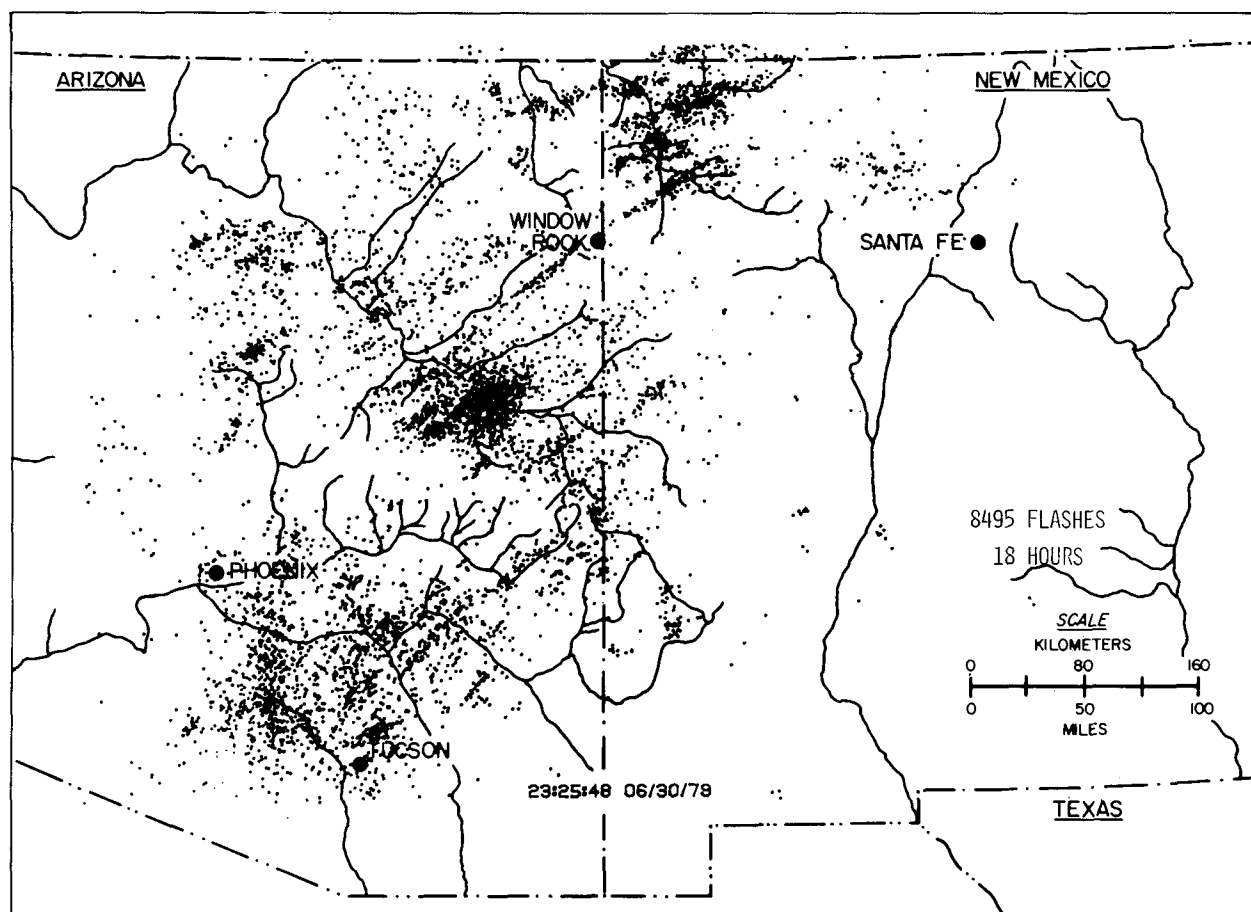


FIG. 8. A map of lightning locations recorded during an 18 h period on 30 June and 1 July 1979 (see also the caption to Fig. 7).

most accurate lightning detection systems that have been installed anywhere in the world.

#### 4. Results

The lightning DF networks have already proved to be a significant aid in wildlife management and fire weather forecasting; fire detection aircraft and sometimes even fire suppression crews are now sent directly to those areas where the networks show lightning is occurring. The costs of detection have been reduced, and the early warnings provided by the system have reduced both the size of fires when first detected and the suppression costs. From records of lightning activity on prior days, the areas of smoldering or possible holdover fires are defined and monitored if the fire danger is sufficiently high.

Weather forecasters have found the networks to be beneficial because lightning and areas of disturbed weather are identified instantly, even in regions that are out of radar range. The locations, motion, and time-development of storms can often be used to forecast hazards and to improve interpretations of the weather radar displays.

Lightning detection systems similar to those described previously are also being used in several research projects designed to measure many of the basic characteristics of lightning, the effects of cloud seeding on lightning, and the effects of lightning on electric power distribution systems (Boulanger and Maier, 1977; Maier *et al.*, 1978; Darveniza and Uman, 1979a,b). In the future, we hope further applications of such systems will help to improve lightning warnings and to reduce lightning damage throughout the world.

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