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A SEARCH FOR RESIDUAL MAGNETISM ALONG A TORNADO PATH

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16. Abstract

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SUMMARY

A search for residual magnetism was made along the damage path of a strong tornado that passed through a residential section of Hazlehurst, Mississippi, on January 23, 1969. The search was made about 3 weeks after the storm. Over 3000 gauss-meter readings were taken on nailheads in 24 frame buildings at various points on both sides of the damage path, but no evidence of residual magnetism attributable to the tornado was found. However, measurements made near ground wires connected to the electric-meter boxes on two buildings indicated that transient currents of about 135 and 300 amperes had occurred in the wires. This finding suggests that residual-magnetism measurements on nails may be useful for detecting possible magnetic fields from ball lightning, damaging lightning strokes, or other sporadic electrical phenomena, since no prior instrumentation is required.

A statistical analysis of the data from seven of the buildings showed that an axial dc electric current, if existent in the tornado, did not exceed 3900 amperes at touchdown near Fayette, Mississippi, and 6100 amperes during its most intense phase at Hazlehurst, Mississippi. These upper-bound values do not support the hydromagnetic vortex hypothesis, which requires 10^6 to 10^7 amperes and was suggested by Costen (Trans. Amer. Geophys. Union, vol. 49, Dec. 1968 and NASA TN D-5964) as possibly relevant to tornadoes. The data are inconclusive concerning the suggestion by Silberg (J. Atmos. Sci., vol. 23, Mar. 1966) that strong alternating electric currents may exist in tornadoes.

INTRODUCTION

Early in the morning on January 23, 1969, an intense tornado touched down near Fayette, Mississippi, and cut a path of devastation 0.4 to 0.8 km wide and approximately 190 km long in an ENE direction. (See ref. 1.) This tornado passed through a residential section in the southern part of Hazlehurst, Mississippi, where it destroyed or damaged many houses and other buildings along the path. Many of these buildings were light frame structures having many exposed nails by which the siding was attached. The accessibility of thousands of such nails along the tornado path made this path ideal for a magnetic survey in search of possible residual magnetism caused by the tornado.

A search for residual magnetism near Hazlehurst and Fayette, Mississippi, was carried out by the authors from February 14 to 20, 1969. Over 3000 gauss-meter measurements on nailheads were made for 24 buildings at various points of the path, including the segment of most intense devastation in Hazlehurst and the original touchdown point near Fayette.

The motivation for this residual-magnetism search was the notion, which has existed for a long time, that tornadoes may form conductors of electricity between the earth and storm clouds. (See ref. 2.) The joule heating from such an electric current could be the power source for a tornado, as explained in references 2 and 3. If an axial dc electric current does exist in tornadoes, the magnetic field due to the current, if sufficiently strong, would magnetize ferrous objects along the path. The purpose of the search, therefore, was to detect, if possible, such residual magnetism and to calculate therefrom the electric current in the tornado.

Residual magnetism has been used to determine the electric current in lightning conductors. (See ref. 4, pp. 58 to 59.) In these experiments, "magnetic links" (consisting of strips of cobalt steel encased in a small tube) were attached to the lightning conductor and were measured for residual magnetism after the passage of a storm. The present experiment which utilizes the nails of a building in place of magnetic links requires no prior on-site instrumentation at all. Residual-magnetism measurements have also been used for scientific investigation of claims about unidentified flying objects. (See ref. 5, pp. 38 to 39.)

Acknowledgment is due Kenneth V. Wilson of the U.S. Department of the Interior, Geological Survey, Jackson, Mississippi, for providing an accurate survey for the declination of Fountain Chapel Church (building 24) from magnetic north.

SYMBOLS AND NOTATION

Symbols:

A	surface area of integration, meters^2
$\vec{B}$	magnetic field, teslas or gauss
$\bar{\vec{B}}$	average magnetic field within nails of a building, gauss

Bn, Bs, Be, Bw magnetic field emergent from a nailhead on north, south, east, and west sides of a building, respectively, gauss

$\vec{B}_o$ geomagnetic field, gauss

$B_{o,h}$ horizontal component of geomagnetic field at location of measurement, gauss

$B_{o,z}$ vertical component of geomagnetic field at location of measurement, gauss

B_t amplitude of magnetic transient at a building due to passage of tornado, teslas or gauss

$\vec{D}$ electric excitation, C/m^2

I axial dc electric current in tornado, amperes

$\vec{J}$ electric-current density, A/m^2

k_n, k_s, k_e, k_w number of gauss-meter measurements on north, south, east, and west sides of a building, respectively

L,R vertical lines of nails (see fig. 5)

$\hat{n}$ unit normal to surface area A

r radial polar coordinate, meters

$S_{Bn}, S_{Bs}, S_{Be}, S_{Bw}$ standard deviation for gauss-meter measurements on north, south, east, and west sides of a building, respectively, gauss (see eq. (5))

$S_{\overline{Bn}}, S_{\overline{Bs}}, S_{\overline{Be}}, S_{\overline{Bw}}$ standard deviation of average gauss-meter measurements on north, south, east, and west sides of a building, respectively (see eq. (6))

$S_{\overline{\theta}}$ standard deviation of average angle $\overline{\theta}$, degrees or radians (see eq. (7) and fig. 2)

t time, seconds

w tornado damage path width, meters

x,y Cartesian coordinates alined with walls of building, meters (fig. 2)

Δ perpendicular distance from a building to tornado damage path center line, meters

$\bar{\theta}$ included angle between average magnetic field $\bar{\vec{B}}$ in nails of a building and y-axis of building, degrees (see eq. (4) and fig. 2)

μ_o permeability of vacuum, H/m

ρ electric-charge density, C/m^3

φ declination angle of $B_{o,h}$ (magnetic north) with respect to y-axis of a building, degrees (fig. 2)

Subscripts:

x,y Cartesian coordinates alined with walls of a building (fig. 2)

Mathematical notation:

$\rightarrow$ vector

$-$ average value

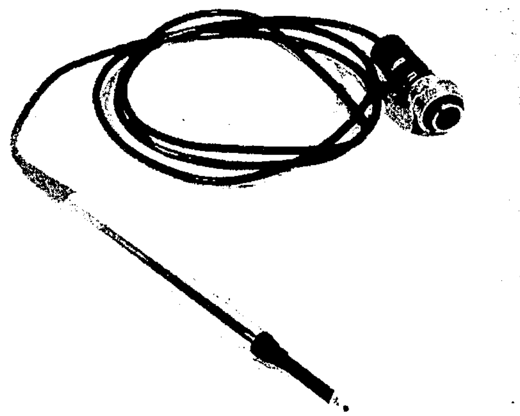
$\hat{}$ unit vector

Magnitude of vector quantity is indicated by omission of arrow.

MEASUREMENT OF RESIDUAL MAGNETISM

The residual-magnetism measurements determine the average magnetic-field orientation within the nails of a building along the tornado path. If this orientation should vary significantly from magnetic north, it might be concluded that the building evidenced residual magnetism from some prior magnetic event (such as the tornado).

The instrument used for these measurements was a Hall effect gauss meter with a ceramic encapsulated transverse probe. (See fig. 1.) The instrument is battery operated and portable. The probe stem is flexible so that the magnetic sensor (with a sensing element size of 4.3 by 2.0 by 0.25 mm) may be positioned flat against exposed nailheads without disturbing the nails. The quantity actually measured at each nail is the axial component of the magnetic field $\vec{B}$ emergent from the nailhead. Since the normal component of $\vec{B}$ is continuous at the nail-air interface, this measured value is proportional to the axial component of $\vec{B}$ within the nail.



