MAGNETISM OF THE EARTH

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Magnetism of the Earth

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Magnetism of the Earth

Chapter I. Introduction

Previous Publications

On several occasions the Coast and Geodetic Survey has publisbed short monographs on geomagnetism, suitable for the general reader. A version prepared in 1945 by Albert K. Ludy and H. Herbert Howe is the basis of the present revision, which seeks to bring in the newer developments without a major reorganization of the material.

Importance of a Knowledge of the Earth's Magnetism

The human race managed without the implements of reliable navigation for untold ages, including most of the span that is covered by written records. Nevertheless, there were seafaring nations from the dawn of history. There is reason to believe that Phoenician traders voyaged to distant Britain and Malaya; they are supposed to have utilized a canal that was dug between the Nile and the Red Sea about 1500 B.C. and was kept open at intervals for 2,000 years. But the maritime commerce of early days was conducted only at frightful cost, in lives and wealth. The writings of Homer bear witness to this, with their frequent reference to the wrath of Poseidon.

The ancients had no compass. Whenever tbe heavens were obscured, any vessel on the open sea was precariously dependent upon her master's success in reading the winds and waves. With the introduction of the compass in late medieval times, all this was changed. Here was something to give reliable directions, regardless of wind and weather. It is scarcely a mere accident that the age of discovery closely followed the development of the compass. The safe return of Columbus from his epoch-making voyage gave impetus to a new spirit of exploration that finally culminated in the mapping of nearly the whole surface of the globe.

Although centuries have passed since the compass released the mariner from his age-old dread of the trackless oceans, it still holds an important place in navigation, and is the simplest and cheapest direction finder on land and sea and in the air.

Since there are few places where the needle points to true north and since the direction is continually changing with time, the user needs correct information regarding both the direction of the pointing and its changes.

Small vessels and boats depend entirely on the magnetic compass. Larger vessels and submarines are usually equipped with the gyrocompass, which has many advantages; but since it has moving parts which must he kept in good order, one or more magnetic compasses are kept in reserve. The magnetic compass has another nautical use, namely, the determination of the direction of sea currents. Air navigation has always relied basically on the earth's magnetism for direction finding. Several special types of compass, the more elaborate employing the principle of the earth inductor and other devices, have been developed. Provision is made at many airfields for determination of the errors in the compass pointings, and this requires accurate knowledge of the earth's magnetic field at the place of testing.

The compass was one of the most important surveying instruments in the early centuries of the modern era. It is not, however, an instrument of precision; results of great accuracy are not to be expected in compass surveys, and the use of a compass as a surveying instrument should be avoided where circumstances permit (espe-

cially in areas where local control surveys have been made), or where pronounced local magnetic disturbance renders the compass unreliable. On the other hand, it has the advantage of speed and simplicity, and is useful for retracing lines of old surveys originally established by compass, and for surveys where great accuracy is not required, particularly in wooded areas. Nearly all the early land surveys of the United States, as for example those by George Washington, were made by compass. Transfers of property often require identification of boundaries established by compass, so that knowledge of the changes in magnetic directions with time becomes important. The extension of the magnetic work of the U.S. Coast and Geodetic Survey to cover the interior of the country was partly due to this need.

The compass has also been much used in reconnaissance surveys, and military use of the compass for the same purpose is made by every army.

Geologists use magnetic instruments to locate deposits of magnetic iron ore and to trace buried magnetic formations which may be associated with oil and minerals. Obviously the importance of this application will increase as known deposits of these natural resources approach exhaustion.

The upper atmosphere is ionized by solar radiations and thereby becomes electrically conducting. The ionization is closely associated with the changes in the earth's magnetism, including those known as magnetic storms. Since the ionization is intimately connected with radio communication and with some of its disturbances, the earth's magnetism has a definite relation to radio communication.

Natural electric currents known as earth currents occur in the ground; they are usually small but at times are strong enough to interfere with wire and cable communication and even with transmission of electrical power. Earth currents have been found useful in studying features of the earth's crust; their rapid fluctuations are intimately connected with those of the magnetic field.

The study of the highly penetrating radiation known as cosmic rays has shown that these rays are affected by the earth's magnetic field and its fluctuations.

The most intense penetrating radiation now known to be present in space lies in the Van Allen radiation belts. These belts, discovered by satellite-borne instruments during the International Geophysical Year of 1957–58, consist of energetic electrons and protons that are trapped in the earth's magnetic field.

Since there are so many practical uses of the earth's magnetism, it is important to know its configuration, its distribution, its short-period and long-period changes, and its relation to other phenomena originating in the sun, in the atmosphere, or within the earth. Its uses are constantly extending, and at any time some phase which has hitherto been of purely scientific interest may be found to have a practical application.

Magnets and Magnetic Fields

The most obvious distinguishing characteristic of a magnet is its ability to attract iron or steel. This property is exhibited in nature by the *lodestone,* a variety of the mineral known as *magnetite* (magnetic oxide of iron, Fe_3O_4). The lodestone is called a natural magnet.

There are generally two regions of the surface of a magnet, one near each end, at which the attraction is the greatest. For descriptive purposes the attractive force may be treated as though it emanated from two internal points called the *poles* ("point poles"). An ordinary magnet has a *magnetic axis,* which is approximated by the line joining the poles. A magnet suspended or supported so as to turn freely in the horizontal plane takes a definite direction, which in most places is roughly north and south. The pole near the north-seeking end is called the *north pole* of the magnet, the one near the south-seeking end the *south pole.* Like poles repel, unlike poles attract each other. (Magnets used aboard ship for compensating compasses are often painted, the north-seeking end red, and the south-seeking end blue. The two portions of the magnets are conventionally said to have "red" and "blue" magnetism respectively.)

The force between two (hypothetical) point-poles is proportional to the strength of each pole, and inversely proportional to the square of the

distance between them. This law was established by Coulomb in 1785, and was one of the first fruits of the intensive studies that led to the modern era of electricity. A unit pole (in the cgs electromagnetic system) is one which, in a vacuum, produces a force of 1 dyne on a similar pole at a distance of 1 centimeter. The strength of one pole of a magnet multiplied by the distance between poles gives the *magnetic moment* of the magnet.

Although point-poles probably have no physical reality, a modification of that concept may be used to give a mathematical picture which represents the behavior of a magnet accurately down to molecular dimensions. Instead of being concentrated at a point, positive and negative pole strength is considered as distributed throughout the magnet. Each bit of the magnet is thus characterized by a definite pole strength per unit volume, which is positive at the north end of the magnet, zero in the middle, and negative at the south end.

Another picture, which is equivalent mathematically and probably more accurate physically, is obtained by considering each bit of the magnet as having a certain magnetic moment per unit volume, which must be specified as to both magnitude and direction. It is greatest in the middle and least at the ends, the rate of change at any point being proportional to the density of pole strength discussed in the previous paragraph.

The effects of a magnet in the surrounding space are conveniently described by saying that the magnet produces a *magnetic field*. At every point, the field is characterized by a definite intensity and direction. Its *magnetic intensity* is usually defined as the force upon a (hypothetical) isolated point-pole: unit field acting upon a unit pole produces unit force.

Although intensity could be measured by the force upon a point-pole, a more accurate method is as follows: The magnetic field tends to impel one pole of a suspended magnet along the field in one direction and the other pole in the opposite direction. Unless the magnetic axis is parallel to the direction of the field, there is a tendency to rotate the magnet about its center; that is, the field produces a torque on the magnet. If the magnetic axis is held at right angles to a uniform field, the torque is equal to the intensity of the field multiplied by the magnetic moment of the magnet.

Such a torque may be measured in various ways. One method is to oppose it with the known torque of a quartz-fiber suspension; in this case, only the horizontal component of the field is measured, since the vertical component is opposed by gravity, not by the suspension.

If a piece of iron is brought near a magnet, or is otherwise subjected to a magnetic field, it will become magnetized by *induction*, and can then attract other iron. Iron is roughly classified as "hard iron" (including most varieties of steel), which can be magnetized only with diffculty but which then retains much of its magnetism; and "soft iron," which can be magnetized much more readily but loses most of its magnetism when the inducing field is removed. Hard iron can be magnetized more readily if it is hammered while held in the magnetic field. (Iron that is "hard" in this sense is not necessarily hard in the various other senses in which the word is used.)

One method sometimes used to magnetize an iron or steel object is to place it between the pole-pieces of an electromagnet; another commonly used procedure is to place the object in a solenoid or elongated coil of wire and pass a heavy unidirectional electric current momentarily through the coil. Sometimes, for special purposes, the object is magnetized by stroking it with an existing magnet. Thus, in observations with a dip circle the magnetization is reversed in the middle of each set by stroking the needle with two bar magnets. Before 1820 the standard way of magnetizing a needle was to stroke it with lodestone or with another magnet. It should be noted that when two magnets are stuck together, pulling them apart by a longitudinal sliding motion might tend to weaken them.

With respect to their magnetic properties, all substances are diamagnetic, paramagnetic, or ferromagnetic. The magnetic behavior of substances of the first two categories is of practical concern only when large volumes of material are acting (as in the effect of the earth's crust upon its magnetic field); but all three are of con-

siderable scientific importance. Most substances are weakly diamagnetic.

A paramagnetic body shows positive *susceptibility* (ratio of induced magnetic moment per unit volume to the field that produces it): it is attracted by either pole of a magnet, and if a rod of such a substance is placed near a powerful magnet, it tends to rotate until its greatest dimension lies along the field. A diamagnetic body shows negative susceptibility: it is repelled by either pole of a magnet, and in the vicinity of a magnet, it tends to rotate until its greatest dimension is across the field. The susceptibilities of diamagnetic and paramagnetic substances are very small, ranging from about -0.000002 to $+0.00012$ (cgs electromagnetic units). In fact, we usually think of such materials as nonmagnetic.

Ferromagnetic substances may be regarded as a special variety of paramagnetic substances, but are here considered a separate class. When the applied field is removed, they retain a portion of their magnetism; their susceptibilities may be several hundred cgs units. Iron, nickel, and cobalt are the elements generally regarded as ferromagnetic.

