Site Errors and Detection Efficiency in a Magnetic Direction-Finder Network for Locating Lightning Strikes to Ground

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ABSTRACT

We have tested a network of magnetic direction-finders (DFs) that locate ground strikes in Oklahoma and surrounding states in order to determine detection efficiency for the network and systematic errors in azimuth (i.e., site errors) for each of four DF sites. Independent data on lightning strike locations were obtained with a television (TV) camera on a mobile laboratory and an all-azimuth TV system at the National Severe Storms Laboratory (NSSL). In two tests using these data, we found a location detection efficiency of about 70% for storms at about 70 and 300 km from the center of the network. Systematic errors in azimuth were determined by comparing locations from the lightning strike locating system with strikes located from the mobile laboratory system; also, for a single DF at NSSL, strike azimuths from the DF were compared with azimuths from the all-azimuth TV system for storms near NSSL. Furthermore, we developed a technique for using redundant DF data to determine systematic errors in azimuth measurements for each DF site. Azimuthal errors found by this analytic technique were consistent with errors found by using the two sets of direct measurements. The azimuthal errors are themselves a function of azimuth, with peak amplitudes ranging from less than 5° for three DFs located at favorable sites to about 11° for one DF located at an unfavorable site.

1. Introduction

Systems for automatically locating lightning strikes to ground have been developed in the last decade and are now deployed over most of the United States and Canada and in several other countries. One such system utilizes a network of magnetic direction-finders (DFs) to determine azimuths to a ground strike and to locate the strike point by triangulation (Krider et al., 1980). With two or more DFs, this system locates lightning strikes out to a range of a few hundred kilometers from the center of the network. A limitation of this system is that errors in each DF can cause the indicated azimuth of flashes to be different from the true azimuth. These errors have several sources, such as nonvertical lightning channels, local site anomalies, background noise, fluctuations in the DF's electronics, a misaligned antenna, or reflection of the electromagnetic signal from the ionosphere (Adcock and Clark, 1947; Horner, 1954; and Krider et al., 1976). Reflection from the ionosphere is unimportant because the DF uses only the ground wave to determine azimuth. Furthermore, Uman et al. (1980) have shown that errors from nonvertical channels are less than 1° beyond a range of 10–20 km, and Krider et al. (1976) report that the total random error (from nonvertical channels, background noise, and fluctuations in the DF's electronics) is usually 1–2°. Thus, if the antenna and gains are adjusted correctly, the source of the largest azimuthal errors will be local site anomalies, caused by nearby structures, such as buildings, power lines, and cables, and by variations in the surrounding terrain. These site errors have been reported to be as large as 30° (Horner, 1954). Site errors are usually expected to be constant, however, so they can easily be corrected once they have been determined; the locating system has the capability of making these corrections during real time operation.

We have used two techniques to measure site errors and system detection efficiency, and we have devised a simple method for objectively determining the site errors from redundant DF data. This method has been evaluated by comparing its results with the site-error measurements.

2. Instrumentation

a. Lightning strike locating system

The National Severe Storms Laboratory (NSSL) uses a magnetic direction-finding system, such as described by Krider et al., (1980), to locate lightning strikes to ground in Oklahoma and surrounding states (see Fig. 1). This system, manufactured by Lightning Location and Protection, Inc., consists of four DF stations sep-