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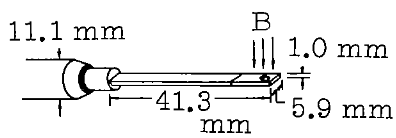

Figure 1.- Flexible ceramic encapsulated transverse probe with accuracy of ±0.5 percent used to measure magnetic field emergent from nailheads. Sensing-element size is 4.3 mm by 2.0 mm by 0.25 mm.

A schematic top view of a building with many exposed siding nails is shown in figure 2. The building is not necessarily alined in the north-south direction, although the "north" wall, "east" wall, and so forth, will be referred to in a relative sense. The emergent field from all the nailheads on the north side of the building can be measured, and its average $\overline{Bn}$ can be determined. The average field at the nailheads on the south wall of the building $\overline{Bs}$ can also be determined from measurements. The nails in the north wall are opposite in direction to the nails in the south wall; hence, the average measurements $\overline{Bn}$ and $\overline{Bs}$ are of opposite sense. These two sets of average measurements may be combined in a single average given by

$$\overline{B_y} = \frac{\overline{Bn} - \overline{Bs}}{2} \tag{1}$$

which is proportional to the average magnetic-field component within the nails in the y-direction of figure 2.

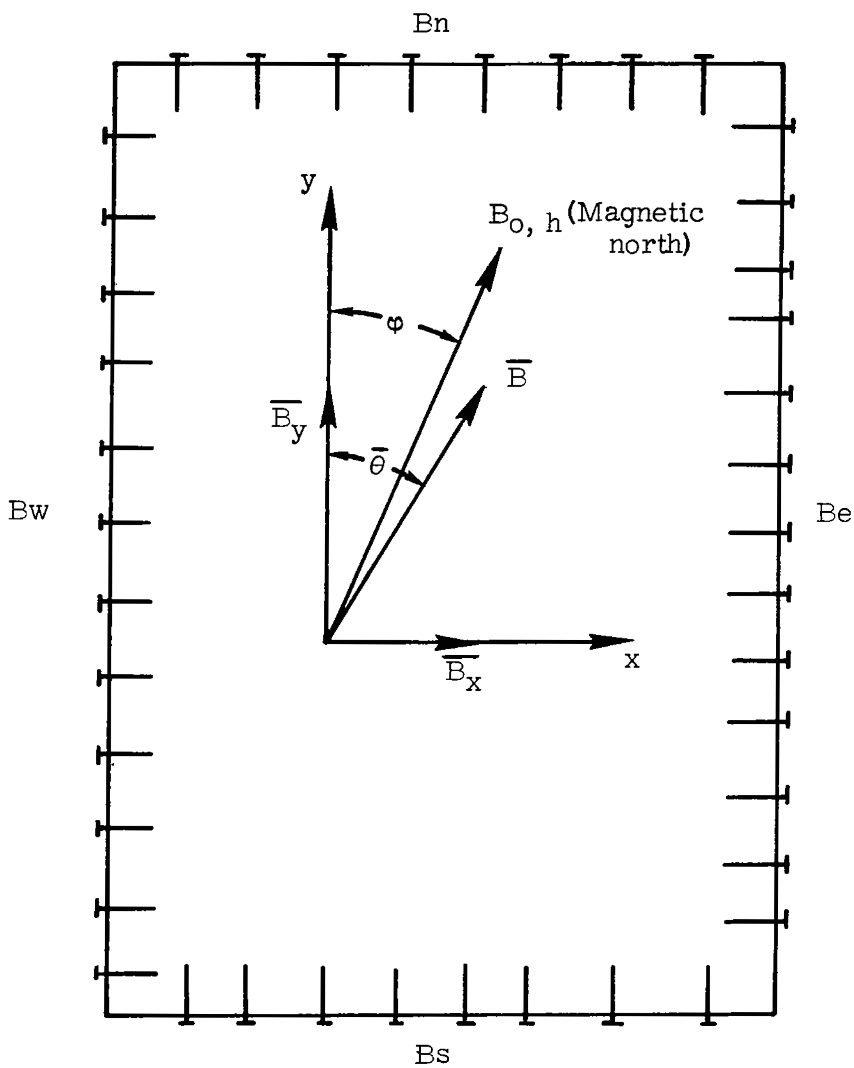

Figure 2.- Top view of building with siding nails (exaggerated) and coordinate system.

Similar measurements and averages may be made on the nailheads of the east and west walls. The quantity

$$\overline{B_x} = \frac{\overline{Be} - \overline{Bw}}{2} \tag{2}$$

is then proportional to the average magnetic-field component within the nails in the x-direction of figure 2. By adding these two perpendicular vector components, an average vector $\overline{\vec{B}}$ given by

$$\overline{\vec{B}} = \hat{x}\overline{B_x} + \hat{y}\overline{B_y} \tag{3}$$

is obtained, where $\hat{x}$ and $\hat{y}$ are unit vectors in the x- and y-directions, respectively. The resultant average vector $\overline{\vec{B}}$ is proportional to the horizontal component of the average magnetic field within the nails of the building. The angle $\bar{\theta}$ of this vector $\overline{\vec{B}}$ with respect to the y-axis is given by

$$\bar{\theta} = \arc \tan\left(\frac{\overline{Be} - \overline{Bw}}{\overline{Bn} - \overline{Bs}}\right) \tag{4}$$

Preliminary magnetic surveys were first made of 17 partially destroyed buildings at various points across the tornado path to detect any strong residual magnetism due to the tornado. Only 16 nails were measured on each of these deformed buildings since tilted walls introduce systematic error, as explained in appendix A. The results of the preliminary survey were negative. More extensive measurements were then made on seven upright buildings (buildings 18 to 24 of figs. 3 and 4) in the hope of detecting weaker residual magnetism. The average measured magnetic fields $\overline{Bn}$, $\overline{Bs}$, $\overline{Be}$, $\overline{Bw}$ and average angles $\bar{\theta}$ computed therefrom for buildings 18 to 24 are tabulated in table I. (The east and west walls of building 24 were measured twice. The first set of measure-

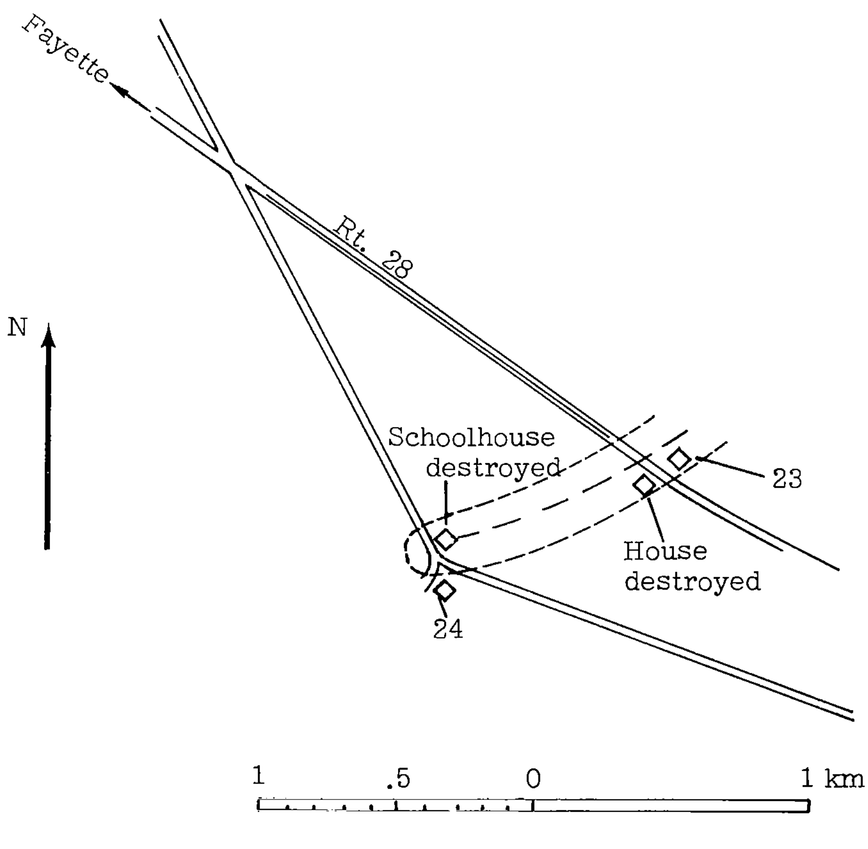

Figure 3.- Initial touchdown point and tornado path about 6.5 km southeast of Fayette, Mississippi, and location of measured buildings 23 and 24.

