An Operational Comparison of Lightning Warning Systems

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ABSTRACT

During the spring–summer of 1979, six lightning warning devices were evaluated in a side-by-side comparison study at three test sites. Stock commercial devices were selected based upon distinct concepts of operation. The devices tested included a sferics counter, a corona point, a radioactive probe, a field mill, an azimuth/range locator and a triangulation locator. The test sites were chosen to provide varied thunderstorm conditions: 1) San Antonio, Texas (cold air advection), 2) Kennedy Space Center, Florida (localized surface heating) and 3) Langmuir Laboratory, New Mexico (orographic effects). The evaluation parameters were advance warning time, time to clear after hazard, alarm reliability, and false alarm and failure to alarm probabilities. The triangulation locator provided the best overall performance; however, all systems indicated a need for improvement in the failure to alarm rate.

1. Introduction

This study was initiated by the Interior Department's Bureau of Mines as a result of concern over the use of electrical detonators in open-pit mining operations. Over the past 20 years, reports on file at the U.S. Mine Safety and Health Administration indicate 13 instances of lightning-induced premature explosions which resulted in 10 persons injured and five fatalities. Another concern is the loss in production due to shutdown when no lightning hazard exists. Therefore, this comparative evaluation was undertaken in an effort to acquire and disseminate information on the characteristics and adequacy of lightning warning systems designed to give warning of atmospheric electrical activity.

A comparative study of lightning warning systems was done by the USAF Air Weather Service at Cape Canaveral, Florida during the period April–September 1970. No details regarding the design of the experiment or the results appear in the open literature; however, a four-page report issued by the U.S. Air Weather Service (Sensor Fact Package, 1978) indicates that five devices were evaluated in this study, and a prototype device developed by the Air Force Geophysical Laboratory best suited the USAF requirements. In another study, an unpublished theoretical analysis was done by Cianos and Pierce (1974) and a summary of that work was later published by Pierce (1977). This study was based upon the existing data base of thunderstorm and lightning statistics and discussed the general problem of lightning warning. The conclusions and recommendations reported in this study were made from theoretical projections of system performance.

Several other studies have been made on the field performance of individual lightning warning devices. These include an evaluation of a radioactive probe by Buset and Price (1975), a field mill by the USAF Air Weather Service (Pittman, 1977), an azimuth/range locator by Schneider and Mangold (1979), a sferics counter by Kohl (1980) and O'Malley (1980), and a triangulation location system by Krider *et al.* (1980).

2. Lightning warning systems

A survey of commercially available lightning warning systems indicated that there were six conceptually distinct devices available. The initial part of the study was to identify those devices which best implemented the design concept. In this section a brief description is offered of the basic concepts and general discussion of the manner in which the concept was implemented in the tested device.

a. Sferics counter

Among the simplest devices tested was a sferics counter. These are generally narrow band receivers which sense the change in the electromagnetic field due to a lightning discharge or streamer process within the thundercloud. A post detection filter is employed to integrate the sferic counts so that an

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alarm can be issued at a predetermined threshold. The premise of operation is that the higher the received rate of sferics, the more intense and/or nearer the proximity of the storm.

A survey of commercial manufacturers indicated that six design versions could be purchased. The capability of sensitivity adjustment was the deciding factor in selecting the candidate unit for test. The sferics counter tested was a 455 kHz tuned receiver with switch selectable ranges for 100, 50, 25 and 10 miles warnings. The receiver gain and alarm threshold could be adjusted from rear panel rotatable knobs. The device sensed the emitted sferic using a monopole antenna mounted 45° to a vertical mast or building.

b. *Corona point*

A discussion of the corona point principle can be found in Latham and Stromberg (1977). If a sharp point is raised to a height h above a ground plane, the corona current in the presence of an electrostatic field E and wind speed W is

$$i = ah(E - E_0)(W^2 + c^2E^2h^2)^{1/2}, \qquad (1)$$

where a and c are constants and E_0 is the threshold field to initiate corona ($\sim$1 KV m^{-1}). For small field values, $E < E_0$, the corona current is essentially constant. Under the conditions of thunderstorm activity, the wind velocity term is such that $W > cEh$ and Eq. (1) reduces to

$$i = ah(E - E_0)W. \qquad (2)$$

Thus, warning levels of corona current should allow for enhanced current due to high wind speeds.