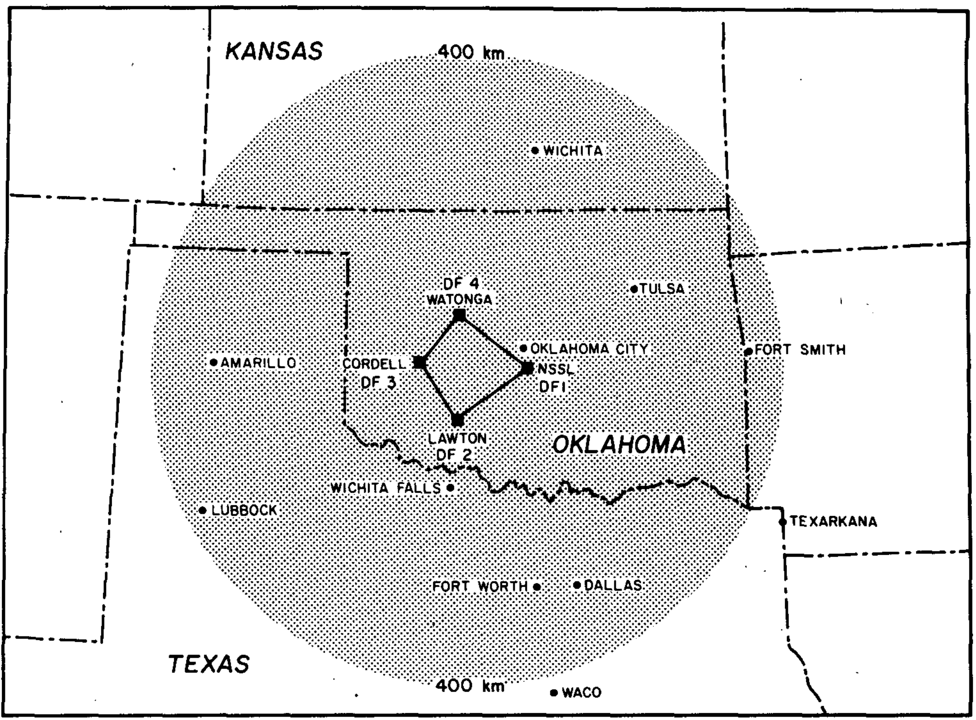

FIG. 1. NSSL lightning ground strike locating system. The squares denote DF locations. Shading indicates the nominal area of coverage, with a range of 400 km. Distances between pairs of DFs are 80–140 km.

arated 80–140 km and a central position analyzer (PA) at NSSL that computes strike locations and operates the system. Each DF tests signals sensed by a crossed-loop antenna in order to identify return stroke waveforms. The DF then determines the azimuth to a lightning strike by using the amplitude from each loop at the peak in the waveform (the signal in each loop is proportional to the cosine of the angle between the plane of the loop and the direction of arrival of the field from a vertical lightning channel). A flat plate antenna senses electric field changes to determine flash polarity and so remove the 180° directional ambiguity from the crossed-loop measurement of azimuth. While the DF processes each stroke in a flash, the azimuth, amplitude, and polarity of only the first stroke are sent to the PA, along with the total number of strokes detected for the entire flash. The DFs include options to detect ground flashes that lower either polarity of charge and to process concurrent flashes that have return strokes interlaced in time.

There are several parameters that must be set for each DF and some of these are particularly pertinent for this study. All DFs in our network for example, are set to high gain, which means that a DF's nominal detection efficiency for ground flashes decreases to 50% at a range of approximately 400 km. Furthermore, the amplitude threshold for acceptance of signals was set at the minimum level (110 mV) recommended by the manufacturer at all DFs except DF2, where it was set at 115 mV because of a slightly higher level of background noise. At DF1 and DF2, there was also a relatively high level of 60 Hz noise generated in the buildings on which the electric field antennas were mounted. This 60 Hz noise was reduced to acceptable levels by utilizing a third plate below the normal sensing plate and ground plane in order to null out the noise (about half of the nulling capacity was used). The utilization of the third plate reduced the sensitivity of these two DFs somewhat.

Accurate alignment of the crossed-loop antennas with true north is essential to keeping systematic errors to a minimum. For our network, a gyroscopic transit was used to place benchmarks within 0.15° of true north from each crossed-loop antenna and to align the antenna with the benchmark. Periodic checks of alignment from the benchmarks indicated almost no shifting in time, and alignment was maintained to well within 0.5° of true north for all DFs during the collection of data for this study.

Communication between the PA and each DF in the NSSL system is over a separate leased point-to-point telephone line. In this configuration, the time of a flash is assigned by the PA as the time at which data arrives at the PA (measured by the PA's clock) minus DF processing time (measured by the DF's clock). For each ground flash detected by a DF, the PA records the DF number, time of occurrence, azimuth to the strike from the DF, peak magnetic field amplitude (in arbitrary units), and flash polarity. When the time of flashes for two or more DFs is within a preselected window (20 ms for the NSSL system), they are considered to be from the same flash, and a location is computed. In addition to the data from the DFs, the system then records the location of the strike and the identifying numbers of the DFs detecting the flash. According to the manufacturer, a PA with point-to-point communication can process over 10 000 flashes per hour. The flash rates recorded by our PA have always been much less than this and were 1100 per hour or less during the storms in which ground truth data were collected for this study.

