A Three-Station Lightning Detection System

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BOULDER, COLO.
JULY 1972
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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
BOULDER, COLORADO 80302
NOAA TECHNICAL REPORT ERL 239-APCL 23

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A THREE-STATION LIGHTNING DETECTION SYSTEM

Lothar H. Ruhnke

A three-station network is described which senses magnetic and electric fields of lightning. Directional and distance information derived from the data are used to redundantly determine lightning position. This redundancy is used to correct consistent propagation errors. A comparison is made of the relative accuracy of VLF direction finders with a newer method to determine distance and location of lightning by the ratio of magnetic-to-electric field as observed at 400 Hz. It was found that VLF direction finders can determine lightning positions with only one-half the accuracy of the method that uses the ratio of magnetic-to-electric field.

1. INTRODUCTION

Lightning positioning systems have been in use for a long time; however, data on their accuracy are difficult to obtain because of the complexity of the physical problem of wave propagation as well as technological problems that must be overcome to verify indicated lightning positions. In addition, the location of a lightning as such is difficult to define, because of its complex space and time structure. Several methods are used to determine the position. Most commonly used are direction finders that use loop antennas to sense the magnetic field radiated from a lightning. The position can be found by having two or more receiving stations and by using triangulation methods. For thunderstorms less than 100 km away, Ruhnke (1971) has recently proposed to use the ratio of magnetic field to electric field as an indicator for distance. The amplitude
of the electric field from a lightning can also be used as an indicator for distance, if we assume that the dipole moment does not change among individual strokes. The latter two methods, in conjunction with direction finders, lead to positioning systems that need only one observation station.

This study tested several of these methods and compared their relative accuracy. The inherent difficulty of such a study is that no data on the actual position of lightning exists; therefore, conclusions about the accuracy can only be derived by comparisons of systems, each having its individual error source. The assumption is then made that no error exists if most or all of the systems indicate lightning at the same location.

For this, three stations spaced in a triangle about 10 km on a side were equipped with crossed loop antennas to sense the magnitude of the magnetic field and the direction to the strokes. These stations also had horizontal wire antennas to sense the magnitude of the electric field. The position of a number of lightning was then calculated from directional data using three baselines, from data of the ratios of the magnetic to electric field (H/E) at three stations, and from the magnitude of the electric field at three stations. For each lightning a set of nine positions is obtained and can be used in an error analysis. A tenth set of data was evaluated from an operational two-station direction finder using crossed loop antennas but having different electronics and different observation frequencies. This data set was included to assess the importance of errors that are introduced by electronic equipment rather than propagation and lightning characteristics.
2. INSTRUMENTATION

At each of the three observation stations identical equipment was used. For the magnetic pickup, crossed loop antennas were used as previously described (Ruhnke, 1971). This reference also describes the horizontal wire antenna to sense the electric field, as well as filters, amplifiers, and pulse-forming networks. The equipment differs from that previously described only by different output signals. Figure 1 is a block diagram that facilitates the understanding of the detailed diagram in figure 2. Voltages from the crossed loop antennas are filtered by a 400-Hz filter and amplified by factors of 10, 100, or 1000 by adjustable amplifiers. Then the signal is processed by precision full-wave rectifiers and peak voltage detectors. The outputs are labeled HX for the

![Figure 1: Block diagram of receiving station.](image)

Figure 1. Block diagram of receiving station.
east-west, and HY for the north-south component of the magnetic field. The voltages of both crossed loop antennas are also multiplied with each other after additional amplification, and the peak voltage of the product is available at the output as signal HXY. This pulse is necessary to sense whether both loop antennas have the same or opposite polarity signals, because the sharp filter and the full-wave rectifier loses the information on polarity. The rectified loop antenna signals are added in a summing amplifier and trigger a one-shot multivibrator. This trigger signal T programs the peak voltage modules. For 1 sec the output of the peak voltage circuit displays the peak voltage.

The signal from the long wire antenna is similarly filtered, amplified, and rectified. The output of its peak voltage circuit is labeled E. Four channel strip chart recorders recorded the output voltages at all three sites at 1 mm/sec. For this study, all 12 values of each lightning were manually read from the chart paper and transferred to punch cards for computer analysis. The time to 1 sec and the date of each lightning was also kept on punch cards. This method of analysis is nonpractical for fast read-out of information on lightning location.