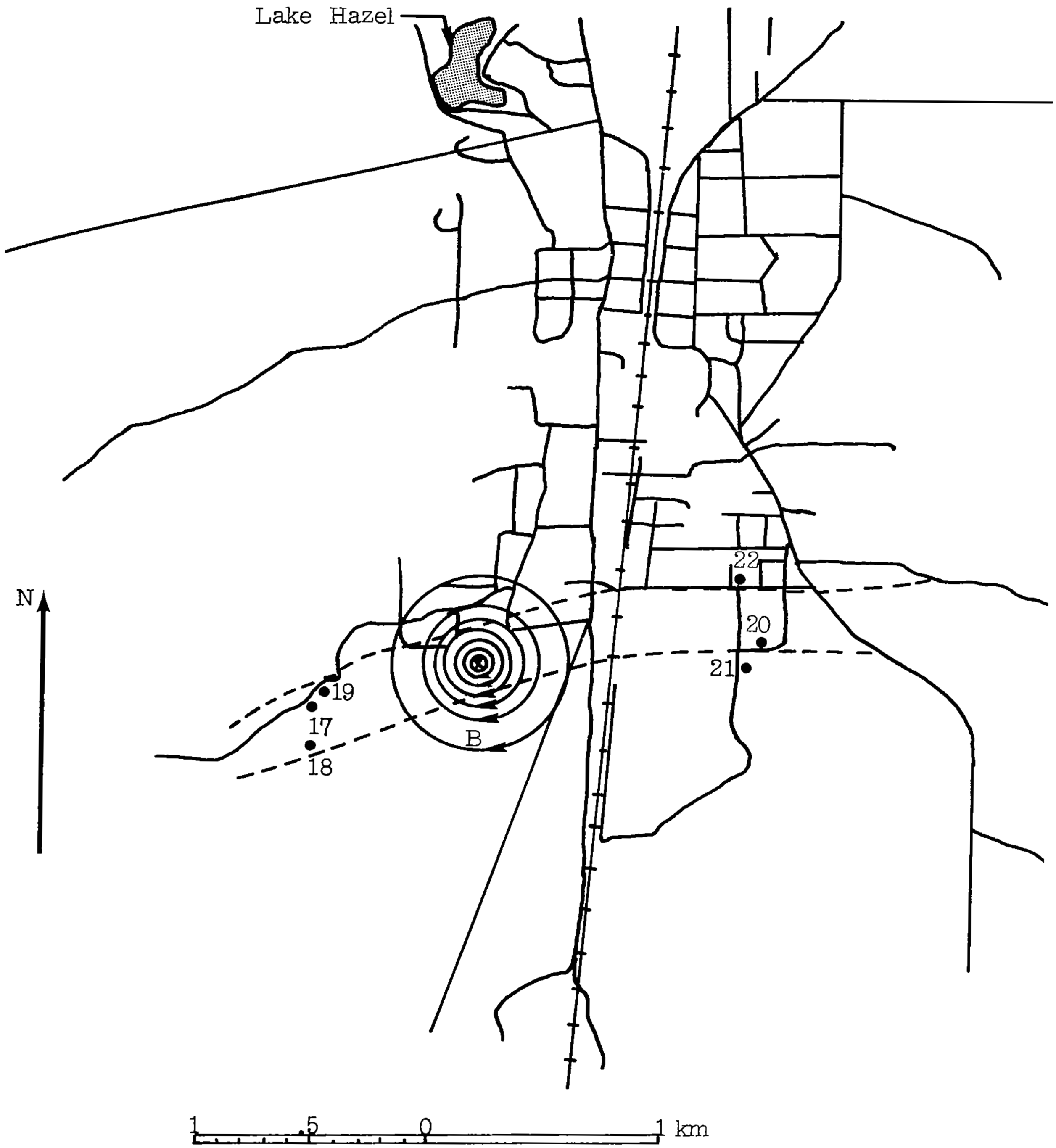

Figure 4.- Tornado damage path (broken lines) through southern part of Hazlehurst, Mississippi, and location of measured buildings 17 to 22. Also shown are magnetic-field lines $\vec{B}$ encircling possible dc electric current flowing downward in tornado core. Tornado moved from left to right.

TABLE I.- AVERAGE VALUES FROM MAGNETIC MEASUREMENTS

Bldg. no.	$\overline{Bn}$	$\overline{Bs}$	$\overline{Be}$	$\overline{Bw}$	$\frac{\overline{Bn} - \overline{Bs}}{2}$	$\frac{\overline{Be} - \overline{Bw}}{2}$	$\bar{\theta}$	φ	$\bar{\theta} - \varphi$
	gauss				gauss		deg	deg	deg
18	0.382	-2.307	-0.746	-1.035	1.345	0.144	6.12	5.00	1.12
19	.607	-1.432	-.752	-1.129	1.020	.189	10.48	10.00	.48
20	.550	-.558	.274	-.284	.554	.279	26.73	22.50	4.23
21	.930	-1.302	-.232	-.333	1.116	.050	2.59	5.00	-2.41
22	1.008	-1.378	-.071	-.203	1.193	.066	3.17	5.00	-1.83
23	.700	-1.531	-1.349	.050	1.116	-.699	-32.08	-30.00	-2.08
24a	1.448	-1.728	.037	-.451	1.588	.244	8.74	10.20	-1.46
24b	1.448	-1.728	.076	-.508	1.588	.292	10.43	10.20	.23

ments is listed as 24a, and the second set is 24b. A larger number of the available nails were included in the second set for greater precision.)

The declination angle φ of magnetic north with respect to the y-axis of each building was independently measured by alining a compass with the walls. (A hand-held compass with accuracy of about $\pm 1^{\circ}$ was used for measuring φ on most of the buildings. For building 24, however, where reduction of the data showed that greater accuracy was warranted, φ was measured by a team from the U.S. Department of the Interior, Geological Survey, using a surveyor's transit.) The declination angles φ and the discrepancies $\bar{\theta} - \varphi$ are also listed in table I.

SIGNIFICANT DISCREPANCY BETWEEN $\bar{\theta}$ AND φ DEFINED

In this section, it is assumed that the measurements were subject to random errors, but not systematic errors. This assumption is discussed in appendix A entitled "Possible Sources of Systematic Error." The angle $\bar{\theta}$, determined by magnetic measurements of the nails in a building, is an average value based on a finite number of measurements. The precision of the values for $\bar{\theta}$ may be determined from analysis of the random errors, as described in the following paragraphs.