Data are routinely recorded on nine-track digital magnetic tape, on digital cartridge tape, and on a printed listing. During selected times, strike locations also are plotted on maps. The recorded locations, which were computed in real time, were not used in this study. Only the individual DF azimuths were compared with the ground truth data.

b. Ground truth systems

The ground truth data used in this study were acquired with two systems: a color television (TV) camera mounted on the University of Mississippi/NSSL mobile laboratory (Arnold and Rust, 1979; Goodman et al., 1984) and an all-azimuth TV system at NSSL. The TV camera on the mobile laboratory uses a color Newvicon tube 1.7 cm in diameter and has a 10–120 mm zoom lens. During the periods analyzed here, the camera had a field of view of about 42° horizontally and 31° vertically. Time is set to within 0.2 ms of a timing signal from WWV and is encoded in the video signal; the resulting timing resolution is about 17 ms, the time required to generate one TV video field. The TV signal with the encoded time is recorded on a standard VHS video cassette.

The all-azimuth TV system is mounted on a 17 m tower at NSSL. As shown in Fig. 2, the TV camera faces downward 19 cm above a conical mirror. The mirror is a polished stainless steel cone 17.8 cm in diameter and 7.6 cm tall, with the cone sloping 37.5° from the horizontal. The TV camera uses a black and white Newvicon tube 1.7 cm in diameter and has an 8.5 mm lens. The field of view of the all-azimuth system is from approximately 5° below to 15° above the horizon of the mirror. Azimuth angles are marked at the base of the mirror on a ring that is aligned with true north from nearby surveyed landmarks and marked in 15° increments. A wiper is mounted on the mirror to clean away rain. Time encoding and recording of the TV video signal are the same as for the mobile camera system. Under good visibility, the system will easily record cloud-to-ground flashes 20 km away. For documenting ground strikes, this all-azimuth system has an advantage over standard all-sky systems using parabolic mirrors or fish-eye lenses in that channels near the horizon have a larger image, while higher elevations are ignored.

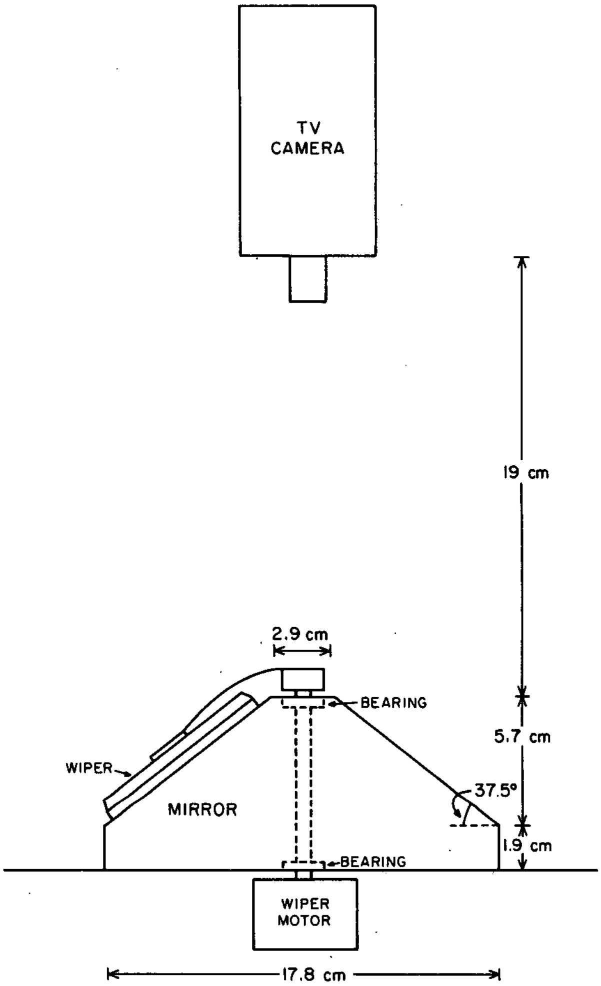

FIG. 2. Diagram of the all-azimuth TV system.