A magnet loses strength when heated, but if it is not heated too much, it will regain full strength when cooled. If it is heated to a higher temperature, it will not recover full strength; and if it is heated to the *Curie point* (750° centigrade for iron), it ceases to be ferromagnetic. If it is then cooled, it becomes ferromagnetic again, but does not automatically regain its magnetism; if, however, it is in a magnetic field as it cools, it will usually be magnetized by induction and will retain some of this new magnetism.

Permanent magnets are finding a wide variety of applications, and their manufacture has become an important branch of the metallurgical industry. In recent years a number of new alloys have been developed which can be magnetized several times as intensely as was possible with the older magnet steels, and which therefore provide magnets especially useful for some purposes. However, the use of these magnets in geomagnetic instruments, including ships' compasses (see p. 47), presents some new problems. It might be supposed that the performance of a compass would be greatly improved by increasing the magnetic moments of the magnets attached to the card, but other problems might arise, such as an increased tendency to oscillate (if the period of oscillation of the compass were brought closer to the rolling period of the vessel) and troubles due to slightly magnetic components of the compass card. Traces of magnetic material in the compass bowl, which might not affect the performance of a compass equipped with weak magnets, may become highly magnetized by induction if excessively strong magnets are used on the compass card. Under such conditions the performance of the card may be quite unsatisfactory, and it is impossible to compensate for the ill effects by the usual methods.

A related problem is the procurement of nonmagnetic alloys from which to make the instruments used for magnetic measurements. (Much commercial brass is magnetic, because of impurities.) The problem may be solved with the aid of special metallurgical techniques.

Electromagnetism.—An electric current produces a magnetic field. In order to produce a field of sufficient intensity without excessive current, it is customary to send the current through a coil of wire, wound so that the fields due to the various turns reinforce one another. A type of coil of special importance in magnetic measurements is the Helmholtz coil. Basically, a Helmholtz coil consists of two wires formed into circles of the same diameter with a common axis; but the planes of the circles are separated by a distance equal to their radius. The field produced near the center of a Helmholtz coil is very nearly uniform over a comparatively large region. In actual practice, it is necessary to use, not single wires, but two closely wound coils. Examples of the use of Helmoltz coils are discussed on pages 49 and 58. A 4-coil array of proper configuration [37][1] is also used and will produce a more nearly uniform field in a given volume for a given diameter. (See p. 58.)

A changing magnetic field produces electrical effects. In a closed circuit (an earth-inductor

[1] Numbers in square brackets refer to the bibliography on pages 78–79.

coil or a fluxgate-magnetometer coil for example) the effect is an induced electromotive force which produces a current. The electromotive force depends on the time rate of change of the flux of induction through the circuit. If the coil is in a vacuum the induction corresponds to the magnetic intensity. If the coil is wound on permeahle material, then the flux of induction includes the effect of the intensity of magnetization within the material. The *flux density,* or induction, is the amount of flux per unit area, taken normally across the flux.[2]

According to present theory, all magnetism is really electromagnetism, the magnetism of an ordinary magnet heing attributed to the unneutralized rotations and revolutions of the electrified particles which it contains. The basis of this conception was proposed by Ampère in 1820.

Definitions

The earth acts like a great spherical magnet. in that it is surrounded by a magnetic field. (See p. 72.) The measurement of the earth's magnetism at any place consists of determining the direction and intensity of that field.

At any place two planes of reference are necessary for such measurements: the plane of tbe horizon; and the *true meridian,* which is defined by the great circle through the geographic poles.

True bearing and *true azimuth* of an object are alternate names for the angle hetween the true meridian at the point of observation and the vertical plane containing the object and the point of observation. The direction adopted for 0° is not always the same—in geodetic and magnetic surveys 0° is usually true south; in sea and air navigation 0° is customarily north.

The *magnetic meridian* at any point is defined as the vertical plane fixed by the direction of the lines of force, i.e., by the direction taken by a perfect compass needle. The *magnetic prime vertical* is the vertical plane at right angles to the magnetic meridian. *Magnetic bearing* and *magnetic azimuth* are similar to true bearing and true azimuth, except that they are referred to the magnetic meridian.

The *magnetic declination, D,* is the angle between the true meridian and the magnetic meridian, and is considered east or west according as magnetic north is east or west of true north. Declination is often called *variation of the compass* or simply *variation.* When it is desired to attach a sign to the declination, east declination is usually considered positive, and west declination negative (though in some older literature the reverse convention is used).

The *dip,* or *inclination, I,* is the angle which the lines of force make with the plane of the horizon. It is considered north or south according as the north-seeking or south-seeking end of the needle dips below the horizontal. North dip is regarded as positive.

The three quantities declination, dip, and horizontal intensity (H) are often called *the magnetic elements.* Since the three elements are a complete vector representation of the total field, F, any other component of the field may be computed from them. The total intensity and horizontal intensity are always regarded as positive. Other magnetic elements are the *vertical intensity, Z,* considered positive when dip is positive; the *north component, X;* and the *east component, Y.* The interrelation of these elements is shown by figure 1. Some of the formulas connecting them are:

$$Z = H \tan I \qquad X = H \cos D$$
$$Z = F \sin I \qquad Y = H \sin D$$
$$H = F \cos I \qquad F = \sqrt{H^2 + Z^2}$$
$$H = \sqrt{X^2 + Y^2} \qquad F = \sqrt{X^2 + Y^2 + Z^2}$$

The *magnetic equator* is an imaginary line passing through the points of the earth's surface at which the field is horizontal; i.e., along this line the dip and the vertical intensity are zero.

A *magnetic pole* of the earth is a point at which the field is vertical; i.e., the dip is 90° and the horizontal intensity is zero. The compass does not point toward the magnetic pole, nor is the pole similar to a pole of a magnet as defined on page 2. A magnetic pole of the earth

[2] In the cgs electromagnetic system of units, the flux density and the magnetic intensity are numerically equal in a vacuum, and nearly so in air. The name *gauss* was long used for the units of both these quantities; for measuring the earth's field the unit *gamma* ($1\gamma = 0.00001$ gauss) was devised. Since 1932 the name *oersted* has come into general use among physicists and engineers for the unit of intensity, "gauss" being reserved for flux density.

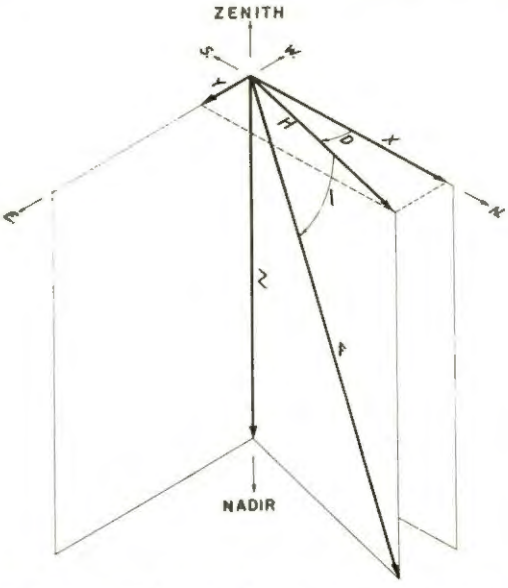

Figure 1.—Typical aspect of vectors showing interrelation of the magnetic elements, seen from the northeast.

D Magnetic declination
I Inclination (or dip)
H Horizontal intensity
X North component
Y East component
Z Vertical intensity
F Total intensity

is sometimes called a *dip-pole*. This term avoids confusion with other poles such as the "geomagnetic poles" defined on page 9, or the "poles" of maximum total intensity.

At any instant, each magnetic element has different values at different points. The gradient in gammas per mile (or minutes per mile) is not uniform. Where the irregularities are large, there is said to be *local disturbance* or *anomaly*. It is *natural* if caused by the presence of magnetic material in the geological formation, and *artificial* if caused by the works of man.

At any specified point, the magnetic elements are continually changing. It is found convenient to separate the change into several portions depending upon the time intervals involved, as described in the next four paragraphs.

The average value of a magnetic element for one year differs from that for the next. This change can only be determined by actual observation, since no general law or formula has been found that fits the facts. It may progress in one direction for many years, but ultimately reverses. This change with the years is called the *secular change*. The amount of secular change in 1 year is called the *annual change*.

When the average monthly values of an element are corrected for the trend of secular change, it is found that there is a small systematic variation from month to month; for example, in North America the horizontal intensity increases slightly during the summer. This is called *annual variation*.

There is a small fluctuation of each of the magnetic elements, which repeats itself with some degree of regularity day after day, and is known as the *daily variation*.

The magnetic elements are usually disturbed to some extent by irregular fluctuations, which tend to affect much of the earth's surface simultaneously. Such fluctuations are ordinarily a minor feature, but occasionally (more frequently in high latitudes) they become violent and prolonged, constituting a *magnetic storm*.

Chapter II. The Earth's Permanent Magnetic Field and its Secular Change

A magnet supported at its center of gravity in such a way as to be free to assume any position would come to rest with its magnetic axis directed along the lines of force of the earth's magnetic field. The angle which this direction makes with the horizontal plane varies according to locality, and may have any value from 0° to 90°. For example, at Washington, D.C., the dip of the needle would be about 71°.

If the magnet is slightly deflected from its equilibrium position, it will oscillate with a frequency inversely proportional to the square root of the intensity F. With a calibrated magnet F could be computed.

Practical methods for determining direction and intensities are described on pages 44 to 58.

A piece of iron subjected to the earth's magnetic field becomes magnetized by induction just as it does when placed in the field of a magnet. This fact is of the greatest importance to navigation in modern ships, since the iron which enters so largely into their construction becomes magnetized by induction and has a disturbing effect on the compass; every time the ship changes its direction, its magnetism changes and the effect on the compass changes. (See p. 42.)