The design of the instrumentation took into account the need for rapid information analysis. The output signals can be scanned by analog-to-digital converters, and real-time computation by moderately sized digital computers can give information on lightning position as well as probable accuracy of the data. On an experimental basis a scanner and digital voltmeter, along with the programmable desk calculator (Model HP 9100B of Hewlett Packard), calculated lightning position, printed it with
Figure 2. Detailed diagram of receiver instrumentation.
time on a digital printer, and plotted lightning position on a map using an x-y plotter. Computational time was 7 sec including printing and plotting.

Within 1 sec of the start of a lightning signal, the instrument puts out voltages proportional to the peak amplitudes. The maximum voltage before instrument saturation is 10 V. Only positive voltages are sensed. Transients, zero drift, and nonlinear effects do not produce errors of more than 10 mV. An exception was station 3, where 60 Hz noise was picked up by the instrument and 160 mV appeared at the output of the north-south component of the magnetic field. This error voltage was eliminated by mounting the instrument in a different location within the shelter. However, the lightning data discussed in this report, contain this error that somewhat decreased the reliability of station 3.

3. THEORETICAL CONSIDERATIONS

3.1 Calculation of Lightning Position

Assume a rectangular coordinate system centered at station 1 with the x-axis toward the east and the y-axis toward the north. Assume further that the coordinates of station 2 are \(X(2), Y(2)\), and for station 3, \(X(3)\) and \(Y(3)\). The position of lightning number \(M\) can be expressed by using the direction to the lightning from two stations together with the station coordinates. The direction to a lightning at station 1 can be expressed by the tangent \(XM(1,M)\) of the angle from the x-axis:

\[
XM (1,M) = \frac{HY1}{HX1} .
\]
The polarity of this tangent is decided by the absence or presence of a pulse at HXY1, namely, whether the product at HX1 and HY1 is positive. If a positive pulse appears at HXY1, the tangent is negative. In FORTRAN notations this is expressed by

\[ \text{IF (HXY1. GT.0.) XM (1,M) = -XM (1,M).} \quad (2) \]

Similar notations are used for the direction to lightning M from stations 2 and 3.

The position of a lightning using station 1 and 2 as baseline is expressed by the coordinates X1(M) and Y1(M):

\[ \begin{align*}
    X1(M) &= (Y(2) - XM(2,M) \times X(2))/(XM(1,M) - XM (2,M)), \quad (3) \\
    Y1(M) &= X1(M) \times XM(1,M). \quad (4)
\end{align*} \]

Similar equations apply for the positions calculated from the other two baselines. Directional data will therefore produce a set of three positions for every lightning. The area of the triangle formed by these three positions can be used to estimate the accuracy, with the assumption that the locating error is zero if the triangle area is zero. This assumption is reasonable, yet not totally convincing. The area F of this triangle can be calculated from

\[ \begin{align*}
    F &= (X1 (M) \times Y2 (M) - X2 (M) \times Y1 (M) + X1 (M) \times Y3 (M) - X3 (M) \times Y1 (m) + X2 (M) \times Y3(M) - X3 (M) \times Y2 (M))/2. \quad (5)
\end{align*} \]

This area F not only can be used to judge the reliability of a particular position calculation but also several statistics can be performed on this number which will assess this system's accuracy relative to other systems.
In particular, the average area $\overline{F}$ will give an indication of random errors and give a means of finding consistent errors in the system, as will be shown later.

An additional set of three lightning positions can be obtained from the ratio of the magnetic-to-electric field ($H/E$) at each of the three stations together with directional information (Ruhnke, 1971). With an observation frequency of 400 Hz, as used in our equipment, $H/E$ increases approximately linearly with distance $D$ between 3 km and 80 km,

$$D1(M) = T1 \times \sqrt{HX1 \cdot HX1 + HY1 \cdot HY1} / E1.$$

(6)

The factor $T1$ depends on antenna length, amplifier gains, and loop antenna size and is best determined empirically so that the average area $\overline{F}$, by using data from three stations, is a minimum. One obtains the $x$ and $y$ coordinates at station 1 by

$$X1(M) = HX1 \times T1 / E1,$$

(7)

$$Y1(M) = X1(M) \times XM(1, M).$$

(8)