c. Time synchronization

To identify coincident ground flashes in the magnetic DF and ground truth systems, it is necessary to determine the relative timing of the different clocks as accurately as possible, since peak lightning ground flash rates are as high as a few per second in many storm systems. A WWV signal was used as the common time standard for each system. The ground truth systems were electronically synchronized to within 0.2 ms of the WWV signal; the PA of the magnetic DF system was set manually to within 1 s. To determine the time offset between the PA and the all-azimuth TV system, a pulse at the beginning of each minute from the PA's clock was recorded along with the NSSL time that was encoded on the all-azimuth TV data. The relative time between these two systems could then be found to $\ll 1$ ms, which is significantly less than the 17-ms resolution provided by the encoded time on a TV video field. Discrepancies in time between the NSSL and the mobile laboratory data were usually small because both clocks were initially synchronized to WWV and they used identical oven-encased crystals. Furthermore, the relative time between them could be determined to $\ll 1$ ms by comparing the time of lightning electric field changes and extremely low frequency waveforms that could be identified unambiguously in both data sets as being from the same flash. Thus, the 17-ms timing resolution of the TV video system dominated the uncertainty in relative time between the PA and the TV systems.

Although the relative time could be determined to within about 17 ms, the time window used to define coincidence between the ground truth and DF data was considerably longer because of two uncertainties associated with the time assigned to flashes by the PA. The first cause of uncertainty arises because the DFs might miss the first one or two strokes in a flash. If this happens, then the time that is assigned to the flash will be late, typically by about 40 ms if one stroke is missed (Uman, 1969). A second source of delayed flash times, one which has been offered in informal discussions as a possibility, is delays during data transmission. As mentioned previously, the time of a flash detected by a DF in our network is defined to be the time that the PA receives a data transmission minus the DF processing time. Leased telephone lines were used for data transmission, and these are reported to have delays that are occasionally tens of milliseconds (A. E. Pifer, personal communication, 1984). This has no effect on data from DF1, which transmits over a direct line. When a transmission from one of the other DFs is delayed, the usual effect, if there is one, is to reduce the detection efficiency of the network by delaying the data from one DF beyond the coincidence window for data from another DF; in this case, there will be no effect on timing for flashes. However, if two or more DFs have a similar transmission delay, it could cause flashes to be assigned a later time. An examination of data from a few days suggests that this second source for delayed times of flashes can probably be ignored.

3. Analysis and results

a. Mobile laboratory TV data

On 3 June 1983, we acquired data on lightning ground strikes with the mobile laboratory TV system for a storm near Paris, Texas, approximately 300 km southeast of the center of the DF network. To locate a flash with these data, it was necessary to determine first the location of the mobile laboratory from the time that the mobile laboratory passed landmarks or stopped at known locations, as indicated in its position log. The direction to the flash from the mobile laboratory could be determined by measuring the direction in the field of view of the camera and then adding this angle to the azimuth toward which the camera was pointed (indicated by tape recorded comments). The range of the flash from the mobile laboratory was determined by estimating the height of cloud base from the nearest atmospheric sounding and dividing this height by the tangent of the vertical angle subtended by the lightning channel between ground and cloud base. We estimate that uncertainties in the inferred range and in the pointing azimuth of the TV camera caused the absolute error in locations derived from this technique to be within 5 km, which corresponds to a maximum azimuthal error of ±1.3° at the closest DF site, 220 km away.

For each lightning strike located from the mobile laboratory TV camera, the uncorrected data from the magnetic DF system were searched for a coincident flash, with allowances being made for possible timing and azimuthal errors. Flashes from the system were accepted if the DF azimuths were within ±20° of the azimuthal extent of the storm from each of the DFs and if the timing was within −20 to +100 ms of the ground truth time. The strike locations were clustered so that larger azimuthal limits did not increase the number of strikes in coincidence with ground truth data. The 20-ms limit before the ground truth time allowed for the maximum possible uncertainty in relative time between the TV and the PA, and the 100-ms limit after the ground truth time allowed for the possibility that the strike locating system missed the first or second return strokes. Of the 168 flashes detected by the mobile laboratory in the storm to the southeast, the 65 best flashes were chosen to calculate strike locations for comparison with the DF network. Errors in the azimuths from each DF were then calculated by taking the difference between the azimuth of the ground truth strike location and the azimuth determined by the DF. The errors that were found for each DF are summarized in Table 1.

TABLE 1. Azimuthal errors at DF stations in NSSL's lightning strike locating system, determined by comparison with 65 flashes located from mobile laboratory data. Positive errors indicate clockwise displacement of the ground truth location relative to the azimuth measured by the DF.