The earth's magnetism does not of itself affect the human senses. It is evidenced only by its effect on magnetic and electrical instruments, and by various geophysical phenomena.

Some General Characteristics of the Earth's Field

The distribution of the field over the surface of the earth is so irregular that observations must be made in many places in order to get a satisfactory picture of the phenomenon. (See chapter IV.) Special names are given to the places where the magnetic field is horizontal (magnetic equator) and where it is vertical (magnetic poles).

Magnetic Equator

At the magnetic equator, the dip is zero. The magnetic equator is south of the geographic equator in South America, and north of it in Africa, Asia, and much of the Pacific. (See fig. 3.) Its position is not fixed, but slowly changes.

North of the magnetic equator, the north end of the dip needle dips below the horizontal, whereas south of it the south end dips. As one goes away from the magnetic equator, the dip angle and the vertical intensity increase.

Magnetic Latitude

If the earth were uniformly magnetized parallel to the axis of rotation, the dip would be related to the latitude (Φ) by the equation $\tan I = 2 \tan \Phi$. For some purposes, it is convenient to compute a quantity Φ by inserting in this equation the actual dip at any point. This quantity is called the *magnetic latitude* of that point. As thus defined, it is 90° at every local dip pole as well as at the principal ones.

Some recent literature considers "magnetic latitude" as equivalent to "geomagnetic latitude," which is defined on page 9.

Magnetic Poles

In the vicinity of the magnetic poles, the horizontal intensity is very small. (See p. 5.) Hence, in those regions the compass cannot be used to determine direction, although the total intensity at the magnetic poles is roughly twice as great as at the magnetic equator.

Strictly speaking, there are many "magnetic poles," most of them associated with local anomalies of small extent and due to geological formations containing traces of magnetic material.

The two poles referred to above are those which characterize the normal field (see p. 11), and are known as the *principal magnetic poles,* or more commonly, as *the* magnetic poles.[1] The principal magnetic poles are more than 1,500 kilometers from the geographic poles and are not diametrically opposite each other; in fact, the line joining them misses the earth's center by some 1,100 kilometers.

There is a widespread belief that the compass points toward the magnetic pole. *As a matter of fact, in large areas the direction of magnetic north differs 10° or more from the direction of the magnetic pole.*

Along the 101st meridian in the United States, the declination ranges from about 9° to 13° East, although the magnetic pole lies due north.

When acted upon by the earth's field alone, the compass needle is not drawn toward any special point (i.e., there is no attraction), but it responds to a turning force exerted by the field upon each of the innumerable tiny magnets of which it is composed. It indicates nothing more than the orientation of the earth's field at the spot where it is used.

The magnetic poles should not be confused with the points of maximum total intensity. Finding these points is even more difficult than finding the poles, but it is unlikely that they are coincident with the poles; only the simplest of the idealized models of the field would require such coincidence.

The locations of the magnetic poles bave practical importance for the following reasons: (1) the compass loses its directive force in their vicinity; (2) the isogonic lines must pass through them (p. 11); and (3) it is of some interest to know just how much they move.

Locating the magnetic poles.—It might be supposed that within a few hundred miles of the magnetic poles the needle should point toward them, but even this appears to be incorrect.

The task of locating the principal magnetic poles is beset with many difficulties: (1) They are in relatively inaccessible regions; (2) there is a large area over which the dip is nearly 90°; (3) they are not fixed points, but move over some tens or even hundreds of kilometers because of daily variation and magnetic storms; (4) because of local disturbance there are probably (as already stated) many magnetic poles at any particular time, so that selection of the principal poles would be difficult even if the field remained constant.

Several Arctic expeditions included attempts to locate the north magnetic pole. In 1831 Captain James Clark Ross gave its position as 70°05′ N., 96°46′ W. From observations by Captain Roald Amundsen in the vicinity of the pole in 1903–06, the position was estimated as 71° N., 96° W. Recent determinations by the Dominion Observatory of Canada provide the current information. The various estimates are sufficiently accurate to refute the old theory that the magnetic pole circles around the geographic pole in a few hundred years, for that would require a change in longitude of the order of 90° in the interval from 1831 to the present.

The earliest information regarding the position of the south magnetic pole was likewise obtained by Ross, who made the first near approach to it in 1839–40. A dip of 89°48′ was observed in 1909 by Douglas Mawson of Shackleton's expedition; from this observation he placed the magnetic pole at 72°25′ S., 155°16′ E. Observations made during the International Geophysical Year (1957–58) and the subsequent period have added much to our knowledge of the field in Antarctic regions.

The positions of eitber the north or the south magnetic pole, determined by successive investigators, should not be interpreted as a record of the movement of the poles. The changing positions are due primarily to the accumulation, especially in recent years, of more observations that permit the designation of the pole locations with much greater confidence. The positions adopted for the 1960 isogonic charts of the world are:

	Latitude	*Longitude*
North magnetic pole	74.9° N.	101.0° W.
South magnetic pole	67.1° S.	142.7° E.

[1] The principal magnetic poles can be theoretically designated even in the presence of anomaly; see S. Chapman, Notes on isomagnetic charts: IV—Geomagnetic dip-poles, their nature and that of the isomagnetic lines in their neighborhood, *Terr. Mag.*, 46, 15–26, 1941; p. 17. This paper is one of a series discussing many features of magnetic charts from a theoretical viewpoint.

Mathematical Analysis

For certain purposes it is useful to have a mathematical analysis or description of the earth's magnetic field. Spherical harmonics are well suited for this purpose, although a satisfactory treatment requires many terms—probably of the order of several score or a few hundred in number.

One of the recent analyses is Vestine's 48-term analysis of the field [38], depicting the 1945 magnetic charts.

In theory, the spherical harmonic analysis can separate the main field into portions of internal and external origin. However, the poor distribution and the weakness of the data preclude a satisfactory separation. Although early analyses have indicated an upper limit of a few percent for the externally originating portion of the field, it is generally believed by geophysicists that the true figure is probably less than 1 percent in accordance with more recent results. This small fraction, generated by currents flowing in the ionosphere and in the space beyond, is of great interest, and it is to be hoped that when the current World Magnetic Survey program (including Project Magnet of the U.S. Navy Hydrographic Office—see p. 42) is essentially complete, the data will be sufficiently extensive and accurate to yield a more reliable percentage figure.

The first-degree harmonics account for certain general aspects of the main field and represent about 80 percent of it on the average. This much of the field (namely that given by the first-degree harmonics) can be exactly duplicated by the field of a short bar magnet located at the center of the earth and properly oriented (centered dipole). Exactly the same surface result would be obtained if the magnetic moment of this bar magnet were distributed uniformly throughout the earth's spherical shape, instead of being concentrated in a centered dipole. From the analysis by Finch and Leaton [40] of the 1955 field this bar magnet would have a magnetic moment of 8.07×10^{25} cgs. units and it will be directed toward a point on the surface at 78.3° South latitude, 111.0° East longitude.

At selected points, the field of the centered dipole may differ from the main field by considerably more than 20 percent. For example, for 44° North latitude, 105° East longitude, we find chart values and centered dipole values as follows:

	D	*I*	*H*	*X*	*Y*	*Z*	*F*
	°	°	cgs	cgs	cgs	cgs	cgs
1955 world chart	2.8W	63.2	.259	.259	−.013	.509	.574
Centered dipole	1.5	51.7	.264	.263	−.007	.334	.425
Difference	1.3	11.5	−.005	−.004	−.006	.175	.149

The surface points associated with the axis of the centered dipole are called the *geomagnetic poles* (or sometimes the magnetic axis poles or poles of homogeneous magnetization). The great circles that lies 90° from the geomagnetic poles is called the *geomagnetic equator*. The *geomagnetic latitude* of a point on the earth is the angular distance of the point from the geomagnetic equator. Geomagnetic coordinates are usually reckoned on the basis of an adopted latitude of 78.5° for the geomagnetic poles.

The portion of the main field that is of internal origin decreases above the earth's surface approximately as the inverse cube of the distance from the center of the earth. In outer space—say at distances greater than 10 to 15 earth radii—the fields of external origin (interplanetary or interstellar) are preponderant.

Magnetic Charts

Our knowledge of the earth's actual magnetic field is derived directly from observations. The results of observations may be listed in tabular form, but from these the field can scarcely be visualized. Accordingly, magnetic charts are prepared which give convenient representation of the different features. On the charts, *isomagnetic lines* are drawn through places having the same value of some element. The names of these lines and of the charts which portray them are as follows: declination—*isogonic;* dip or inclination—*isoclinic;* and intensity (e.g., horizon-

tal, vertical, or total intensity)—*isodynamic*. For most parts of the earth, the data are more complete for the isogonic charts than for other charts. Isogonic charts are indispensable, since from them are derived data shown on every mariner's chart and every aeronautical chart.

Since the average strength and direction of the field change from year to year, a chart must be prepared as of a given date or "epoch." Most countries have agreed that isogonic charts shall be published at 5-year intervals, for epochs represented by years ending in "0" and "5" (for example, 1960.0, meaning the beginning of the calendar year 1960); and that the charts of other elements shall be revised at 10-year intervals, for 1955.0, 1965.0, etc.

Available data.—In some countries, the observations of magnetic declination are quite numerous, whereas in a few remote regions none at all have been made. (See p. 40.) For the United States, observations at about 10,000 points are available, with a smaller number for the other magnetic elements. Without a far greater density of observations, only general trends can be shown by the lines.

In many parts of the earth, and especially in the United States, there has been a vast amount of detailed magnetic mapping, especially of vertical intensity or total intensity, in connection with geological exploration. Such measurements have limited utility in the generalized charting program, owing to their scattered coverage and the character of the data. When a component is measured for geological purposes, the values are not usually expressed in absolute terms but are differences referred to an arbitrary zero point, so that they are not directly usable if absolute values are needed.