The number of measurements made on each wall of a building is listed in table II for buildings 18 to 24. The standard deviation of the measurements on the north wall of a building S_{Bn} may be determined from the formula (ref. 6, p. 9)

$$S_{Bn} = \sqrt{\frac{\sum_{i=1}^{k_n} \left[(Bn)_i - \overline{Bn}\right]^2}{k_n - 1}} \tag{5}$$

TABLE II.- STANDARD DEVIATIONS OF VALUES FROM MAGNETIC MEASUREMENTS

Bldg. no.	k_n	k_s	k_e	k_w	S_{Bn}	S_{Bs}	S_{Be}	S_{Bw}	$S_{\overline{Bn}}$	$S_{\overline{Bs}}$	$S_{\overline{Be}}$	$S_{\overline{Bw}}$	$S_{\overline{\theta}}$	$3S_{\overline{\theta}}$
					gauss				gauss				deg	
18	28	29	99	98	0.827	0.433	0.570	0.550	0.1563	0.0804	0.0573	0.0556	1.73	5.18
19	40	40	120	120	.381	.420	.482	.384	.0602	.0664	.0440	.0351	1.59	4.78
20	50	50	100	100	.676	.205	.184	.333	.0956	.0290	.0184	.0333	2.60	7.80
21	50	50	100	100	.486	.393	.626	.361	.0687	.0556	.0626	.0361	1.86	5.57
22	50	50	100	100	.643	.559	.359	.348	.0909	.0791	.0359	.0348	1.21	3.63
23	51	51	103	100	.720	.433	.486	.524	.1008	.0606	.0479	.0524	1.89	5.66
24a	50	50	100	100	.498	.263	.304	.390	.0704	.0372	.0304	.0390	.90	2.70
24b	50	50	317	295	.498	.263	.301	.317	.0704	.0372	.0169	.0185	.51	1.53

where

$(Bn)_i$ individual gauss-meter measurement on north wall

k_n number of measurements on north wall

$\overline{Bn}$ average measured value on north wall, $\dfrac{\sum_{i=1}^{k_n} (Bn)_i}{k_n}$

Analogous formulas hold for the south, east, and west walls.

The standard deviation $S_{\overline{Bn}}$ of the average measured value $\overline{Bn}$ on the north wall is given by (ref. 6, p. 30)

$$S_{\overline{Bn}} = \frac{S_{Bn}}{\sqrt{k_n}} \tag{6}$$

where S_{Bn} is given by equation (5). Values for $S_{\overline{Bn}}$ are also presented in table II.

With the assumption that the measurements on the four walls of a building are independent, the standard deviation $S_{\overline{\theta}}$ of the average angle $\overline{\theta}$ is given by (ref. 6, p. 31)

$$S_{\overline{\theta}} = \sqrt{\left(\frac{\partial\theta}{\partial Bn}\right)^2 S^2_{\overline{Bn}} + \left(\frac{\partial\theta}{\partial Bs}\right)^2 S^2_{\overline{Bs}} + \left(\frac{\partial\theta}{\partial Be}\right)^2 S^2_{\overline{Be}} + \left(\frac{\partial\theta}{\partial Bw}\right)^2 S^2_{\overline{Bw}}} \tag{7}$$

where $\theta = \text{arc tan} \frac{Bn - Bs}{Be - Bw}$ and $S_{\overline{Bn}}$, $S_{\overline{Bs}}$, $S_{\overline{Be}}$, and $S_{\overline{Bw}}$ are tabulated in table II. Values of $S_{\overline{\theta}}$ are also presented in table II.

According to reference 6, p. 24, the probability is 0.003 that $\overline{\theta}$ differs from the true average angle (determined conceptually from an infinite number of measurements) by as much as $3S_{\overline{\theta}}$. Therefore, the discrepancy between $\overline{\theta}$ and φ will be regarded as significant only if $|\overline{\theta} - \varphi| > 3S_{\overline{\theta}}$. This relation ignores the errors in measuring φ; but it should be possible to make the errors in φ negligible by using a surveyor's transit. Where the deviation is significant, the sign of $\overline{\theta} - \varphi$ is important for indicating the direction of the transient magnetic field and the sense of the axial electric current in the tornado. The transient magnetic field should have opposite directions on opposite sides of the damage path, as shown in figure 4.

Comparison of the last columns of tables I and II shows that for none of the buildings was there a significant discrepancy between $\overline{\theta}$ and φ (even considering the possible $\pm 1^{\circ}$ error in φ for measurements of buildings 18 to 24a). The conclusion is that the mean magnetic field within the siding nails of each building was closely alined with the horizontal component $B_{o,h}$ of the geomagnetic field, and no residual magnetism due to the tornado was detected by the measurements.

THRESHOLD OF DETECTABILITY

Since no residual magnetism due to the tornado was detected, the most that can be expected of the measurements is to establish an upper bound for the transient magnetic field which could have occurred at each building without being detected. According to the statistical analysis of the preceding sections, the threshold of detectability occurs when $\overline{\theta}$ is displaced by the angle $3S_{\overline{\theta}}$ from the angle φ of magnetic north. Such an angular displacement could be caused by subjecting the building to a transient east-west magnetic field of magnitude

$$B_t = 6B_{o,h} \tan 3S_{\overline{\theta}} \tag{8}$$

where $B_{o,h}$ is the horizontal component of the geomagnetic field at the location in question. (At Hazlehurst, $B_{o,h} = 0.244$ gauss.) After the transient has subsided, a residual east-west magnetic field of approximately $B_{o,h} \tan 3S_{\overline{\theta}}$ would remain in the east-west direction. The factor of six between the transient field and the increment in residual magnetism measurable at the nailheads was determined experimentally. The initial magnetic field of several dozen typical siding nails of various types was measured in the laboratory. Then the nails were subjected to magnetic transients of various small amplitudes and were remeasured to determine incremental changes in residual magnetism. The increments in residual magnetism were found to be typically 1/6 the amplitude of the transient magnetic field. Values for the maximum transient magnetic field B_t which could have occurred undetected at buildings 18 to 24 are determined from equation (8) and are listed in table III.

TABLE III.- UPPER BOUND ON AXIAL DC ELECTRIC CURRENT IN TORNADO (AND RELATED DATA) AS INDICATED BY MEASUREMENTS ON EACH BUILDING

Bldg. no.	B_t	w	Δ	I
	gauss	m	m	A
18	0.133	280	120	8 000
19	.122	280	100	6 100
20	.200	270	110	11 000
21	.143	270	195	13 900
22	.093	270	160	7 400
23	.145	230	95	6 900
24a	.069	220	*200	6 900
24b	.039	220	*200	3 900

*Distance from touchdown point.

UPPER BOUND CALCULATIONS FOR POSSIBLE AXIAL DC ELECTRIC CURRENT IN THE MISSISSIPPI TORNADO OF JANUARY 23, 1969

Portions of the damage path of the subject tornado are shown in figures 3 and 4. The locations of buildings 18 to 24 are also indicated. Figures 3 and 4 were prepared from visual inspection of the damage path with reference to maps from the U.S. Department of the Interior, Geological Survey, which show streets and individual buildings.

Figure 3 includes the initial touchdown point of the tornado about 6.5 km southeast of Fayette, Mississippi. Figure 4 shows the path of the tornado through part of Hazlehurst, Mississippi, where it had reached its full intensity. The path width w near each building and the perpendicular distance Δ from the building to the path center line, as indicated in figures 3 and 4, are listed in table III.