Commercially available corona point devices are produced by one manufacturer. The candidate unit used in this test was a sphere of $\sim$20 cm in diameter with two rows of 10 cm spikes welded on the perimeter to enhance corona discharge. Upon the manufacturer's recommendation, the device was mounted atop a 20 m tower. The alarm current level in the sensing electronics used for this evaluation was 15 μA.

c. *Radioactive probe*

The principle of the radioactive probe involves measurement of the electrostatic field in the presence of ionizing particle emission. The radioactive element is connected to a conductor and the emitted α particles ionize a small volume of air about the probe which brings the potential of the conductor to that of the atmospheric gradient. The field strength is estimated by measuring the current through the conductor and using the predetermined coupling resistance of the probe to the surrounding air. A detailed description of radioactive probe devices is given by McCready (1958).

Two radioactive devices are available commercially, one using a polonium probe and the other tritium. Both devices measure the potential gradient; however, the polonium device also responds to *changes* in the field gradient. The two-parameter device was selected for this test.

d. *Field mill*

A description of field mill devices can be found in Israel (1973) and Anderson (1980). The field mill device consists of a fixed circularly disposed array of conducting surfaces. Rotating above this plate is a plate with apertures corresponding in geometry to the conducting surfaces on the fixed plate. By rotating the upper plate, the conducting elements are alternately exposed to and shielded from the electric field lines between the earth and atmosphere. The upper rotating plate is grounded so that the conducting elements become charged during the exposure cycle and are discharged during the shielding cycle through a sensing network. The resulting signal is sinusoidal with an amplitude proportional to the charge deposited on the conducting surfaces and hence to the electric field strength.

Four manufacturers currently market field mill devices. One of the devices senses the *change* in the electric field intensity. Two of the devices use a combination of field strength and field changes to detect a lightning hazard. The fourth system is a three-parameter sensor which measures field strength, field changes and ambient noise background. The fourth system was chosen for this test because it included the measurements of the remaining three but also included the noise parameter.

e. *Azimuth/range locator*

The technique of azimuth/range location is given by Ryan and Spitzer (1977). The sensor is a crossed loop direction finder with a monopole sense antenna as developed by Watson-Watt and Herd (1926). The receiver is broad-band tuned with a center frequency of 50 kHz. The crossed loops are quadrature summed to form a composite signal which is compared to a threshold level. Provided the signal exceeds the threshold value, the analog signals from each crossed loop are integrated for a period of 500 μs. The integrated signals are then divided by the square of the composite signal, in what is termed a "folded back" signal which is smaller in magnitude for larger received signals and larger in magnitude for smaller received signals. This results in a range estimate which coupled with the directional data, produces a dot on a CRT screen. The points of electrical activity resemble the polar trace of a weather radar CRT.

The device selected for this test has range coverages of 40, 100 and 200 nautical miles. The range values are calibrated assuming a peak return stroke current of 19 kA and a far-field propagation model.

f. Triangulation locator

The triangulation location system is described by Krider *et al* (1976, 1980). Crossed loop direction finders exhibit significant directional errors when the electric field has an appreciable horizontal component. To overcome this problem, a system has been developed to 1) discriminate between the intracloud and cloud-to-ground discharges, and 2) to gate the direction finder on the initial portion of the cloud-to-ground stroke which emits a predominately vertically polarized electric field, typically occurring during the first 100 m of the return stroke channel.

The system consists of two remote DF stations which transmit data to a central facility. The central site determines a point of intersection of the directional data reported by each remote site. Two sensors are located at each remote site, a crossed loop antenna and a flat plate antenna. The flat plate antenna is used as a sense element to resolve the 180° bearing ambiguity of the crossed loop. The system was designed to operate only upon negative cloud-to-ground strikes, i.e., those discharges which lower negative charge to ground.

In the system selected for this evaluation, the digital processors at each of the remote sites communicates with the central facility over a 300 bit per second telephone line link. The positional data of the lightning strike, computed at the central facility, are output to teletype giving time, northing,[1] easting,[1] number of strokes in the flash, and relative signal strength at each of the two sites. Also, the position is presented graphically on an x-y plotter.