Construction of the charts.—The method of using observed data to prepare charts varies with the number and spacing of the observations. Usually, the more observations, the greater the irregularity they reveal. In general, the available values of the desired element are plotted on a base map and isomagnetic lines are drawn to conform best with them. It might seem desirable to draw the isomagnetic lines so that all greater values would be on one side and all lesser ones on the other. This, while always possible, is not usually desirable, since the principal purpose of the chart is to indicate the most probable values at places where no observations have been made. The problem of the magnetic cartographer is somewhat similar to that of the topographer, who has to draw his contours (lines of equal elevation) from observations at a limited number of points. His situation is even more that of the hydrographer in that both, unlike the topographer, are without information regarding the intervening region. The chief difficulty is in dealing with irregularities.

In some parts of the earth, there is little local disturbance. As discussed in greater detail on page 14, the effect of magnetic material diminishes rapidly with distance. This effect might be called a "natural smoothing process."

The amount of smoothing on a magnetic chart is determined in part by its scale and in part by the density of the observations. On the same chart the smoothing will be greater in areas of sparse data. Cartographers are not in complete agreement as to the amount of smoothing that should be done; there is no generally accepted criterion for this step [41]. There are arguments for showing on world and regional charts only that portion of the geomagnetic field that has its origin in the earth's core. The objective is to suppress fine-structured anomaly and preserve regional patterns, without injecting intermediate features of kinds that do not exist in nature.

The Coast and Geodetic Survey compiles and publishes magnetic charts of the United States on a scale of 1:5,000,000. This scale seems appropriate for showing all the detail that is warranted, in general, by the density of the observations, although in Alaska the paucity of the observations probably necessitates more smoothing than would be required by the scale of the chart alone. Many other countries issue magnetic charts on comparable scales, but with more or less smoothing.

The various maritime nations issue single-sheet world magnetic charts on a scale averaging perhaps 1:40,000,000. Their principal use is for ocean and air navigation.

Figures 2, 3, 4, and 39 are small reproductions of various magnetic charts, redrawn with much

of the detail of the base map omitted. In figures 2 and 3, many of the isomagnetic lines have also been omitted. Figure 39 is a simplified copy of the 1960 isogonic chart of the United States. The full-size chart is printed at a scale of 1:5,000,000.

Since world magnetic charts are ordinarily presented on Mercator projections, it is necessary to show the polar regions on separate polar projections, as is done for the world charts published by the United States. The American world charts are compiled by the Coast and Geodetic Survey in callaboration with the U.S. Navy Hydrographic Office (and, in the case of the 1960 isogonic chart, in consultation with the Royal Greenwich Observatory of Great Britain), and are published and distributed by the Hydrographic Office. The somewhat limited number of observations in the polar regions is currently being augmented by several magnetic survey operations.

Because of the limited number of observations in the region within 20° of the North Pole and within 30° of the South Pole, the lines for large parts of these regions are still somewhat conjectural.

Of course all isogonic lines necessarily converge at the geographic poles and at the magnetic poles. This is shown in figure 4, and is explained by Chree in reference [42].

Interpretation of the charts.—A value scaled from a chart is strictly valid only for the year given as the epoch of that chart, but it may be reduced to another date by applying a correction for secular change. (See p. 16.) Many charts contain an auxiliary set of lines of equal annual change (called *isopors*) which may be used for this purpose if the desired date is within a few years before or after the epoch of the chart. If the desired date is a considerable number of years earlier than the epoch of the chart, the reduction should be made by using secular-change tables prepared for the purpose.

A value obtained from a chart is to be considered as the mean for several days, with the daily variation and irregular fluctuations averaged out.

A chart value is not, in general, the actual value at the point of observation, but differs therefrom because of the effect of local disturbance. Rather, it may be considered as the *normal value* for the point, which is approximately equal to the mean for a fair-sized region centered at the point. For the United States, there is perhaps an even chance that a value of declination scaled from the chart issued by the Coast and Geodetic Survey will be within one-half degree of the actual value. At some points the true value and the chart value differ by many degrees.

The accuracy of values obtained from a chart may be judged somewhat by the agreement between chart and observations in the region. Where the observed values differ markedly from the values scaled from the chart, the region is disturbed to the amount of the differences or even more. One should remember that there may be local disturbance where none is indicated by surrounding stations, and also that an anomalous observed value may be due to a disturbed area of very limited extent; but in general the difference between chart and observations in any region is a fair guide to the reliability of a chart value in that region.

Local Magnetic Disturbance

Almost everywhere, the earth's magnetic field differs from the regular pattern indicated by the ordinary isomagnetic chart, to a greater or less extent, because of magnetic material in the earth's crust. (These differences are of a different sort from those due to man-made structures.) Although these irregularities are not uncommon, it is customary to speak of them as *local disturbance* or *local anomaly*, or as departure from normal values. In many regions the anomalies in declination are probably less than a quarter of a degree over considerable areas, but in other regions they are known to be much larger.

Areas of marked local disturbance are found in many parts of the earth. In southeastern Alaska, there are large disturbed areas in Lynn Canal and near Dixon Entrance, and there are probably local magnetic poles at Port Snettisham and near Juneau.

There are many disturbed volcanic areas

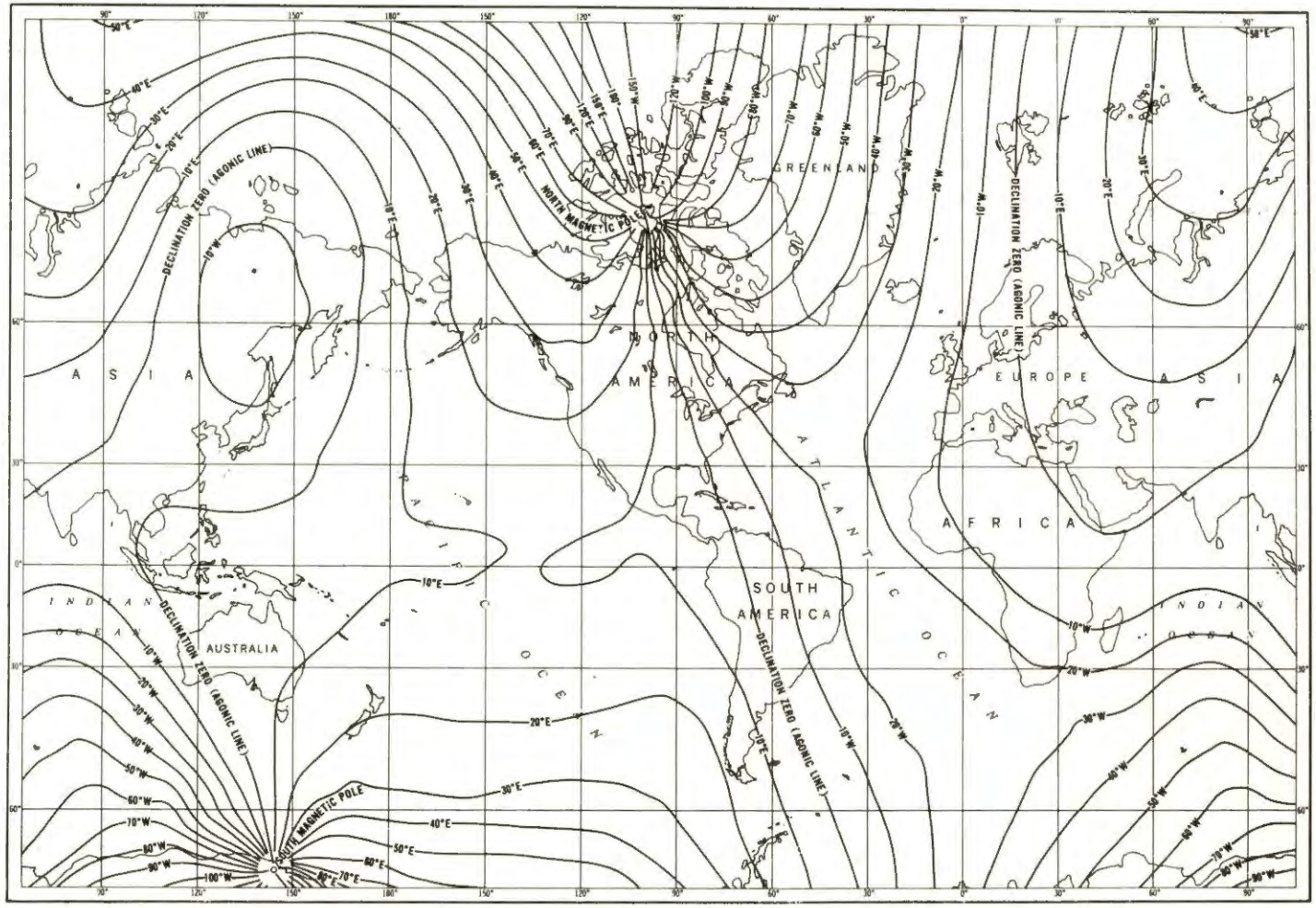

Figure 2.—Simplified isogonic chart of the entire world except polar regions, for 1955. Mercator projection. (Derived from U.S. Navy Hydrographic Office Chart 1706.) For the north polar regions see figure 4.