Figure 4 shows the form of the magnetic-field lines that would be produced by a dc electric current I flowing downward in the center of the tornado. As the tornado moves along the path, the east-west magnetic field at each building along the edge of the path builds up to its peak value at nearest approach and then subsides. The peak value of the magnetic transient B_t at each building is related to the electric current I in the tornado by

$$B_t = \frac{\mu_o I}{2\pi\Delta} \tag{9}$$

where $\mu_o = 4\pi \times 10^{-7}$ H/m and Δ is the perpendicular distance to the path center line. In equation (9), the displacement current is neglected; but this is permissible, as explained in appendix B, for magnetic measurements made close to a tornado or along its damage path. Solving equation (9) for I gives

$$I = \frac{B_t \Delta}{2} \times 10^7 \tag{10}$$

Table III lists upper-bound values for B_t at each building as determined from statistical analysis of the measurements. Equation (10) then gives corresponding upper-bound values for the dc electric current I in the tornado, and these also are listed in table III. The least upper bound established in Hazlehurst was 6100 amperes from measurements on building 19, and near Fayette was 3900 amperes from building 24b. Therefore, dc electric current, if existent in the tornado, did not exceed 6100 amperes during its passage through Hazlehurst and 3900 amperes at its initial touchdown near Fayette.

DISCUSSION

Real-time measurement of electric currents in tornadoes is hindered by the sporadic occurrence of tornadoes, their rapid speed over the ground, and their brief life. An advantage of the residual-magnetism method is that it can be performed after the tornado event. Real-time measurements have been performed on small waterspouts near Key West, Florida, by Rossow (ref. 7). These measurements were made from an airplane passing within about 100 meters of the waterspouts, and they indicated electric currents of 1 ampere or less. Whether or not these data apply to tornadoes is commented on by Rossow (ref. 7, p. 16) as follows: "The applicability of the data on the events described here to larger and more intense waterspouts and to tornadoes is questionable. The location of the funnel relative to the tall clouds, the jet stream, etc., indicates that substantial differences may exist on occasion."

Brook (ref. 8) has presented indirect evidence that an onset of axial dc electric current of 225 to 1000 amperes occurred in a tornado when it touched down near Tulsa, Oklahoma, on May 27, 1962. The basis for this estimate was a sudden increase in the magnetic field recorded on a magnetometer operated by Geoffrey Boucher, which was located 9.6 km east of the tornado; however, Brook neglected the displacement current when calculating the electric current in the tornado from the measured magnetic field. Since 9.6 km is comparable with the radius of a severe storm, the contribution of the displacement current from accumulating charge could signficantly reduce the magnetic field at the point of measurement, as shown in appendix B. Therefore, the estimate 225 to 1000 amperes does not furnish an upper bound on dc current in the tornado. The validity of Brook's calculation of current is also obscured by a magnetic storm that occurred about the same time as the tornado (ref. 7, p. 2).

The residual magnetism measurements reported herein do set upper bounds on possible axial dc electric current in the Mississippi tornado of January 23, 1969. During the tornado's greatest intensity at Hazlehurst, Mississippi, electric current did not exceed 6100 amperes, and at touchdown near Fayette, Mississippi, it did not exceed 3900 amperes. The current of 225 to 1000 amperes reported by Brook (ref. 8) for the Tulsa tornado of May 27, 1962, is well within these upper-bound values.

A much larger dc current on the order of 10^6 to 10^7 amperes in tornadoes has been suggested by Costen (refs. 9 and 10), who speculated that tornadoes may be hydromagnetic vortices. The basis for this suggestion is that it would account for the apparent retarded revolution rate (retarded with respect to the local flow) of the funnels of a twin tornado about their common center. (See ref. 10.) The twin tornado occurred on April 11, 1965, near Elkhart, Indiana, and is documented in reference 11. The upper bounds on current inferred from the residual-magnetism measurements and listed in table III do not support the hydromagnetic vortex hypothesis.

Silberg (ref. 12) has suggested that alternating electric currents may exist in tornadoes. He considers a horizontal-ring current of 10^4 to 5×10^5 amperes to exist in a tornado about 275 meters above the ground and to be oscillating with a frequency of 10 to 150 kHz. The radiation from such a magnetic dipole could cause burning and dehydration of vegetation along the path, which has sometimes been observed.

The near field of the dipole would include an alternating magnetic field at the ground of magnitude 0.6 to 30 gauss. Since nails usually come from the manufacturer in a magnetized state, partial demagnetization of nails along the path would result, with the degree of demagnetization dependent upon the amplitude and frequency of the alternating magnetic field. Higher frequencies are less effective for demagnetizing nails. Unfortunately, partial demagnetization could not be detected by the simple residual-magnetism search herein reported, and no evidence was obtained either in support of Silberg's ring-current model or in contradiction of it. It should be possible to detect whether or not demagnetization has occurred by attempting to demagnetize the nails further. If the nails are in a partially demagnetized state, the alternating magnetic field needed to achieve further demagnetization is larger than that required to partially demagnetize nails which are in a simple magnetized state and have had no demagnetization; however, no such measurements were attempted along the tornado path in Mississippi.

RESIDUAL MAGNETISM NEAR ELECTRIC-METER GROUND WIRES

On two of the buildings measured in Mississippi, a local discrepancy in magnetization was noticed near a ground wire leading downward from the electric-meter box on the exterior of the building. The ground wire was located in both cases between two vertical lines of nails about 0.41 meter apart, as shown in figure 5. The average residual magnetization differed from 1 to 2 gauss between these two lines of nails, as shown in tables IV and V. This discrepancy may be attributed to the prior occurrence of a transient electric current in the ground wire, since the magnetic field from such a current would have opposite directions on opposite sides of the ground wire.