DF number	Azimuth (deg from DF)	Number of flashes	Mean error (deg)	Standard deviation (deg)
1	135–140	41	8.56	1.08
1	140–145	7	8.06	1.41
1	145–150	14	10.58	1.49
2	110–115	18	1.43	1.15
2	115–120	13	3.45	1.77
3	115–120	10	−0.60	0.76
3	120–125	15	−0.54	0.75
3	125–130	9	1.41	1.23
4	130–135	24	−1.83	0.71
4	135–140	22	−1.03	1.24

b. All-azimuth TV data

The all-azimuth TV system was used to determine the azimuths of cloud-to-ground flashes that were near NSSL for comparison with azimuths measured by DF1. Because of the difficulty in determining the distance to a flash from just the all-azimuth data, azimuths were measured only relative to the TV camera, and comparisons were not made with azimuths from other DFs. The flash azimuths were determined by first playing back a video cassette tape recorded during daylight, so that an azimuth indicator marked in 5° increments could be aligned on the TV screen with the azimuth markings around the all-azimuth mirror. Thus, the azimuth could be determined for flashes at night, when the azimuth markings around the mirror were not illuminated. Because of errors in aligning and reading the scale, we estimate that measurements of azimuth with the all-azimuth TV system have an uncertainty of ±3°. The all-azimuth mirror was located about 50 m from DF1, so parallax errors between the mirror and the DF were significant only for very close flashes. Such flashes usually saturate the DF circuitry, so that the DF cannot determine azimuth. Thus, parallax errors can be ignored.

All-azimuth TV data were analyzed for six storms. Out of 314 flashes recorded by the all-azimuth TV system, 219 were detected by DF1. Of these, approximately 25% saturated the DF1 circuitry and were labeled by the system as "over-ranges". Azimuths from the all-azimuth TV system and from DF1 were compared for the remaining 163 flashes. The difference is plotted as a function of azimuth in Fig. 3. In most cases, the spread in the value of the difference at a particular azimuth can be explained by the random errors that are inherent in the all-azimuth TV measurements. In a few cases, such as those involving two flashes near 245°, there may also have been a false identification of two nearly coincident ground flashes in the DF1 and all-azimuth TV data. Since azimuths from only a single DF were used, it is possible that the local flash was not accepted by the DF and that a more distant flash occurring at about the same time was mistaken for it. (On a number of occasions, we have observed lightning strikes occurring within 100 ms of each other at different locations.) Note that the site error near 140° from the all-azimuth TV data (Fig. 3) is somewhat smaller than the error from mobile laboratory data (Table 1). However, in most cases, the differences are within 4°, as one would expect from the estimated 1.3° error in mobile laboratory data and 3° error in all-azimuth data.

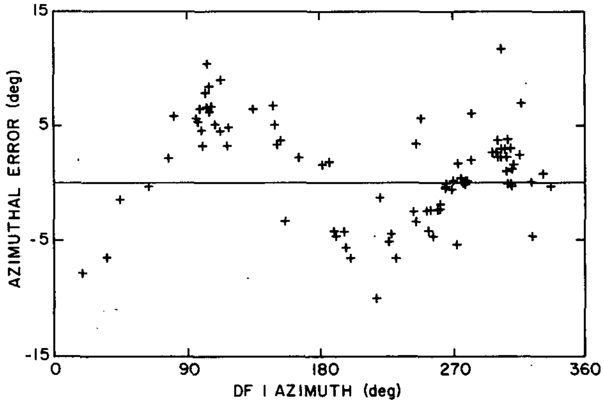

FIG. 3. Azimuthal error versus azimuth from DF1. The error is the difference between the all-azimuth TV and DF1 azimuths; positive values indicate clockwise displacement of the ground truth relative to the DF azimuth.

c. Detection efficiency

The same ground truth locations that were derived from the mobile laboratory and all-azimuth TV systems can also be used to determine detection efficiencies for our magnetic DF system. For the mobile laboratory data, the limits on azimuth and time for identifying coincident lightning strikes in the DF data are the same as for the analysis of site errors. For the all-azimuth TV data, instead of analyzing only DF1 as for the determination of site errors, the analysis of detection efficiency was broadened to include all DFs. Since flashes in the all-azimuth record are relatively close to NSSL, flashes detected by any DF except DF1 within the 120-ms interval about the ground truth time were assumed coincident if the azimuth of the strike was within ±20° of the azimuth of NSSL from that DF. For DF1, only the time criterion was used to determine coincidence with the all-azimuth TV data.