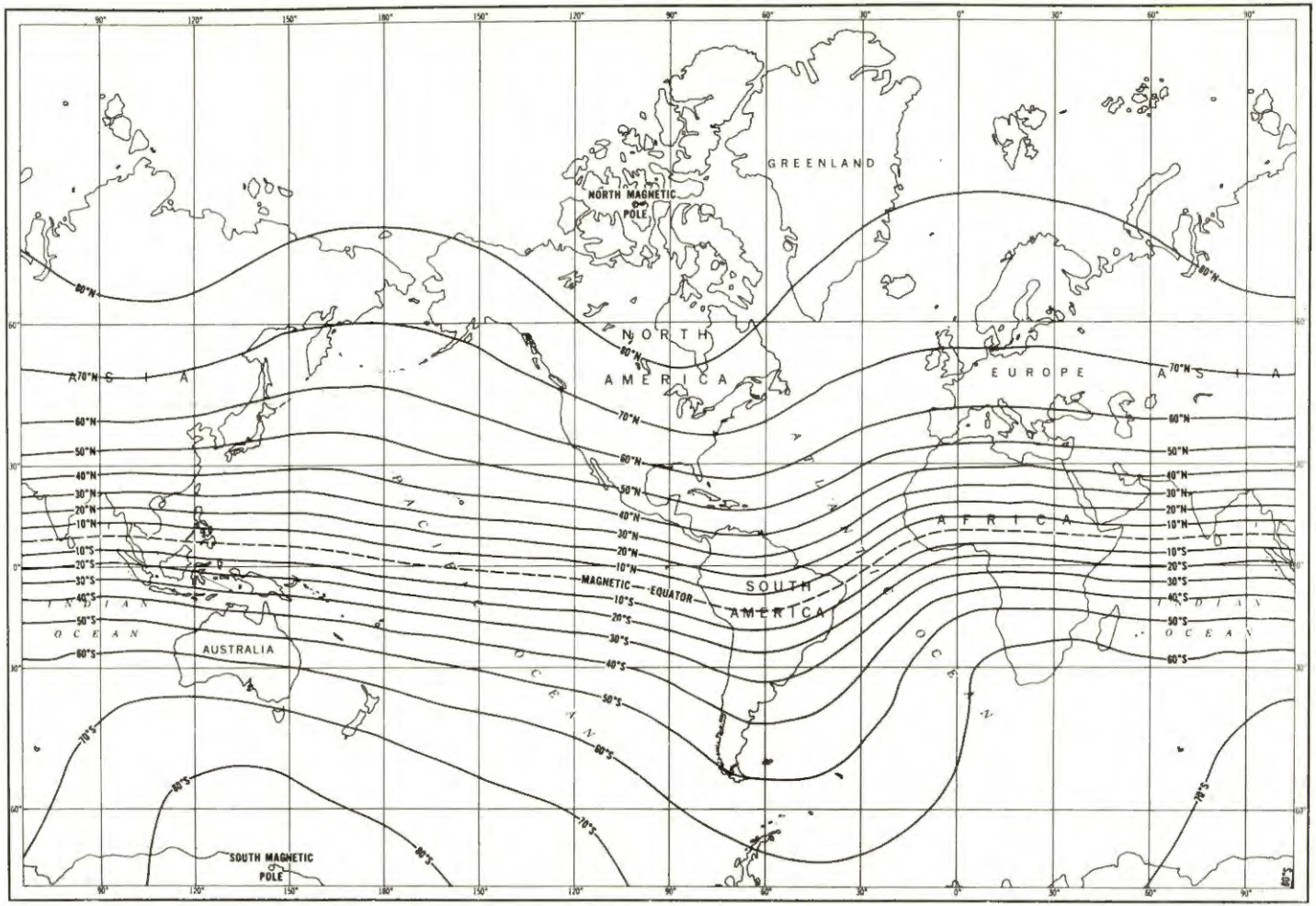

Figure 3.—Simplified isoclinic chart of the entire world except polar regions, for 1955. Mercator projection. (Derived from U.S. Navy Hydrographic Office Chart 1700.) North of the magnetic equator, the north end of the dip needle dips below the horizontal; south of the magnetic equator, the south end dips.

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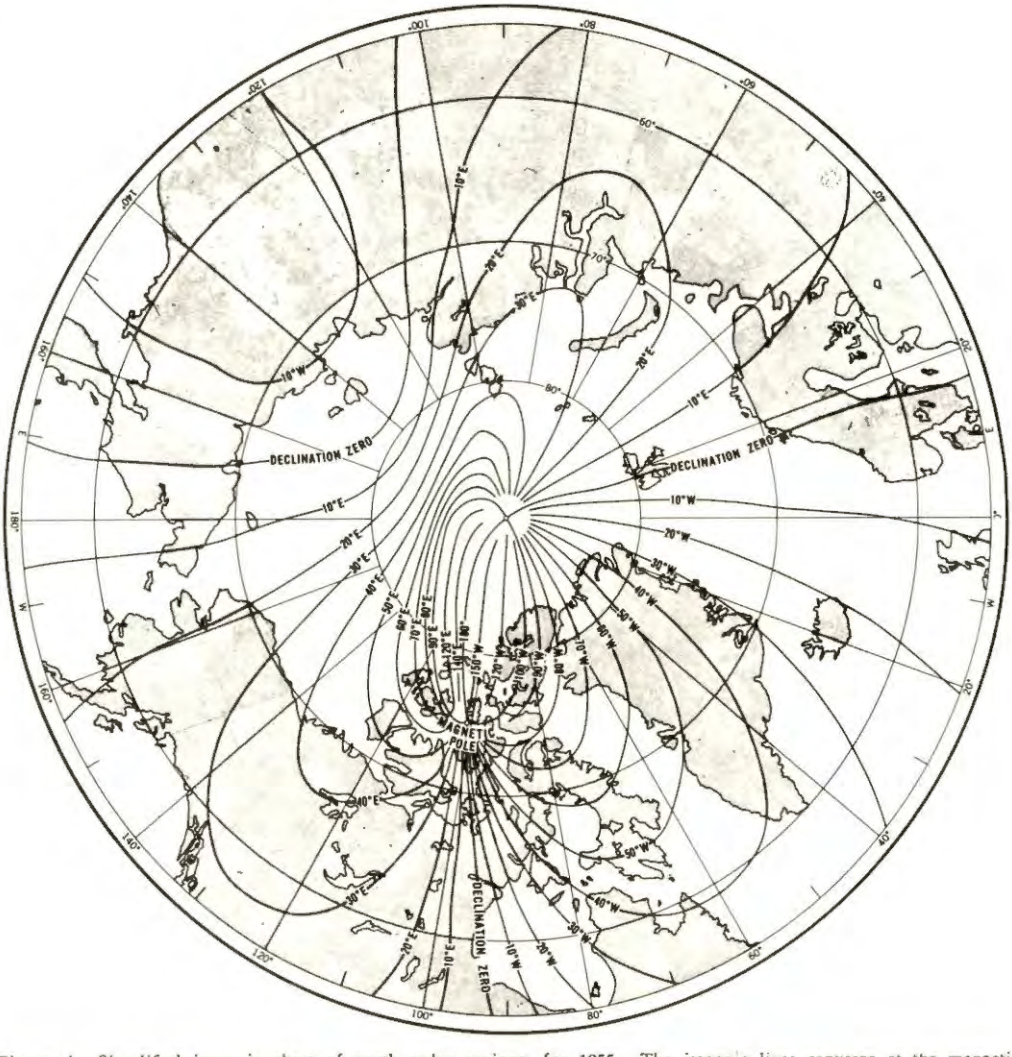

Figure 4.—Simplified isogonic chart of north polar regions, for 1955. The isogonic lines converge at the magnetic poles as well as at the geographic poles.

throughout the world and special mention should be made of the lava flows of Washington, Oregon, and other States. In Europe, the disturbed areas are well known and the following are worthy of special note: (1) The Kursk anomaly in the Soviet Union, extending 270 km in a northwest-southeast direction, the greatest known disturbed area anywhere; (2) an anomaly in Lapland (northern Sweden); (3) one in the Baltic Sea west of Finland, which is claimed to have caused many shipwrecks. There are important anomalies in South Africa in the mineralized regions. Probably because of the wide spacing of observations, little is known about important disturbed areas in Asia and South America. There are examples in New Zealand and the Antarctic Continent.

Since the effect of magnetic material decreases rapidly with increasing distance, magnetic anomalies are attenuated with altitude. This effect is most marked for the fine-structured constituents of the anomaly pattern. A similar attenuation is produced when a volcanic island has a thick bed of coral at its surface (the volcanic material is magnetic but the coral is not) or when the magnetic material is at the bottom of the

sea. In the polar regions, thick ice sheets should have a similar effect.

The area near Port Snettisham in Alaska has been investigated on land and sea, and in the air as well (by an observer of the Coast and Geodetic Survey in an aircraft of the U.S. Navy). Though there is probably a local magnetic pole on the land, it has not been located. At a point where the water is 100 meters deep, the surface anomaly is 30° in declination. It is about 15° at an altitude of 300 meters, and is still detectable at 1,000 meters.

Whenever a requirement exists for precise and accurate knowledge of the earth's magnetic field at a specified point on the surface, observations must be made at precisely that point. Values derived by scaling from a magnetic chart cannot be certified with absolute assurance, but are stated to be estimates subject to a specified probable error. The scaled value, as stated earlier, represents a mean value for a fair-sized region (perhaps several tens of square miles) centered at the point.

Artificial disturbance.—Whenever magnetic observations are being made for any purpose, the possibility of artificial magnetic disturbance should constantly be borne in mind. Any iron or steel or direct-current electrical circuits near the instrument will have an effect, the magnitude of the effect diminishing rather rapidly with increasing distance.

At sea, the iron of a ship is a source of artificial magnetic disturbance. However, means have been found to compensate for the effect on the compass.

On land, there may be iron in buildings, fences, or buried pipes. Electric currents may be encountered in all sorts of installations. Fortunately, alternating currents have no perceptible effect on the ordinary compass, since the direction of the resulting magnetic field changes so rapidly that the compass cannot respond to it. However, powerlines are often supported by steel towers large enough to have considerable effect. The most troublesome source of artificial disturbance is a direct-current electric railway using grounded rails for the return current, since the leakage current may affect sensitive instruments located several kilometers from the railway. For ordinary compass surveys, it is considered that 500 meters from such a railway is sufficient. (See also pp. 40, 41.)

Geophysical explorations by magnetic methods.—The existence of local disturbance is an obstacle which limits the usefulness of the earth's magnetism for showing direction. Local disturbance is not, however, to be thought of solely as an inconvenient obstacle; the study of such irregularities has led to the finding of important natural resources such as oil and minerals buried beneath the surface, which are often associated with geological formations that can be traced by magnetic methods. There are other kinds of geophysical exploration, such as seismic investigation and the study of irregularities in gravity and in electrical conductivity. The magnetic measurements are easier to make than some of the others, but in many cases the interpretation is more difficult. Correct interpretation often requires the judicious use of several methods.