3. Hazard definition

To simulate an open-pit mine blasting operation, electrical models of commercial detonators were fabricated. There are at least three mechanisms which exist for the detonation of electric blasting caps by electrical storms. The most obvious is a direct lightning strike. The second, and most probable, is the induction of current impulses in the cap by nearby intracloud or cloud-to-ground lightning. Third, massive electric potentials can occur through large static buildups during electrical storms. These large electric fields can build to the point of flashover, causing a spark between bridgewire and case.

A typical bridgewire detonator was modeled using a 1 Ω resistor connected to an external 300 m perimeter loop of No. 22 gage copper wire laid on the ground. Since firing lines are generally twisted pair, the open loop represents a worst case condition. Two energy levels in the 1 Ω resistor were of particular interest: the no-fire (2.5 mJ) and the all-fire (10 mJ) levels. The bridgewire to detonator case arcover simulation was a resistor-capacitor circuit connected to a linearly extended 200 m length of No. 22 gage copper wire which was grounded at both ends. A 2 kV level was established as the breakdown threshold voltage.

In addition to the above criteria a hazardous condition was determined to exist when 1) a radar echo of "heavy" (VIP[2] level 3, 26–30 dB) or more had entered within an 18 km radius of the site, 2) thunder was heard, or 3) lightning was observed. The hazard was defined to no longer exist when 1) radar echoes of "heavy" (VIP level 3) or more had left an 18 km radius of the site, 2) 30 min had transpired since the last premature detonation, or 3) the operator was able to visually determine that no hazardous condition existed within the area of interest.

4. Results

The six lightning warning systems were initially deployed at the Southwest Research Institute in San Antonio, during the period 1 April–15 May 1979. Thunderstorm activity is primarily due to cold air advection in this region during springtime.

The performance parameters of the lightning warning systems were assessed in terms of:

1) MEAN WARNING TIME—the lapsed time between first warning and storm arrival at 18 km radius. Positive time implies time before reaching 18 km, and negative time indicates time after the storm reached 18 km radius. Zero time means alarm first occurred when the storm was at 18 km radius.

2) PERCENT INCIDENCE OF FALSE ALARM—the percentage of total alarms for which an alarm was given when no storm event was observable.

3) PERCENT INCIDENCE OF FAILURE TO ALARM—the percentage of total storm events within 18 km range for which no alarm was given.

4) PERCENT VALID ALARMS—percent of alarm events for which storm activity was within 18 km range.

5) MEAN TIME TO CLEAR—time after storm events passed beyond 18 km range to clear the alarm condition.

The system performance data for the conditions of frontal type storm activity is given in Table 1. Four devices evidenced reasonably good performance: radioactive probe, field mill, sferics counter and triangulation locator. One of the poorer perfor-

[1] Northward or eastward progress.

[2] Video Integral Processor.

TABLE 1. Cold air advection storms.

Device	Average warning (min)	False alarm rate	Failure to alarm rate	Alarm reliability	Time to clear (min)
Sferics counter	35	0%	9%	100%	44
Corona point	−20	27%	55%	73%	−19
Radioactive	33	9%	9%	91%	15
Field mill	40	18%	9%	82%	22
Azimuth/range locator	121	73%	0%	27%	109
Triangulation locator	21	0%	9%	100%	5

mances was indicated by the corona point device. This device indicated warning on the average of 20 min after the hazard existed. The device also indicated a clear condition 19 min prior to the return of a "safe" condition. Had the alarm threshold been decreased to 10 μA, the already high false alarm rate of 27% would have significantly increased. In the case of the azimuth/range locator, the ranging algorithm produced 73% false alarms which reduces its effectiveness for use as a warning device in terms of the criteria for this study.

In the second phase of this study, the systems were deployed at Kennedy Space Center, Florida during the period 1 June–15 July 1979. Thunderstorm activity was initiated by frontal passages during the early part of the experiment and was due to localized surface heating throughout the remainder of the period.