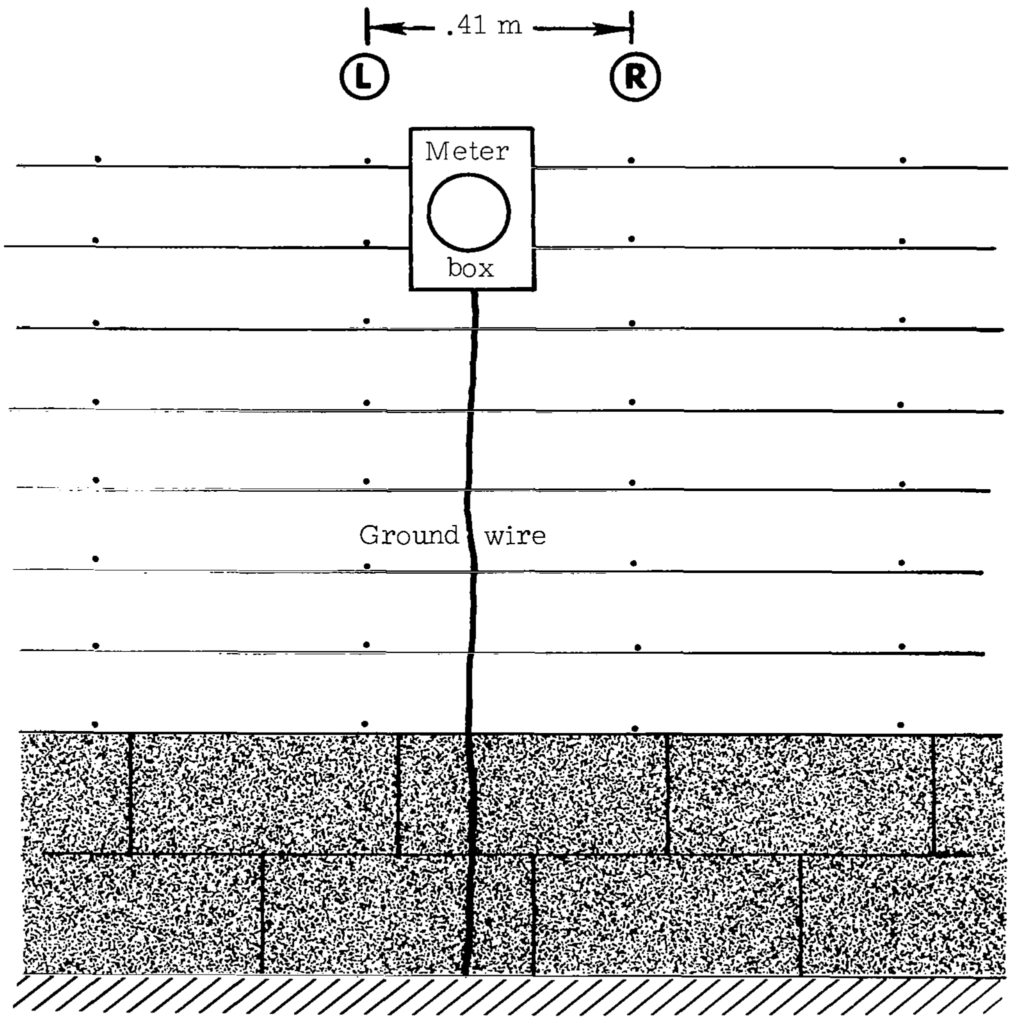

Figure 5.- Ground wire from electric-meter box between vertical lines of nails R and L.

Although the number of nails on each line is small, some idea of the magnitude of this current can be obtained. On building 21, the mean magnetic field $\overline{Bs}$ is 1.3 gauss for all the nails on the south side of the building where the meter was located. From table IV, then, the nails on the line R were magnetized an additional 0.15 gauss on the average, and the nails on line L were demagnetized by 0.43 gauss on the average. The transient magnetic field which had occurred at line R is then $B_t(R) = 0.9$ gauss and at line L is $B_t(L) = 2.6$ gauss, where the factor 6 has been used in computing these transients, as explained in the section entitled "Threshold of Detectability."

TABLE IV.- MAGNETIC MEASUREMENTS OF NAILS NEAR GROUND WIRE ON SOUTH SIDE OF BUILDING 21

Bs(L)	Bs(R)
gauss	
0.8	1.8
.7	1.1
1.0	1.6
1.0	1.3

This magnetic transient on lines R and L could be caused by a transient electric current of 135 amperes if the ground wire were located off center about 0.1 meter away from line L. Unfortunately, the exact location of the ground wire with respect to lines R and L was not noted during the measurements. However, the true value of current is probably this order of magnitude.

On building 17, insufficient data were taken to calculate a mean magnetic field $\overline{Be}$ for all the nails on the east wall where the meter box and ground wire were located. Therefore, the value taken for $\overline{Be}$ shall be simply the mean magnetic field of the nails on lines R and L; that is, from table V, $\overline{Be} = -1.7$ gauss. (This calculation is equivalent to taking the ground wire to be centered between lines R and L.) The magnetic transients at lines R and L are then $B_t(R) = -B_t(L) = -0.49$ gauss, and these correspond to a transient electric current of about 300 amperes in the ground wire.

The 135- and 300-ampere currents calculated in this section indicate the sensitivity that the residual-magnetism method is capable of when the distance between the nails and the electric current is small. This method may, therefore, prove useful for detecting possible magnetic fields associated with ball lightning, or for determining the electric current in lightning strokes which cause damage to aircraft in flight or to trees near buildings. The method seems well suited for such sporadic events, since it does not require any prior instrumentation.

TABLE V.- MAGNETIC MEASUREMENTS OF NAILS NEAR GROUND WIRE ON EAST SIDE OF BUILDING 17

Be(L)	Be(R)
gauss	
-2.0	-1.6
-.7	-2.0
-1.9	-1.8
-.9	-3.5
-1.0	-2.5
-.9	-1.8
-1.1	-1.6
-1.2	-2.7

CONCLUDING REMARKS

A conclusion of this study is that transient electric currents of several hundred amperes may be detected after their occurrence by measuring the residual magnetism in nearby nails or other ferrous objects. This technique may be convenient for gathering magnetic data on ball lightning, damaging lightning strokes, and other sporadic electrical phenomena, since no instrumentation is required prior to or during the event.

Another conclusion of this study is that an axial dc electric current, if existent in the Mississippi tornado of January 23, 1969, did not exceed 3900 amperes at touchdown near Fayette and 6100 amperes during its most intense phase in Hazlehurst. No residual magnetism attributable to the the tornado was detected on either side of the damage path; but if current in excess of these upper-bound values had existed in the tornado, it should have been detected by the measurements. These upper-bound values do not disagree with the measurement reported by Brook (Science, vol. 157, Sept. 22, 1967) for the tornado of May 27, 1962, near Tulsa, Oklahoma. They are in disagreement, however, with the suggestion by Costen (Trans. Amer. Geophys. Union, vol. 49, Dec. 1968 and NASA TN D-5964) that tornadoes may be hydromagnetic vortices with currents on the order of 10^6 to 10^7 amperes.

The residual-magnetism measurements reported herein lack (by several orders of magnitude) the sensitivity of magnetometer measurements reported by Rossow (NASA TN D-5854) and Brook (Science, vol. 157, Sept. 22, 1967), but they do have two desirable features:

(a) They relate to an intense tornado, in contrast to the waterspouts measured by Rossow.

(b) They were made along the damage path where the effects of displacement current on the magnetic field of the tornado could be neglected, in contrast with the measurement from 9.6 km away reported by Brook.

The residual-magnetism data obtained thus far are inconclusive concerning the suggestion by Silberg (J. Atmos. Sci., vol. 23, Mar. 1966) that strong alternating electric currents may exist in tornadoes. But it should be possible to draw more definite conclusions about alternating currents in tornadoes by making demagnetization tests on buildings along a tornado path.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., August 31, 1971.

APPENDIX A

POSSIBLE SOURCES OF SYSTEMATIC ERROR

Initial Magnetization of Nails

If a bag of nails is purchased and the magnetic field emerging from the nailheads is measured, the readings are found to vary over a range of about ± 5 gauss; that is, the nails come in an initially magnetized state. Driving the nails in with a hammer tends to diminish this initial magnetization, but it does not eliminate it entirely. Evidently, the nails are subjected intentionally or otherwise to magnetic fields during processing or packaging.

Were nails entirely symmetrical, such prior magnetic exposure should not introduce a bias in the average measured value of the magnetism. But because of the shape of nails, the average initial magnetization along the axis of the nails from point to head may differ from zero. Then the average measured value $\overline{Bn}$ of all the nails on the north side of a building is biased by this amount. However, the average measured value $\overline{Bs}$ of the nails on the south side would also be biased by the same amount. Therefore, subtraction of these two average values $(\overline{Bn} - \overline{Bs})/2$ should eliminate the bias due to initial magnetization of the nails during manufacture.

Other Sources of Error

The geomagnetic field at the latitudes of interest has a vertical component $B_{o,z}$ of comparable strength with its horizontal component $B_{o,h}$. If the nails being measured were all perfectly horizontal, this vertical component would not affect the measurements. However, along the damage path of a tornado, there are many buildings which have been blown from their foundations and are no longer level so that the walls are in a position of considerable tilt from the vertical. Now the vertical component $B_{o,z}$ of the geomagnetic field contributes to the axial magnetic field within the nails of the tilted walls. It does not appear that this systematic error can be eliminated from the measurements; therefore, buildings with tilted walls should be avoided.