An example of magnetic prospecting in the early days is described in the following passage [43]:

> The discovery of iron in Michigan was made by William A. Burt, Deputy U.S. Surveyor, who in the spring of 1844, while running special township lines, observed by means of the solar compass remarkable variations in the direction of the needle of his instrument, amounting to as much as 87 degrees from the normal. Ascribing this to the occurrence of iron ore, he sought and found it in the ridges and outcrop at several points.

In addition to surveys made directly for the purpose of locating oil and minerals, various surveys have been made to get a better understanding of the broad features of the earth's structure without regard to direct economic results. For example, magnetic studies of active volcanoes have been based on the change of magnetism of the lava with change of temperature.

Since all these surveys are made primarily for geological purposes, only differences are needed, and relative methods suffice.

In the earlier years of this work magnetic "field balances" were used to measure differences in the vertical component of the field. With the development of magnetometers responding to the changes of total field, requiring no orientation with respect to either horizontal or vertical ref-

erences, measurements could be made much more quickly; indeed, most of the magnetic exploration work is now done with aircraft. Maps are drawn showing patterns developed in the observations, whether in terms of actual values of a magnetic element or of differences from the value at an arbitrarily selected base station. Since, however, the normal change of vertical or total intensity with position would tend to distort the irregularities, it is customary to apply "latitude and longitude corrections" proportional to the distance from the hase station, derived in a somewhat arhitrary way. Often, the corrections are derived by scaling the approximate rate at which vertical intensity changes with latitude or longitude on an isodynamic chart. However, surveys made by different organizations ordinarily use somewhat different corrections; as a result, such surveys cannot he joined together.

Secular Change

The secular change, unlike the transient variations to be considered in chapter III, partakes largely of the character of the main field itself. For example, the underlying causes are obscure, and are believed to lie within the earth (see p. 20); also, the distribution of secular change, like that of the main field, is characterized by complex regional features, which must be charted to serve the everyday needs of navigation by sea and air.

To determine the course of secular change, observations must be repeated in precisely the same places at regular intervals. These repeat observations are the basis of the isopors or lines of equal annual change. (See p. 11.) The effect of magnetic anomaly on the secular change has not heen investigated thoroughly, but the available data indicate that the secular change is about the same in moderately disturbed localities as in nearby undisturbed areas.

The change is not uniform from year to year, though in general there are definite trends. However, over a long period the change does not go indefinitely in one direction; eventually a turning point is reached. The secular change of declination at a number of typical locations is shown in figure 5. It will be seen that at London the declination was 11° East in 1580, and 24° West in 1810, a change of 35° in 230 years. At one time, this was thought to indicate that it varied in cycles with a period of 460 years; but it is now known that the actual phenomenon is much more complicated. In some cases, there has been a reversal in direction of change for a few years, and then resumption of the original direction of change.

A serial compilation of observatory results [44] shows the values of seven magnetic elements, tahulated by years. See also reference [45].

Figure 5 includes the trend of declination for one point in the United States. Further details on this subject, including tables intended for the actual use of surveyors and others who desire to know the secular change, are published by the Coast and Geodetic Survey in Publication 40–2 [46].

The secular change of dip has the same general character as does that of the magnetic declination. From Norman's value (p. 69) of 71°50′ in 1576, the dip at London increased to about 74°30′ in 1700, and since then has heen decreasing until it is now less than 67°. The earliest determination of the dip in the United States was made by Capt. Othniel Beal at Boston in 1722, 68°22′. From that time it increased to over 74° in 1860, then decreased to 73° in 1905, and then began to increase. In 1940 it again began to decrease.

Figure 6 shows the combined secular change of declination and dip at a nnmber of points. Each curve shows the path of the lower end of an imaginary needle beld above the page and free to orient itself in the earth's field.

Our information about secular change of intensity is much less extensive than that for declination and dip. No method of making absolute measurements of intensity was known until 1830, and there have always been in most countries more observations of declination than of intensity.

Heretofore tbe determinations of the rates of change of vertical intensity and total intensity have been particularly unsatisfactory. A value of F or Z was usually ohtained by combining

Figure 5.—Curves showing approximate secular change of magnetic declination at selected points.

values of H and I; hence F and Z were less accurately determined than were H and I (since they were subject to error from both of these elements), and these errors in turn produced considerable uncertainty in the secular change of Z and F. During the past few years, however, the development of the proton-precession magnetometer has provided the magnetic observer with an instrument of high precision for the direct measurement of F. In the future, therefore, it is probable that the accuracy of determination of secular change of the intensity of the field and its components will be limited more by the uncertainty of correcting the individual observations for daily variation (time disturbance) of the field than by lack of precision of the measuring instrument.

At most places the rate of secular change varies somewhat; the detailed changes from year to year are seldom known, except at magnetic observatories. The expedient adopted for other places is to determine the rate of change from observations at intervals usually related to the frequency with which magnetic charts of a region are issued. An ideal situation was that in Denmark, where observations were made within a period of a few weeks at eight uniformly distributed stations, and repeated on a similar schedule every 5 years. In larger areas such as the United States, the observations to determine change must be spread over several years; since the rate of change is constantly changing, careful study is required to interpret such observations.

Foci.—The lines of equal annual change are interesting when plotted on a world map. For much of the earth the changes are small. In some places the isopors form closed curves known as isoporic foci whose maximum (in declination) may be as much as 15 minutes of arc per year.

At present, the principal isoporic foci are over the continents and the Atlantic and Indian Oceans, whereas those over the Pacific Ocean are unimportant. The location of each focus constantly changes, as does the maximum amount of change which it represents. The most striking illustration of this is found in South Africa and the Indian Ocean. At the magnetic observatory at Tananarive, Madagascar, the rate of change

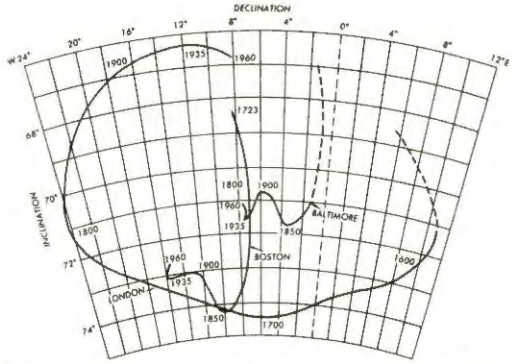

Figure 6.—Secular change of magnetic declination and dip at London, Boston, and Baltimore. Each curve represents approximately the motion of the lower end of a perfectly balanced needle.

of declination in 1911 was about +11′ per year; in 1938 it was about −11′ per year. At the earlier date, there was a positive focus in the region of Madagascar, and a negative one in the Indian Ocean. But both of these foci underwent rapid changes; on the later date the negative one was centered near Madagascar, and the positive focus had apparently subsided.

Figures 7 and 8 show the change in the position of the zero *D*-isopor in the United States. In general, the north end of the compass was moving to the westward on the northeasterly side of the line, and to the eastward on the southwesterly side. For 1940 and for 1950 there are two branches of the line. For 1955 there is a loop centered in Pennsylvania and a branch crossing northern Maine. It may be noted that figures 7 and 8 involve only minor isoporic foci, since there are no major foci in the vicinity of the United States.

One surprising result of the study of secular change is the conclusion that over a long interval the earth's magnetic moment was decreasing at a rate of perhaps one-fifteenth percent per year. If such a rate continued, it would mean that the moment would be reduced to half its value every thousand years. This would require incredibly large intensities in even recent geological eras. It therefore appears that either the rate of decrease during the last hundred years must be greater than the rate existing in past centuries, or else there must be some method by which the earth can be remagnetized, some other form of internal energy being transformed into magnetic energy. There is some indication that a minimum in the earth's magnetic moment was reached about 1935–40.

This change of magnetic moment is not the same as the regional changes in intensity previously discussed. In some regions the intensity is increasing while in others it is decreasing. The change of moment refers to the general average, over the whole earth, of all these trends.

Paleomagnetism.—Actual observations of the earth's magnetism cover a period of a few hundred years at most, and for most of the earth they are confined to a much shorter interval. However, there are several methods of obtaining very approximate secular-change data for longer periods.

One method is based on the hypotheses that lava has a Curie point above which it is nonmagnetic (see p. 4), that as it cools it is magnetized by induction from the earth's existing field, and that it is not thereafter affected by changes in the earth's field. The direction of the magnetic axis of a piece of the lava can be determined by suitable measurements, and the difference between that direction and the present direction of the earth's field is then to be taken as resulting from secular change. However, even if the original hypotheses were correct, it is quite possible that the lava may not lie in its original position, in which case incorrect results would be obtained. Some experiments using this method have not proved conclusive. In any case, no accurate time scale or rate of change can be determined.

Another method is based on the fact that sedimentary deposits usually form slowly, the individual particles, if magnetized, orienting themselves in the direction of the earth's field as they settle. Vertical samples from the sea bottom, 6 to 10 feet in length, have been examined by special devices and the magnetization was found to change direction in different parts of the column. There is a possibility that currents and eddies may affect the direction taken by the particles. Only estimates can be made about long periods of time as nothing is known about the actual rate of sedimentation corresponding to any given small section of the column.