The polarity of the $x$-coordinate must be determined independently, since our direction finders have an inherent $180^\circ$ ambiguity. In principle, there is no difficulty in eliminating this ambiguity by comparing the polarity of the electric signal with that of the magnetic signal. For our study, data from the other two stations were used to eliminate the $180^\circ$ ambiguity.
3.2 Error Analysis

Several error sources in lightning positioning systems can be identified. Two basic philosophies can be used to investigate and eliminate such error sources. First, one can study the physics of lightning and the physics of its propagation and make measurements pertinent to deviations from idealized or standardized conditions. Such measurements can then be used to correct the lightning data. Second, one can look statistically at the data. Because we have measurements from which the lightning position can be determined in more than one way, one can use this overdetermination to find statistical correction terms.

A lightning is an electrical discharge in the atmosphere and has a physical length that often is comparable with the distance to the observation point. The approximation of a lightning by the position of a point on the ground already introduces errors because the measuring method uses possibly a different approximation scheme than the method to verify the result. For instance, the sensing of the magnetic fields produced by a branched lightning with horizontal components inside the thundercloud will yield an average direction to a lightning. This direction is different than the direction obtained for the same lightning by optical observation of the visible part beneath the cloud. Another direction may be obtained by detecting the location where the lightning made contact with the ground. This error, or uncertainty in position,
usually will be less than the horizontal extent of the lightning. A positioning error of 1 km from the source must be expected; therefore, any system judged to be accurate in positioning lightning to within 1 km must be considered excellent.

Limiting the error analysis to lightning that are approximated as point sources and sensed by their electric and magnetic field, one must now differentiate between (1) distortion produced by the propagation path, namely, such distortions that apply to all lightning at one locality like finite ground conductivity, secondary radiator, and inhomogeneities in the propagation path, and (2) between height above ground and orientation in space of individual elementary lightning dipoles. While the first category is fixed in time and space such that compensations for it can be calculated or empirically applied if the cause for such distortions can be assessed, the second category is random from one lightning to the next and can only be reduced by using less affected measurement parameters.

Additional errors are introduced by the instrumentation. A difference in gain of the loop antennas will cause directional error, as will inaccuracies in positioning the loop antennas. The coordinates of the observation station must also be accurate. Noise in the electronics, nonlinearities, and drifts in the amplifiers will introduce errors. However, these are accessible to investigation, and periodic checks and calibration can minimize instrumental errors of a well-designed system.

Other systems errors are those inherent in triangulation systems: the length of the baseline and the direction to a lightning in relation to baseline direction. In particular for lightning near baseline direc-
tion, the positioning error becomes very large if small angular errors are made. Assume the origin of the coordinate system to be at midpoint of a 10-km baseline, which extends along the x-axis. Figure 3 shows the distribution of maximum positioning error \( E_1 \) in kilometers for a directional error of 1° at each station.

For distances larger than the baseline, this error \( E_1 \) increases approximately with the square of the distance and it approaches high values when the lightning is near baseline direction. The plot in figure

![Figure 3. Magnitude of positioning error for direction finders with 10 km baseline and 1° azimuthal error at each station.](image-url)
3 is based on the following formula, where $D_1$ and $D_2$ are the distances to the lightning from stations 1 and 2, $a$ is the baseline length, and $y$ the lightning coordinate perpendicular to baseline direction

$$E_1 = \frac{\pi}{180} \frac{D_1 \cdot D_2}{y \cdot a} (D_1 + D_2) .$$

(9)

A similar analysis is possible if the position of a lightning is calculated by using distances to lightning at two stations. Of more importance to this study, however, is the position error, if the location is determined by direction and distance from one station only. Assuming that errors caused by uncertainties in direction are equal in magnitude to errors caused by uncertainties in distance, the positioning error $E_2$ is obtained similar to (9) for directional uncertainties of $1^\circ$:

$$E_2 = \frac{\pi}{180} \cdot \sqrt{2} \cdot D .$$

(10)

$E_2$ is always smaller than $E_1$, which encourages the development of single-station systems for locating lightning. How well the assumption -- that uncertainties in determining distance from one station are equal in magnitude to uncertainties in determining direction to lightning -- holds is subject to experiments.