Even in an upright building the vertical component $B_{o,z}$ of the geomagnetic field may affect the measurements if the nails are not driven in horizontally. As a matter of fact, siding nails are frequently driven in at a slightly downward slant, so that the axial magnetic field within the nails is influenced by $B_{o,z}$. If the nails on opposite walls are driven in at the same downward angle, the effect is analogous to the effect of initial magnetization due to manufacture, and it is eliminated in the values $(\overline{Bn} - \overline{Bs})/2$ and $(\overline{Be} - \overline{Bw})/2$. However, suppose that the nails on the east wall were driven in with a downward slant, and the nails on the west wall were driven in with an upward slant. The error would be analogous to that obtained for walls which are tilted from the vertical, and the data would have to be discarded. Fortunately, visual inspection of the exposed nailheads can often indicate whether or not they were driven in at more or less the same angle. Nails that are obviously crooked should not be measured.

A number of different types of nails are often used on the exterior of a single building. Measurements should be confined to only one type of nail, because different types may have different average values for initial magnetization due to manufacture, in which case the bias due to initial magnetization would not vanish in equation (4). Therefore, the likelihood of systematic errors in the measurements can be reduced by (1) avoiding tilted buildings, (2) avoiding nails which have clearly been driven in crooked, and (3) measuring only one type of nail on a given building.

APPENDIX B

EFFECT OF DISPLACEMENT CURRENT ON MAGNETIC FIELD AT VARIOUS DISTANCES FROM A TORNADO WITH ASSUMED AXIAL DC ELECTRIC CURRENT

Brook (ref. 8) has presented indirect evidence that an onset of axial dc electric current of 225 to 1000 amperes occurred when a tornado touched down near Tulsa, Oklahoma, on May 27, 1962. The basis for this estimate was a sudden increase in the horizontal component of the magnetic field (shown in fig. 1 of ref. 8) recorded by Geoffrey Boucher on a magnetometer located 9.6 km east of the tornado.

Brook calculated the electric current I in the tornado by applying the Biot-Savart law to the current filament in the tornado and to several assumed current-path configurations in the cloud and their images in the ground. In his calculation of $I = 225$ amperes, he took the current filament in the tornado to be vertical up to an altitude of 6 km and then to become horizontal to allow the accumulating charge from the current in the tornado to spread over the horizontal extent of the storm. Although acknowledging that a large charge accumulated, he neglected the displacement-current density $\partial\vec{D}/\partial t$ in determining I from $\vec{B}$. It is the purpose of this appendix to show that the displacement current may have a large effect on such calculations. Maxwell's integral equation

$$\oint_l \vec{B} \cdot \vec{dl} = \mu_o \iint_A \left(\vec{J} + \frac{\partial\vec{D}}{\partial t}\right) \cdot \hat{n}\, dA \tag{B1}$$

is used, where

μ_o magnetic permeability of vacuum, H/m

$\vec{J}$ electric-current density, A/m^2

$\partial\vec{D}/\partial t$ displacement-current density, A/m^2

and where the integrals are taken over an arbitrary surface A and its bounding circuit line l, with the surface unit normal $\hat{n}$ related to the unit vector $\hat{l}$ (which points in the positive direction along the circuit) by the right-handed screw rule. When A is a closed surface, so that the bounding circuit line l degenerates to a point, equation (B1) becomes

$$\oiint \left(\vec{J} + \frac{\partial\vec{D}}{\partial t}\right) \cdot \hat{n}\, dA = 0 \tag{B2}$$

These equations will be applied in the following idealized example: Suppose that a steady current I is flowing in a tornado between a storm cloud and the ground, as shown in figure 6, where the tornado is drawn disproportionately large. Take the storm to be axially symmetric with the tornado at its center.

Equation (B1) is applied to the circular area A_1 of radius r which is horizontal, just above the ground, and centered upon the tornado in figure 6. Because of axial symmetry, the magnitude of the magnetic field B at radius r is then given by

$$B = \frac{\mu_o}{2\pi r} \iint_{A_1} \left(\vec{J} + \frac{\partial \vec{D}}{\partial t} \right) \cdot \hat{n} \, dA \tag{B3a}$$

or

$$B = \frac{\mu_o}{2\pi r} \left(I + \iint_{A_1} \frac{\partial \vec{D}}{\partial t} \cdot \hat{n} \, dA \right) \tag{B3b}$$

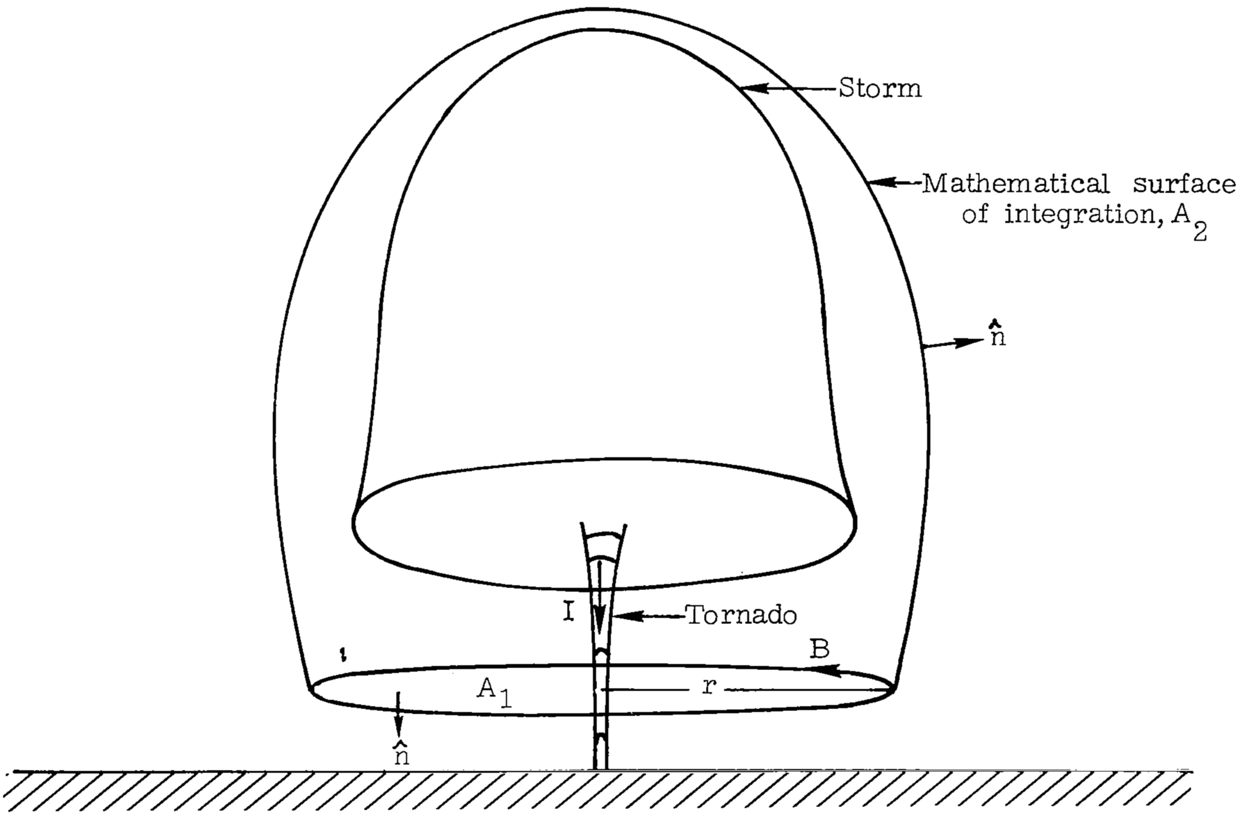

Figure 6.- Idealized axially symmetric storm cloud with pendent tornado and electric current I flowing between cloud and ground. Horizontal circular surface A_1 of radius r intersects surface A_2 along circular line l to form a closed surface. Magnetic field $\vec{B}$ on l is also indicated. Figure is not drawn to scale.