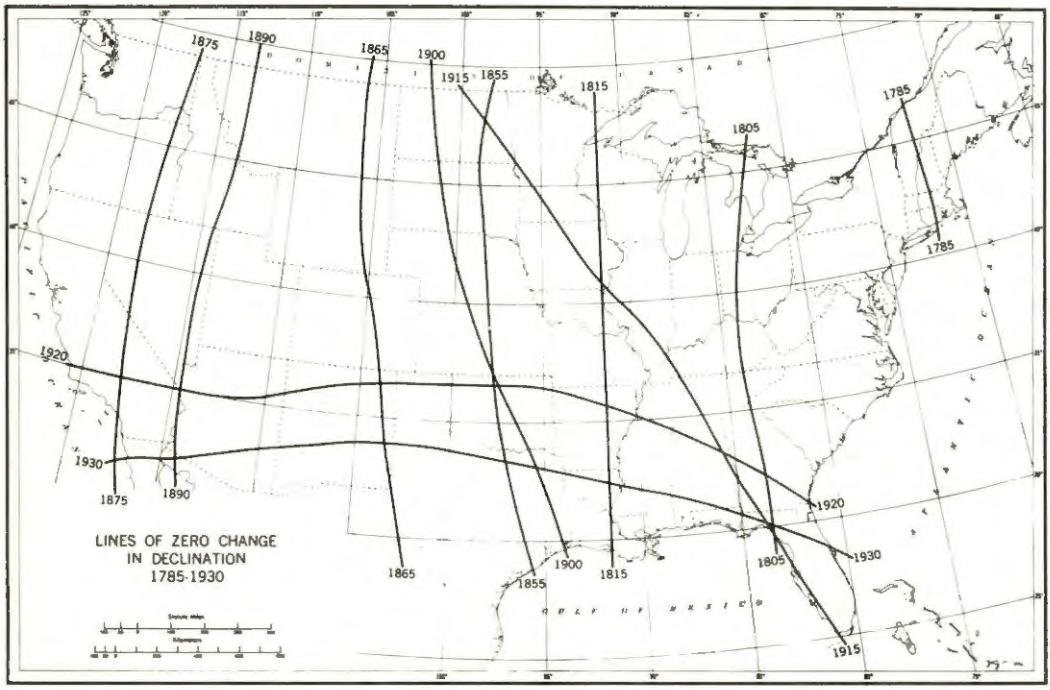

Figure 7.—Positions of the line along which annual change of magnetic declination in the United States was zero, at various epochs from 1785 to 1930.

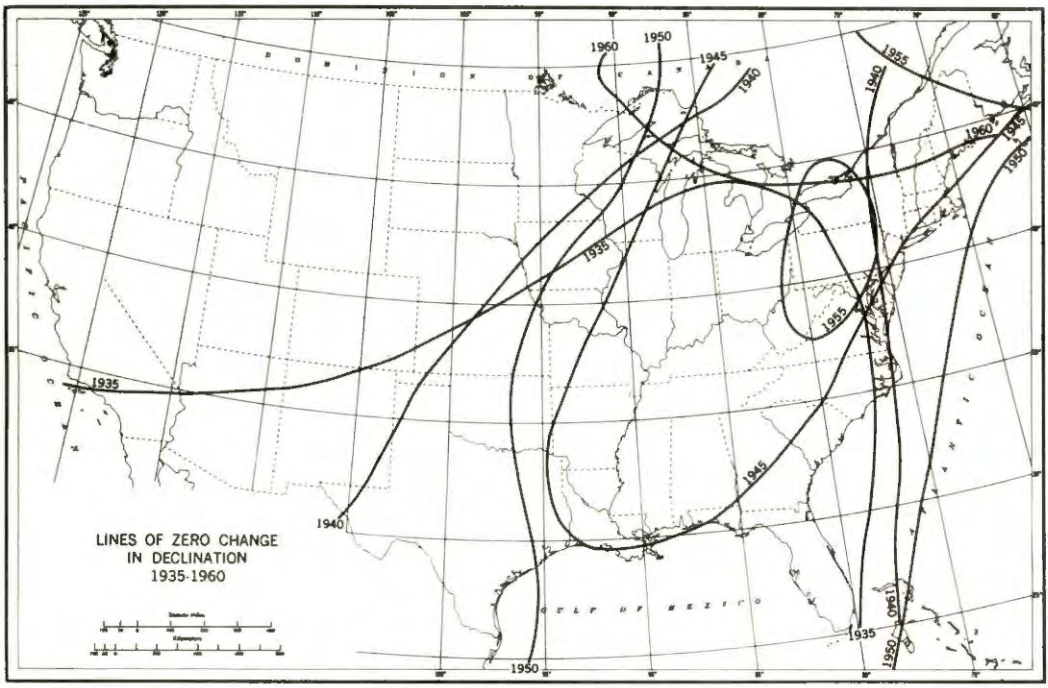

Figure 8.—Positions of the line along which annual change of magnetic declination in the United States was zero, at various epochs from 1935 to 1960.

A related method for estimating magnetic changes for long periods of time is that of examining varves (annual deposits of ancient lakes which have disappeared). The principle is the same as that for the sea deposits, but the results are more promising since there is less likelihood that currents have influenced the orientation of the particles. The varves are identified by variations in type of sediment throughout a year, as shown by Antevs, so that time intervals can he recognized, though the relation to the present time is lacking. The specimens can be oriented to true north; hence the directions of magnetization yield declination as of an unknown date. The actual curves are very similar to those in figure 5, and the results seem to have real significance; i.e., that the changes over a given period are of the order of magnitude of the changes observed in modern times.

The broad results of paleomagnetic investigations are very surprising. There is somewhat inconclusive evidence of geologically frequent reversals in the polarity of the geomagnetic field. There has been a slow wander in the mean direction of magnetization through geological time. Efforts to correlate such data from widely separated sites have been numerous. The results may be interpreted in support of the idea that relative to the axis of rotation in space, there must have been movement of the earth or its crust as a whole (hypothesis of polar wandering) and that superimposed on this polar wandering there may have been relative movement between the continents (theory of continental drift).

Origin of the Main Field and of the Secular Change

Various hypotheses have been proposed to explain the existence of the earth's main field and its secular change. It is known that the source is almost entirely internal. Gilbert, who was the first to visualize the field as a whole, conceived the earth as a great spherical body, uniformly magnetized. Other proposals have invoked a wide variety of mechanisms: motions of static charges carried around by the earth's spin; alignment of atomic magnets by gyroscopic action; electrical currents maintained by self-induction, hy thermoelectric forces, or by self-exciting dynamo action. The main-field theory of greatest current interest and promise is the self-exciting dynamo theory first proposed by Larmor to explain the sun's magnetic field. The dynamo action would take place in the earth's fluid core [47]. Secular variation is thought to result from motion of material near the surface of the core relative to the mantle, but a fully satisfactory theory is still lacking.

The main field and the secular-change field can each be described in terms of a small number of discrete sources situated on or heneath the boundary of the earth's core. There may be some correlation between the two sets of sources; there is some evidence that the secular variation is due in part to a westward drift of that portion of the main-field source structure that produces the regional anomalies [48].

Chapter III. Transient Variations of the Earth's Magnetic Field

The major portion of the transient variations of the earth's magnetism may be regarded as the culmination of events on a wider stage, the immediate "cause" being a complex of changing currents in the ionosphere and beyond. A smaller part of the transients, perhaps one-fourth to one-third, stems from internal currents induced by the variation of the external currents. The transients are definitely known to be associated with solar effects and with conditions in the ionosphere. This association leads to important relations with radio communication, which in turn throw new light on magnetic problems. It is known also that a very complex relationship exists between the magnetic field and other geophysical phenomena; many investigators are intensively studying earth currents, cosmic rays, auroras, radiation trapped in the Van Allen radiation belts, and effects of the earth's magnetic field on artificial satellites.

Daily Variations

Although the daily variation differs from day to day, it is capable of being associated with a reasonable cause more readily than is any other feature of the earth's magnetism. It is a phenomenon depending primarily upon local time—that is, upon the hour angles of the sun and moon. The lunar daily variation is much smaller than the solar daily variation.

Description of the Solar Daily Variation

The cycle of changes is not simultaneous for different longitudes, but each phase of the cycle in turn traverses the globe from east to west, leading or lagging the sun by a nearly constant time interval. The main features of the variation occur during the daytime. During the night, there is usually little departure from the mean of the day.

The mean daily variation varies much throughout the earth, as shown in figures 9–12 for four of the well-distributed observatories of the Coast and Geodetic Survey. It must be borne in mind that these curves are based on days selected because of their freedom from storms. They represent the average of a large number of days, so that minor irregularities are ironed out. The difference between extreme values on these curves is somewhat less than the average of the ranges on individual days, because even on quiet days the times of the extremes may vary as much as two hours.

There are important differences in the character of the daily variation from one station to another. The reasons for some of these disparities are still obscure. Furthermore, both in amplitude and in shape the actual curves undergo seemingly fortuitous changes from day to day, so that average curves are hardly ever valid for specific dates.

The amplitude of the daily variation, even for quiet days, is substantially larger during periods of maximum sunspots than during sunspot minima. It should also be noted that on many days there is superimposed on the quiet-day daily variation a greater or less amount of the disturbance-daily variation, discussed on page 31.

Figure 13 is a reproduction of a standard magnetogram for a quiet day, and figure 14 for a magnetic storm (p. 27). Figure 15 shows a rapid-run magnetogram (p. 53) for a moderately disturbed day.

Declination.—In northern latitudes the daily variation of declination is characterized by an easterly motion of the north end of the needle in the morning, with an easterly extreme about 8 or 9 a.m., local time; then a westerly motion, with a westerly extreme about 1 or 2 p.m.; then an easterly motion for 4 or 5 hours. From dusk to the early morning there is little change.

The daily range is greater in summer than in

winter, and greater in high latitudes than toward the Equator. It should be noted, however, that for the winter months the daily range is about the same at Sitka as at Honolulu, and less than at the intermediate stations.

In the Southern Hemisphere conditions are reversed. The westerly extreme occurs in the morning and the easterly extreme in the afternoon. The greatest amplitude occurs in the southern summer; i.e., in December.

A portion of the Tropics constitutes an inversion zone, in which the northern type of daily variation predominates in June and the southern type in December [49].

The practical significance of the daily variation of declination may be seen from the following example: In the United States in summer the north end of the compass needle points on the average about 10′ more to the west at 1 p.m. than it does at 8 a.m. Consequently a line 1,000 feet long run by compass at the time of the westerly extreme would have its terminal point 2.9 feet to the left of a line of the same length run from the same starting point at the time of the easterly extreme.