The next error considered is random noise from either external sources or from within the electronics. At station 3 the receiver electronics was accidentally mounted in a rack near a strong power supply that induced noise into the $y$-component of the magnetic field. Since such error signals can appear to some extent at each location, it is
advantageous to consider compensating for this error. This is possible, to some degree, if the noise source is steady and if noise on the average increases the output signal. The lightning signal $S$ after the input filters is quasi-sinusoidal and has the form

$$S = S_0 \sin (\omega t) , \quad (11)$$

with $S_0$ being the amplitude. Similarly the noise signal $N$ has the form

$$N = N_0 \sin (\omega t + \varnothing) , \quad (12)$$

where $\varnothing$ is an arbitrary phase angle and $N_0$ the amplitude of the noise signal. The output of the lightning detector is proportional to the amplitude of the sum of noise and lightning signal. Depending on the phase angle of the noise signal, the output signal either increases or decreases. On the average, the amplitude of the output signal $S'$ is approximately given by

$$S'^2 = N_0^2 + S_0^2 . \quad (13)$$

This formula can correct the output signal. The amplitude of the noise signal can easily be determined by manually triggering the peak voltage sensing circuit.

When more than two stations are used as direction finders, it is possible to detect from a sufficient number of lightning whether the direction finders are properly aligned. Suppose that a lightning from direction $\alpha$ is received by one station that is $\beta$ degree's misaligned. The indicated angle $\gamma$ relates to $\alpha$ and $\beta$ by
\[
\tan \gamma = \frac{\tan \alpha + \tan \beta}{1 - \tan \alpha \cdot \tan \beta}
\]

Such a misalignment will affect the area of the triangle computed from the positions of the lightning determined from directions from three stations. The average of such an area computed from many lightning incidents will also be affected. One can assume with good reason that this average area is a minimum for a 0° misalignment error. A calculation of the average area as a function of \( \beta \) will readily indicate if misalignment of any of the antennas is evident. In the experiment performed for this study, no such misalignment could be detected. This was as we expected because during installation the antennas were very carefully aligned.

There are several error sources that lead to consistent directional changes and which are difficult to eliminate after the system is installed. These sources are associated with inhomogeneities of the propagation path; with permeable materials of nearby manmade structures, like steel frame buildings or railroad tracks that at very low frequencies influence the magnetic field of a lightning signal; and with secondary radiators near the receiving site. To this category of errors also belong differences of antenna sensitivity between both crossed loop antennas as well as differences in the gain in the electronics of the two channels that process the crossed loop antenna signals. The effect of all these error sources is that certain magnetic field components are distorted. That means that the magnetic field component in direction \( \alpha \) of a lightning from an arbitrary direction is increased by a factor \( M \).
M and \( \alpha \) are two numbers that characterize a single disturbance. For this case the x component \( H_X \) as well as the y-component \( H_Y \) of the magnetic field is influenced. The disturbed values \( H_X' \) and \( H_Y' \) can be expressed by

\[
H_X' = H_X \cdot A + H_Y \cdot B, \quad (15)
\]
\[
H_Y' = H_X \cdot B + H_Y \cdot C. \quad (16)
\]

The constants \( A, B, \) and \( C \) depend on the two constants \( M \) and \( \alpha \):

\[
A = \sin^2 \alpha + M \cos^2 \alpha,
\]
\[
B = (M-1) \sin \alpha \cos \alpha, \quad (17)
\]
\[
C = M \sin^2 \alpha + \cos^2 \alpha.
\]

When \( M \) and \( \alpha \) are known, (15) and (16) can be inverted to obtain the undistorted magnetic field components \( H_x \) and \( H_y \),

\[
H_X = H_X' \cdot A' + H_Y' \cdot B', \quad (18)
\]
\[
H_Y = H_X' \cdot B' + H_Y' \cdot C'. \quad (19)
\]

For the constants \( A', B', \) and \( C' \), one finds

\[
A' = \sin^2 \alpha + \frac{1}{M} \cos^2 \alpha,
\]
\[
B' = \left(\frac{1}{M} - 1\right) \sin \alpha \cos \alpha, \quad (20)
\]
\[
C' = \frac{1}{M} \sin^2 \alpha + \cos^2 \alpha.
\]