The resulting detection efficiencies are given in Table 2. Since DF1 was so close to the all-azimuth TV data, its detection efficiency may have been reduced, because at close ranges either local intracloud processes or electrostatic and induction components of the electromagnetic field change can contaminate return stroke waveforms and cause them to fail tests designed for the radiation field regime. As discussed previously, DF1 and DF2 were adjusted to be somewhat less sensitive than the other two DFs because of higher noise levels at those sites.

d. Error analysis using redundant DF data

To estimate site errors in azimuthal sectors for which we have no direct measurements, we developed a procedure that derived these errors by optimizing, in a simple sense, the self-consistency in the redundant DF data for a number of flashes. The analysis uses only azimuths and ignores location information that can be derived from the magnetic field amplitudes. The first step in this procedure was implemented by Maier in MacGorman et al. (1984).

The analysis begins by selecting cloud-to-ground flashes that have been recorded by at least three DFs. One of these DFs, termed the "target" DF, is assumed

TABLE 2. Detection efficiencies for 314 flashes recorded by the all-azimuth TV and for 168 flashes recorded by the mobile laboratory. Since two DFs must detect a flash to locate it, the detection efficiency labeled "Any 2 DFs" corresponds to the location detection efficiency for the DF network. In the all-azimuth TV data, the number and percent detected include 63 flashes that saturated DF1's electronics.

	All-azimuth TV data			Mobile laboratory data		
Sites detecting strikes	Range (km)	Number detected	Percent detected	Range (km)	Number detected	Percent detected
Any 2 DFs	—	220	70	—	113	67
Any 3 DFs	—	156	50	—	82	49
All 4 DFs	—	87	28	—	62	37
DF1	≤25	219	70	240	128	76
DF2	100	150	48	260	74	44
DF3	140	165	53	350	79	47
DF4	100	194	62	340	104	62

to have an error in its azimuth that will be found by comparison with the ground strike locations calculated from two other DFs. The location calculated from this pair of DFs is then assumed to be the "true" location, and its azimuth from the target DF is calculated. The error is simply the difference between the target azimuth and the true azimuth. Azimuth is divided into 10° bins, and the error is then tabulated in the 10° bin containing the target azimuth. For example, if the target DF recorded the ground strike between ≥0° and <10°, the information would be tabulated in bin 1 of the target DF. For each ground flash, errors are calculated for all possible combinations of target DF and pairs of true DFs.

Since errors in the true location create larger errors in the true azimuth as the location nears the target DF, flashes within 50 km of the target DF are rejected. Ground flashes at distances over 300 km are also rejected because triangulated locations are very sensitive to small azimuthal errors at long ranges.

When all ground flashes have been processed, the error data are analyzed to determine a site error correction curve for each DF that can be used in the next iteration of the procedure. For this analysis, three quantities are calculated for every 10° bin of each target DF and for every combination of true DFs: 1) the average difference between the target azimuth and the true azimuth, i.e., the mean error; 2) the standard deviation in the error; and 3) the number of flashes in the bin. Thus, with a total of 4 DFs in the network, each DF has three sets of curves, one set for each pair of true DFs. The standard deviation curve associated with each of the three mean error curves typically has large values in some sectors and low values in others. To construct a first estimate of the site errors for a particular target DF, the mean errors for a given azimuthal sector are assumed to be the mean errors from the true DF pair with the lowest standard deviation for that sector. If two different pairs have nearly the same standard deviation for an azimuthal sector of the target DF, the mean errors are averaged.

In practice, only a fraction of the resulting site error curve for each DF is entered as a correction for the next iteration. A fraction is used because azimuths of both the true and target DFs are being corrected in one iteration. Thus, the corrections that are derived from a particular true pair are biased by their own site errors, and these biases will change the correction for a target DF. The fraction that we used for the first iteration was 0.5.

In the next iteration, when these corrections have been added to the measured lightning strike azimuths and the strike locations have been recomputed, the procedure is repeated to derive a new set of error curves for the uncorrected, residual errors. A fraction of these residual errors is then added to the corrections from the first iteration to produce new site error corrections, and the process is repeated again. In our studies, the fraction that was added varied from about 0.5 for initial iterations to 0.7 for the last one or two.