System performance data are given in Table 2. The corona point device continued to exhibit erratic behavior throughout this period of the experiment due to its susceptibility to extraneous noise. The azimuth/range locator exhibited reasonably good performance data; however, these data are significantly biased by the method of data acquisition. Specifically, the data from this device were manually acquired. The site operator initiated data acquisition based upon warning received from the USAF Air Weather service at Cape Canaveral. At the time the operator reached the site, the device was generally in an alarm state. Thus, the data more nearly reflect the period of time over which the site was manned. The sferics counter evidenced a high degree of noise susceptibility and continually required recalibration of the alarm threshold due to the significant variability in ambient noise levels between storm systems. The radioactive probe and the field mill showed an increased rate in failure to alarm as compared with earlier results. Best overall performance was given by the triangulation location system.

In the third phase of this study, the systems were deployed at Langmuir Laboratory near Socorro, New Mexico during the period 20 July–20 August 1979. Thunderstorm activity in this region was strongly influenced by orographic effects.

The system performance data are given in Table 3. The data for the corona point device were acquired during the first half of the experiment period since the sensor was struck by lightning and rendered inoperative. Concurrent with this lightning strike, a transient on the ac power line damaged the internal power supply of the field mill device. Thus, data from this device were acquired only during the initial portion of the experiment. The sferics counter and azimuth/range locator performance data are similar to that observed at the previous two sites. The radioactive probe and the field mill evidenced a considerably higher failure to alarm rate than had been observed in earlier experiments. Again, the best performance was indicated by the triangulation location system.

5. Summary and conclusions

During the frontal storm period in Texas, 10 thunderstorm events were monitored over a period of 36 h. In the second phase of the test conducted in Florida, 22 thunderstorm events were monitored over a cumulative period of 43 h. During the test period in New Mexico, 16 thunderstorm events were observed over a cumulative time of observation of 37 h.

The best overall performance of the various systems was indicated by the triangulation locator system. A concern is the failure to alarm rate which ranged between 6 and 9%. Among the systems tested,

TABLE 2. Local surface heating storms.

Device	Average warning (min)	False alarm rate	Failure to alarm rate	Alarm reliability	Time to clear (min)
Sferics counter	32	0%	55%	100%	−18
Corona point	−15	0%	80%	100%	22
Radioactive	28	0%	10%	100%	−8
Field mill	27	0%	15%	100%	9
Azimuth/range locator	39	0%	5%	100%	17
Triangulation locator	21	0%	6%	100%	−4

TABLE 3. Orographically initiated storms.

Device	Average warning (min)	False alarm rate	Failure to alarm rate	Alarm reliability	Time to clear (min)
Sferics counter	−4	0%	64%	100%	23
Corona point	−20	0%	80%	100%	40
Radioactive	21	0%	27%	100%	33
Field mill	50	0%	20%	100%	67
Azimuth/range locator	101	82%	0%	18%	117
Triangulation locator	20	0%	9%	100%	0

this system represents the highest purchase cost and the greatest expense to operate due to the leased telephone lines.

Systems which provided reasonably good performance were the radioactive probe and the field mill devices. However, these devices evidenced a significantly higher failure to alarm rate than did the triangulation locator system. The radioactive probe and the field mill devices are moderately priced systems. The field mill requires a high degree of maintenance to keep the conducting plates free of insects and corrosion. The primary failure in the radioactive probe was the inability of the splash shield to maintain a high-impedance coupling with the space charge in the vicinity of the probe. Thus, the device frequently indicated a low field intensity when in fact a high field intensity existed.

The azimuth/range locator consistently indicated the correct movement of storm centers of electrical activity in a gross sense; however, the erroneous estimation of range and the azimuthal error due to horizontally polarized electric field components, produced intolerable false alarm rates. The utility of this device appears to be in the area of lightning avoidance rather than lightning warning.

The sferics counter appears to be useful in the sense that it will indicate when lightning exists within the detection range of the sensor. It is pointed out that this same detection capability has been achieved by using inexpensive transistor radios. The evidence gathered in this study indicates that due to the significant variability in ambient noise level from storm to storm this device requires a continual recalibration which vitiates its usefulness.

Due to the sensitivity of the measurement parameter in the corona point device, the high-gain electronics at the input sensor results in a high degree of susceptibility to extraneous noise. An additional problem results from the fact that the amount of corona current is a function of the height of the point. The height requirement provides a vulnerability to lightning strikes.

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