In general, distortions do not occur in only one direction but are distributed as a function of \( \alpha \). If \( M(\alpha) \) is known, then the three parameters in (17) can be determined.
\[ A = \frac{1}{\pi} \int_{0}^{2\pi} M(\alpha) \cos^2 \alpha \, d\alpha , \quad (17) \]
\[ B = \frac{1}{\pi} \int_{0}^{2\pi} M(\alpha) \sin \alpha \cos \alpha \, d\alpha , \quad (22) \]
\[ C = \frac{1}{\pi} \int_{0}^{2\pi} M(\alpha) \sin^2 \alpha \, d\alpha . \quad (23) \]

The constants for the inverted equations (18) and (19) are

\[ A' = \frac{C}{AC - B^2} , \quad (24) \]
\[ B' = \frac{-B}{AC - B^2} , \quad (25) \]
\[ C' = \frac{A}{AC - B^2} . \quad (26) \]

From a practical point of view, it is impossible to determine \( M(\alpha) \) as a continuous function. \( A, B, \) and \( C \) are best determined by experiment. As an error function, again the average area \( \bar{F} \) of all triangles can be used as determined by directions to a number of lightnings from three stations. A computer program can search for the optimum values of \( A, B, \) and \( C \) which give the smallest average area \( \bar{F} \).

With this last procedure any other possibilities of compensating for consistent errors in lightning direction finder systems seems to end. Still remaining are random errors which depend in magnitude on the type of measured parameters as well as on the variability of lightning characteristics. The experiment was aimed to derive a measure of this random error for the particular measurement system described in this report.
4. EXPERIMENTS

During the summer of 1971, the equipment described in this report was installed at three sites at Kennedy Space Center, Florida. Station 1 was on top of a four-story building with the approximate coordinates 28° 31' 26" N and 80° 38' 52" W. This station was used as the origin of a rectangular coordinate system in which the positive x-axis and y-axis point east and north, respectively. In this system, station 2 had the coordinates \( X(2) = -3.80 \) km and \( Y(2) = 11.32 \) km. Station 3 was located at \( X(3) = 7.00 \) km and \( Y(3) = 1.04 \) km. Several thunderstorms were recorded between June 25 and July 8, 1971, of which a storm period on July 2, 1971, between 15:30 LST and 18:00 LST was analyzed with particular care. During this time each lightning incident that produced a signal at all three stations was used for the data base. About 20 percent of all lightning signals were either too weak to trigger all three stations or occurred within less than 1 sec of each other, so that the two independent lightnings could not be differentiated. The data base consists of 268 lightning incidents and is tabulated in table A1 (see appendix). Time was recorded to within 1 sec in column 1. The data columns 2 to 13 are marked \( HX, HXY, HY, \) and \( E \) to denote the components of the magnetic field, the polarity signal, and the magnitude of the electric field from all three stations. Columns 14 to 17 are magnetic field data from the KSC operational lightning locating system with its two stations located very close to our stations 1 and 2. \( X_1, X_2, Y_1, Y_2 \) denotes the x and y components of the magnetic field. The last column is a counter to help to identify individual lightning strokes. The values in data column 2 to 13 are output voltages in
The resolution of the chart paper recordings from which the data were taken is ± 50 mV; which means that the last digit already includes a considerable uncertainty. The sensitivity of the electric field channel at station 1 was decreased at 16:28 LST by a factor of 10. All data of E1 from lightning 124 to 268 are therefore in units of 200 mV. Full scale and voltages higher than full scale are denoted by 500.

Columns 14 to 17 are readings taken from a digital printer and are in units of 10 mV.

On July 2, 1971, the Cape Kennedy Space Center area in Florida had typical thunderstorm conditions for this time of the year. On the synoptic chart for that day a long cold front extended from Texas, through Georgia, and North Carolina up to Labrador moving slowly towards Florida. The Showalter Stability Index from Cape Kennedy radiosonde data at 2:00 p.m. LST was zero, indicating increasing chances of thunderstorms. Winds were variable at about 10 mph from the SW. After a clear morning, cumulus clouds began developing at 10:00 LST in the west. Over the water and east of station 3, the sky stayed clear until after the measuring period. During the measuring period, a large area west of station 3 was covered with clouds. Intermittent heavy rain was observed at stations 1 and 2 with lightning and thunder occurring about three times per minute. Figure 4 is a graph of the number of lightnings per minute during the observation period averaged over 5-min intervals.