After a few iterations, we found that the next-order residual errors derived from various true pairs generally appeared random from one pair to another, with an amplitude of about 2°. Standard deviations at corresponding azimuths were approximately equal, so no one true pair was more likely to be correct and there was no justification for continuing the iterative procedure. The final site error curves, derived by analyzing redundant DF data for 58 000 flashes, are plotted for each DF site in Fig. 4.

e. *Test of results from redundant-data analysis*

To test the above procedure, we compared the site error correction curves in Fig. 4 with the direct measurements from the mobile laboratory and the all-azimuth TV systems. Table 3 shows the mean and standard deviation of the differences in azimuth between the ground truth strike locations from the mobile laboratory and the locations from the DF network after DF azimuth measurements were corrected by applying the error curves in Fig. 4. Note that the differences are all within the 1.3° error in the ground truth measurements and the 2° residual error in the correction procedure.

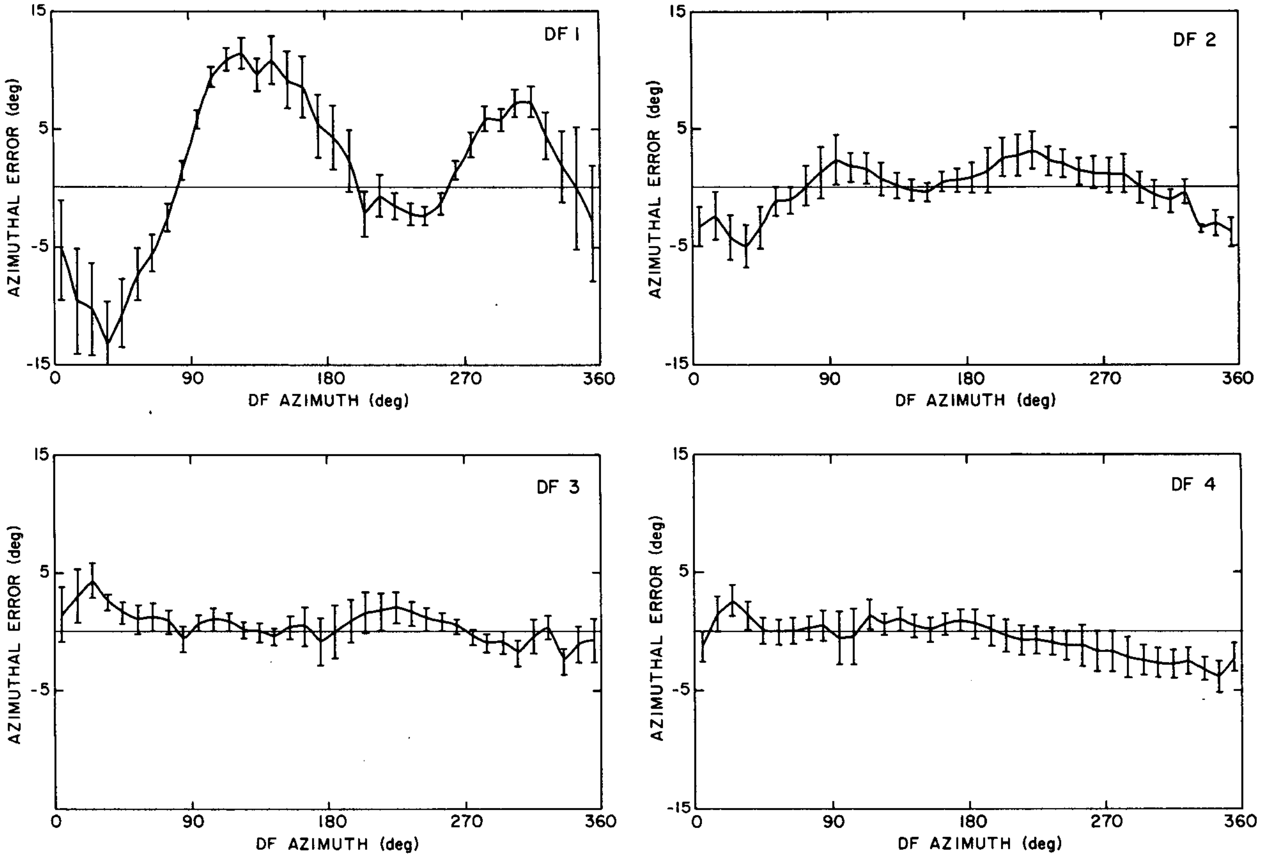

FIG. 4. Corrections indicated by the analysis of redundant DF data for each DF. Error bars are ±1 standard deviation. Positive corrections indicate clockwise displacement relative to the uncorrected DF azimuths.