Applying equation (B2) to the entire closed surface $A_1 + A_2$ in figure 6 also yields

$$I + \iint_{A_1} \frac{\partial \vec{D}}{\partial t} \cdot \hat{n}\, dA + \iint_{A_2} \frac{\partial \vec{D}}{\partial t} \cdot \hat{n}\, dA = 0 \tag{B4}$$

which shows that the total displacement current through surfaces A_1 and A_2 is equal and opposite to the conduction current I. The first two terms of equation (B4) appear in formula (B3b) for the magnetic field B at radius r. If much of the displacement current passes through surface A_1, it will decrease B accordingly.

In order to assess roughly the proportion of displacement current passing through surface A_1, one may consider the incremental $\vec{D}$ field caused by the deposit of an incremental charge in the cloud at an altitude of 6 km – an altitude which corresponds to one of the current paths treated by Brook. The incremental $\vec{D}$ lines may be computed for the axisymmetric model being considered from the equations

$$\left.\begin{aligned} \operatorname{div} \overrightarrow{\delta D} &= \delta\rho \\ \operatorname{curl} \overrightarrow{\delta D} &= 0 \end{aligned}\right\} \tag{B5}$$

where δ indicates incremental quantities. Approximate incremental $\vec{D}$ lines are shown in figure 7 together with the outline of the storm above the ground drawn

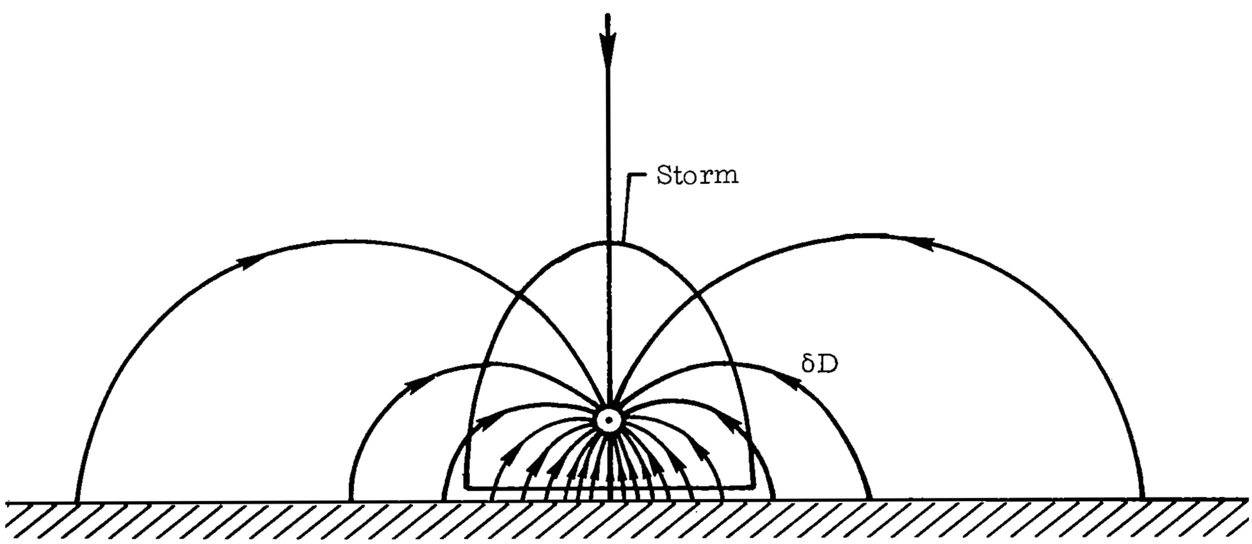

Figure 7.- Approximate incremental $\vec{D}$ field lines due to deposit of an incremental negative charge at altitude 6 km in axially symmetric severe storm cloud. This sketch is intended to be symbolic of any incremental charge distribution which preserves axial symmetry.

approximately to scale. Surfaces A_1 and A_2 are omitted from this figure, and for them the reader must refer to figure 6. Two cases will be considered:

(1) Radius r of surface A_1 taken approximately equal to the radius of the base of the storm. This corresponds roughly to the case considered by Brook where $\vec{B}$ was measured at a distance of 9.6 km from the tornado. It is then apparent from figure 7 that for charge accumulating at altitude 6 km, a large proportion of the displacement current passes through surface A_1, and the magnetic field calculated from equation (B3b) is substantially reduced from that calculated using only the electric current I. Therefore, Brook's estimate for the current I in a tornado from the magnetic field measured 9.6 km away could have been much smaller than its actual value.

(2) Radius of surface A_1 taken much less than the radius of the base of the storm. (Surfaces A_1 and A_2 still enclose the storm; this requires A_2 to stretch below the storm as A_1 shrinks.) Because the area of surface A_1 is small in this case, the flux of displacement current through A_1 is small compared with the electric current I in the tornado, and equation (B3b) may be approximated by

$$B \approx \frac{\mu_o I}{2\pi r} \tag{B6}$$

Therefore, the displacement current may be neglected when calculating the electric current I in a tornado from measured B only when the measurements are made close to the tornado.

REFERENCES

1. Anon.: Storm Data, vol. 11, no. 1, Jan. 1969, pp. 4-5.
2. Vonnegut, Bernard: Electrical Theory of Tornadoes. J. Geophys. Res., vol. 65, no. 1, Jan. 1960, pp. 203-212.
3. Colgate, Stirling A.: Tornadoes: Mechanism and Control. Science, vol. 157, no. 3795, Sept. 22, 1967, pp. 1431-1434.
4. Viemeister, Peter E.: The Lightning Book. First ed., Doubleday & Co., Inc., 1961.
5. Condon, Edward U., project director: Scientific Study of Unidentified Flying Objects. Bantam Books, 1968.
6. Beers, Yardley: Introduction to the Theory of Error. Second ed., Addison-Wesley Pub. Co., Inc., c.1957.
7. Rossow, Vernon J.: Observations of Waterspouts and Their Parent Clouds. NASA TN D-5854, 1970.
8. Brook, Marx: Electrical Currents Accompanying Tornado Activity. Science, vol. 157, no. 3795, Sept. 22, 1967, pp. 1434-1436.
9. Costen, R. C.: Are Tornadoes Hydromagnetic Vortices? Trans., Amer. Geophys. Union (Meteorol. Abstr.), vol. 49, no. 4, Dec. 1968, p. 690.
10. Costen, R. C.: An Equation for Vortex Motion Including Effects of Buoyancy and Sources With Applications to Tornadoes. NASA TN D-5964, 1970.
11. Fujita, Tetsuya: Aerial Survey of the Palm Sunday Tornadoes of April 11, 1965. SMRP Res. Paper No. 49 (Grant WBG-41(NSSL)), Univ. of Chicago, Jan. 1966.
12. Silberg, P. A.: Dehydration and Burning Produced by the Tornado. J. Atmos. Sci., vol. 23, no. 2, Mar. 1966, pp. 202-205.

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