Figures 5 to 17 show lightning positions on a 100 km by 100 km map. Station 1 is in the center. All three stations are connected by a solid line to show the observational network. In figure 5, directional data
No. of Lightning per minute

Figure 4. Lightning frequency during observation period on July 2, 1971.

from stations 1 and 2 were used to calculate lightning positions. No corrections were applied to the data, and all positions outside the 100 km by 100 km were as shown on the borderline. Two thunderstorm areas can be recognized. The cluster of lightning 10 km west of station 2 occurred mainly between 1530 and 1645 LST. The storm which was 30 km southwest of station 1 occurred between 1645 and 1800 LST. In figure 6 the same lightning positions are shown from directional data of stations 2 and 3. The first storm now appears in a wide scatter up to 20 km west and north of station 2, while the second storm now is fairly concentrated at 18 km southwest of station 2. For the earlier storm, 10 percent of the lightnings were so close to the baseline direction of stations 2 and 3 that they appeared in the wrong quadrant. Finally in figure 7 directional data from sites 1 and 3 are used for calculating
Figure 5. Lightning positions from uncorrected directional data from stations 1 and 2.
Figure 6. Lightning positions from uncorrected directional data from stations 2 and 3.
Figure 7. Lightning positions from uncorrected directional data from stations 1 and 3.
Figure 8. Lightning positions from operational VLF direction finders at stations 1 and 2.
Figure 9. Lightning positions from uncorrected data of H and E at station 1.
Figure 10. Lightning positions from uncorrected data of $H$ and $E$ at station 2.
Figure 11. Lightning positions from uncorrected data of H and E at station 3.
Figure 12. Lightning positions from corrected directional data from stations 1 and 2.
Figure 13. Lightning positions from corrected directional data from stations 2 and 3.
Figure 14. Lightning positions from corrected directional data from stations 1 and 3.
Figure 15. Lightning positions from corrected data of H and E at station 1.
Figure 16. Lightning positions from corrected data of H and E at station 2.
Figure 17. Lightning positions from corrected data of H and E at station 3.
lightning positions. The first storm seems centered over station 2 while the second storm seems centered over station 1. Most lightnings of this storm are close to baseline directions which results in a distortion such that the storm appears elongated along the baseline. These three figures show that the measurement system contains systematic errors, but before discussing data treatments, the other positioning data will be shown. In figure 8, lightning positions are plotted from the present operational lightning locating system. The direction finders were located at stations 1 and 2. The center of the first storm is 5 km southwest of station 2, but a wide scatter is apparent. The second storm stretches from station 1 for 15 km on westward. Thirty percent of the data appear either at unlikely locations (remember that during the observation period blue sky prevailed east of station 3), or unreasonably far away, as evidenced by the magnitude of the magnetic and electric field. Nevertheless, this plot represents fairly well the centers of thunderstorm activities.

In figure 9, lightning positions are plotted from data collected by station 1 only. Directions were derived from the ratio of the magnetic components as before, but the distance was calculated from the ratio of the magnetic field to electrostatic field. The inherent 180° ambiguity in the directional information was eliminated by determining the proper quadrant from directional data at site 2. The first storm appears centered over station 2, while the second storm seems to be clustered about 14 km southwest of station 1. The data scatters
much less than the triangulation data, and no unreasonably far lightning is indicated. A similar plot is obtained from direction and distance data at station 2 (fig. 10). Most of the lightning of the first storm saturated the electric field channel, indicating the closeness of the storm. The position of the second storm appears 15 km west of station 1 and agrees reasonably with directional and distance data from station 1. Figure 11 finally depicts positions when using distance and direction data from station 3. In this plot a somewhat larger scatter is evident due to the 60 Hz noise pickup at this station. The first storm is centered again near station 2 and the second storm is indicated 15 km southwest of station 1.