For each of the DFs, there seems to be an indication of a pattern in the differences between the mobile laboratory azimuths and corrected DF azimuths. Throughout the whole ground truth dataset, the average difference for each DF was within 2°, but for individual flashes it could be as large as 4°. The differences do not appear to be random, but suggest that the applied corrections have errors that vary systematically with azimuth by more than 2° within some 10° bins. Since the applied corrections were interpolated linearly between the bin centers, this implies that the true correction is of higher order than piece-wise linear between 10° bin centers. These higher order errors will, of course, add to the standard deviations derived for the bin. To be able to detect and correct for higher order errors, the bin size in our iterative procedure would need to be reduced.

TABLE 3. Comparison of ground truth azimuths from the mobile laboratory with DF azimuths that are corrected for errors found in the analysis of redundant data. A positive mean difference indicates clockwise displacement of the ground truth azimuth relative to the corrected DF azimuth.

Site	Mean difference in azimuth (deg)	Standard deviation (deg)	Range of corrections to DF data (deg)	Number of flashes
DF1	−1.23	1.34	9.4–11.4	61
DF2	0.93	1.75	1.6–1.7	31
DF3	−0.22	1.25	0.1–0.8	33
DF4	−1.82	1.07	0.4–1.0	46

Azimuths from the all-azimuth TV system were used as a second test of our correction procedure for DF1. A comparison of the corrections from the all-azimuth system (Fig. 3) and the corrections derived from redundant DF data (Fig. 4) shows that they are similar. The differences between the two error curves vary from 0° to 6°, but were usually less than 3°. The major differences between the curves are that the all-azimuth TV data yielded a larger negative peak in the errors around 230° and yielded smaller errors in most other directions.

4. Discussion

We have described three techniques for determining site errors in a network of magnetic DFs, two by direct measurements and one by analyzing redundant DF data. Agreement between the errors determined by these different techniques is about what we would expect from the estimated errors in the measurements (±3° for all-azimuth data and ±1.3° for mobile laboratory data) and in the analysis technique (±2° for redundant DF data). The standard deviation in the errors is similar to that found by Krider et al. (1976) in a comparison of TV data with data from a single DF.

The largest site error corrections are for DF1, a site that has its antenna on a large building and is surrounded by various types of cables. These structures are known to cause significant errors in DF systems (Horner, 1954). The smaller corrections for the other DFs are consistent with the absence of large structures, long cables, and significant variations in terrain near the sites.

The major advantage of our procedure for deriving site errors from redundant DF data is its simplicity. The calculations are straightforward and easy to implement, and the corrections converge after just a few iterations, usually about five. However, the simplicity of the procedure is also the source of its limitations. Errors that change rapidly across a 10° bin may be distorted, and a linear fit through the center of the bins may not be the best fit to the data. This problem can be surmounted by using smaller bins, although more data would be needed to preserve the same accuracy. However, even at azimuths where the mean error is changing slowly and significant higher order errors appear unlikely, the differences between error curves for different true DF pairs indicates that the potential accuracy of the technique is limited to approximately ±2°. If better accuracy is needed, then perhaps a more sophisticated technique, such as that described by Maier et al. (1984), should be implemented. We recommend, however, that results from any analysis of redundant DF data be verified independently with ground truth data for at least some azimuths.

The same ground truth data used in the site error analysis were also used to measure the location detection efficiency of the magnetic DF system. In both of the ground truth data sets, about 70% of the flashes could be located by our network of four high-gain DFs. Detection efficiency is a function of the range and azimuth to each of the DFs, however, and neither of these tests was made at an optimum combination of range and azimuth. The detection efficiency for a single DF should be highest near azimuths of 45°, 135°, 225°, and 315°, because the absolute value of signals from the two loops of the antenna are added in the test for amplitude thresholds. The optimum range from a DF is far enough away that the DF is in the radiation field regime for a flash (⩾20 km), but close enough that most return stroke waveforms are above the amplitude thresholds. In this study, mobile laboratory data were at a favorable azimuth, but were relatively distant from the DFs. The all-azimuth TV data were at favorable azimuths from two DFs and were only 100–150 km from three DFs, but were too close to DF1.

While detection efficiency can be either better or worse in other locations covered by our DF network, we expect 70% to be a typical value for locations within 200–300 km of the center of the network. A somewhat better detection efficiency might be obtained if DF1 and DF2 were moved to sites with less background noise so that these DF's could be made more sensitive. DF1 has already been moved for this reason, and we will be evaluating the resulting detection efficiency as data become available.

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