From the data in figures 5 to 11 it is evident that lightning positions from single-station data are more consistent with each other than triangulation data. But before a final judgment can be made, it is appropriate that consistent errors be removed from the data and that an average error number also be derived for each data system.

By using directional data, we can plot a triangle with area $F$. The average area $\bar{F}$ over all lightning data was 36.4 km². Part of this value is due to random errors and cannot be eliminated, but part of it can be due to consistent errors such as antenna misalignment or secondary radiators. In a first test, (14) was applied to see if all three stations had properly aligned antennas. By calculating $\bar{F}$ as a function of $\beta$ at all three stations, we found that misalignment errors were less than 1°. Next the constants $A$, $B$, and $C$ of (17) were determined by using a computer search program to find the lowest average area $\bar{F}$. We found that station 1
had the largest distortion, probably because the antennas were mounted on top of a large steel-frame building. For this station the distortion parameters were \( A = 1.11, B = 0.19, \) and \( C = 1.31, \) which is equivalent to an increase of 40 percent of the magnetic field component at an azimuthal angle of 30° from true north. At station 2 only a 15 percent error in gain of the north-south component could be detected. This could be caused by poor adjustment of recorder amplifiers, or differences in the gain of the loop antenna circuits. The distortion components at station 2 were \( A = 1, B = 0, \) and \( C = 0.87. \) At station 3 no distortion could be detected.

After applying distortion corrections, the average area \( \bar{F} \) over all lightning was 18.2 km\(^2\), which is a considerable improvement. From this area we can estimate that the positioning error is about 6 km. This positioning error is equivalent to approximately 3° directional error at each station. When we consider that data leading to this estimate came from one storm that was overhead of one of the stations and a second storm that was only 15 km away, the experimentally found directional errors were expected.

Positioning data from ratios of the magnetic and electric field can also be used to calculate the average error area \( \bar{F} \). The value using uncorrected magnetic field data is 9.5 km\(^2\). Applying distortion correction changed this number to 4.8 km\(^2\). This also is a significant improvement. The positioning error is about 3 km for this system. Figures 12 to 17 show again the same lightning positions as in figures 5 to 11 but with distortion correction applied. It is evident that improvements have been made and that data from single stations are
inherently more consistent with each other than directional data from two-station networks.

The third system that gives positioning data is based on the assumption that the electrostatic field of a lightning decreases with the third power of the distance. Again an average area $F$ can be calculated assuming a constant dipole moment for all lightning. The area $F$ so obtained was $13.9 \text{ km}^2$. That is larger than the error area obtained from data on the ratio of magnetic-to-electric fields but smaller than the error area obtained from triangulation data.

5. CONCLUSIONS

It has been demonstrated that lightning position can be sensed by automatic equipment. A three-station network senses at 400 Hz the north and east component of the magnetic field and the electrostatic field. This three-station arrangement that uses three methods of evaluation gives redundant data on lightning positions.

The first method uses only directional data from which triangulation lightning positions are derived. This method proved the least accurate when compared with the other two methods. Apparently random errors caused by horizontal component of lightning signals combined with finite ground conductivities limit the accuracy of this method, so that on the average the indicated lightning position is within 6 km of the real lightning.

The second method uses directional and distance data from one station. Distance is determined from the ratio of the magnetic to
electric field. This method is less affected by distortions produced by inhomogeneities in the ground and by secondary radiators and also less affected by random error sources. The accuracy of determining lightning position is on the average 3 km.

The third method uses distance information derived from the magnitude of the electrostatic field produced by lightning. Because the electrostatic field decreases with the third power of the distance, distance to a stroke can be estimated well from the field amplitude if the electric dipole moment of lightnings have only a modest variation. The data indicate that lightning position can be determined within 5 km on the average with this method. This agrees well with earlier observations of determining distance to lightning strokes from electrostatic field strength measurements (Ruhnke, 1962).

5. ACKNOWLEDGMENTS

This work was cosponsored by the National Aeronautics and Space Administration under contract number NASA-CC-59753.

6. REFERENCES


Ruhnke, L.H. (1962), Distance to lightning strokes as determined from electrostatic field strength measurements, J. Appl. Meteorol. 1, No. 4, 544-547.
APPENDIX

Lightning Data at Kennedy Space Center During July 1971
(Raw Data)

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