Horizontal intensity.—The daily variation of horizontal intensity has the same general characteristics in the Northern and Southern Hemispheres, but they vary according to latitude. At stations within 25° or 30° of the Equator, the predominant feature is a pronounced maximum shortly before noon without a well-defined minimum. From about latitude 40° to high latitudes the predominant feature is a pronounced minimum shortly before noon. Between, there is a transition belt, where the range is smaller and the variation less regular, sometimes with two maxima and two minima. This difference is clearly shown by the curves for Sitka, Tucson, and Honolulu, in figure 11. Tucson is in the transition belt, and the form of the curve is quite different for different times of the year and even for successive days. Since the average curve is derived from days of different type, the Tucson curves do not represent a single type.

Dip.—The daily variation of dip is of the same general character as that of horizontal intensity, but with a maximum where H has a minimum, and vice versa. There is a predominant maximum or minimum shortly before noon, except in the transition belt.

Total intensity.—There is a predominant minimum about noon at Tucson as well as at Cheltenham, Md., and at Sitka. At Honolulu and at San Juan the range is small, and the phases are less pronounced and are different for different times of the year.

Daily variation near the Equator.—An outstanding phenomenon of the daily variation is found in a narrow belt, no more than 2 or 3 degrees of latitude in width, approximately centered on the magnetic dip equator. At the center of the belt the daily range of horizontal intensity is nearly 3 times as large as the range at points no more than 300 miles north or south. This abnormal daily range in H, as well as a midday enhancement of minor disturbances in D, Z, and H, is ascribed to a current called the *equatorial electrojet.*

Description of the Lunar Daily Variation

The variation which depends upon the hour angle of the moon is known as the lunar daily variation. In most cases it is very small (of the order of 2 gammas or less) and can be detected only by statistical analysis of observations covering many months or years.

Unlike the solar daily variation, it undergoes a progressive change in character throughout the lunar month, in a regular relation with the moon's phases. Like the solar daily variation, it shows abnormal amplitude at stations along the magnetic equator.

Theory of the Daily Variation

It is known from spherical harmonic analyses of the daily variation that some two-thirds to three-fourths of it is due to causes outside the earth. The sun is too far away to have a direct magnetic effect, and it has been found that the most reasonable cause is a system of electric currents in the ionosphere. The changes in these

external currents induce currents within the earth, furnishing the internal source for the remaining portion of the daily variation.

A current system that has been worked out for an average day is shown in figure 16. In the Northern Hemisphere, the flow of current is counterclockwise (as viewed from above) over the daylight portion of the earth. The average current system remains fixed with respect to the line joining the earth and the sun, while the earth rotates beneath it. The actual current system, of course, fluctuates from day to day and from hour to hour.

The height of the currents cannot be determined solely by study of the earth's magnetism. For data on that point, we must turn to research connected with radio.

Ionosphere.—Long-distance radio transmission is dependent upon ionization of the upper air; the ionization must be such that there will be layers which bend the radio waves back to earth, somewhat as a mirror reflects light. The waves proceed by successive reflections back and forth between the ionosphere and the earth. The ionization is caused by X-rays and ultraviolet light from the sun, much of the energy being absorbed in this process so that it does not reach the earth. The currents which cause daily variation are due to motion of the ions.

The existence of electric currents above the earth was suspected as long ago as 1832, when Faraday suggested them as a cause of auroras. Overhead currents were suggested as the cause of the magnetic variations by several persons, including G. A. Rowell, W. A. Norton, and Balfour Stewart; of these, only Stewart explained the generation of the current by a mechanism that won acceptance (see below). In 1902 A. E. Kennelly in the United States and O. Heaviside in Great Britain independently proposed a reflecting layer to explain the transmission of radio signals across the Atlantic. Their hypothesis was supported by various subseqnent experiments, and this envelope came to be known as the *Kennelly-Heaviside layer.* It was then found that there were two or more layers; these are known collectively as the "ionosphere."

The ionosphere is now regularly investigated at various observatories by sending brief radio signals directly upward and recording the interval between outgoing signals and their echoes as returned after reflection. These intervals are very short, since the waves travel with approximately the speed of light (300,000 km per second) until they reach the ionosphere, where they are reflected. The altitude at which the wave is reflected depends on the frequency of the wave and on the electron density. As the frequency increases the necessary density is greater; hence, the wave must go farther before reflection, and the time interval between impulse and echo is greater. But this interval does not increase steadily with frequency; rather, at certain frequencies, there is an abrupt increase in the time interval. This indicates that there are several different layers or regions of ionization so that a wave which penetrates the lower region continues until it reaches a region with sufficient electron density to cause reflection. If the radio frequency is high enough, the signal will not be reflected.

Recent rapid advances in space exploration by rocket and satellite have added much to our knowledge of the ionosphere. However, there is much that is still obscure [56].

The approximate heights of the principal regions, with their identifying letters, are as follows:

D region:	65–85 km
E region:	85–140 km
F_1 region:	140–200 km
F_2 region:	200–1300 km

All these heights are quite variable. At night the F_1 and F_2 regions join and the D region practically disappears. During magnetic storms a region may be completely broken up and give no reflection at all.

The above description applies to the region between 40° South and 40° North; in the polar regions, conditions are more complex.

Tides in the ionosphere.—The ionosphere is subject to tides that are somewhat analogous to those in the sea, but with important differences. The gravitational tide-producing force of the moon is about twice that of the sun; however, the lunar atmospheric tide is only one-fifteenth as great as the solar atmospheric tide.

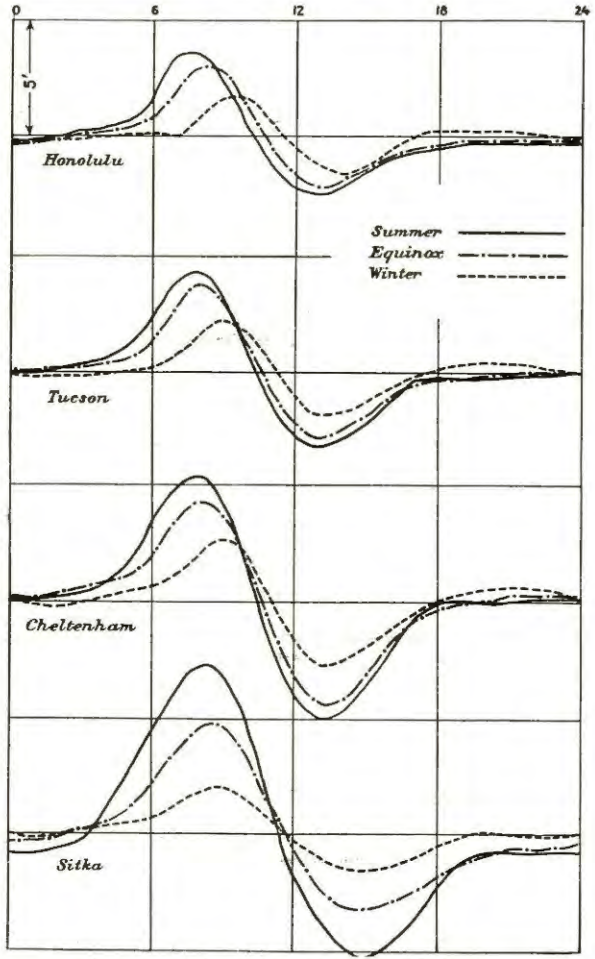

Figure 9.—Daily variation of magnetic declination.

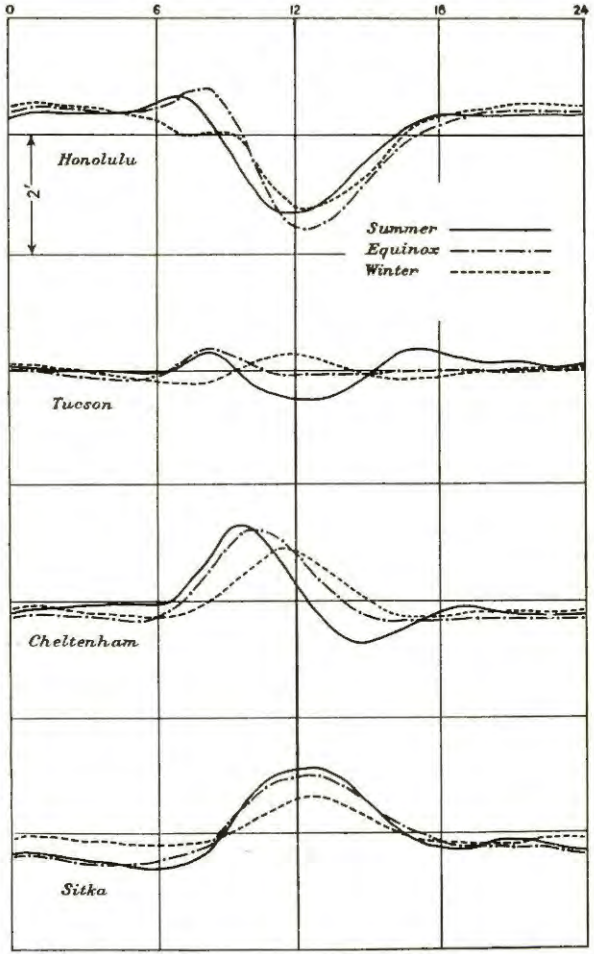

Figure 10.—Daily variation of inclination (dip).

In figures 9–12, each curve shows the average variation for a large number of magnetically quiet days, for the observatory, season, and magnetic element specified. The time is local mean time: 0=midnight; 6=6 a.m.; 12=noon; 18=6 p.m.; 24=midnight. For some of the Tucson (Arizona) curves, the quiet days are of two distinct types, and the mean does not well represent either type. The geomagnetic latitudes of the four observatories are: Honolulu, 21°; Tucson, 40°; Chltenham, 50°; Sitka, 60°. The curves are based on data in reference [19], tables 8–11.

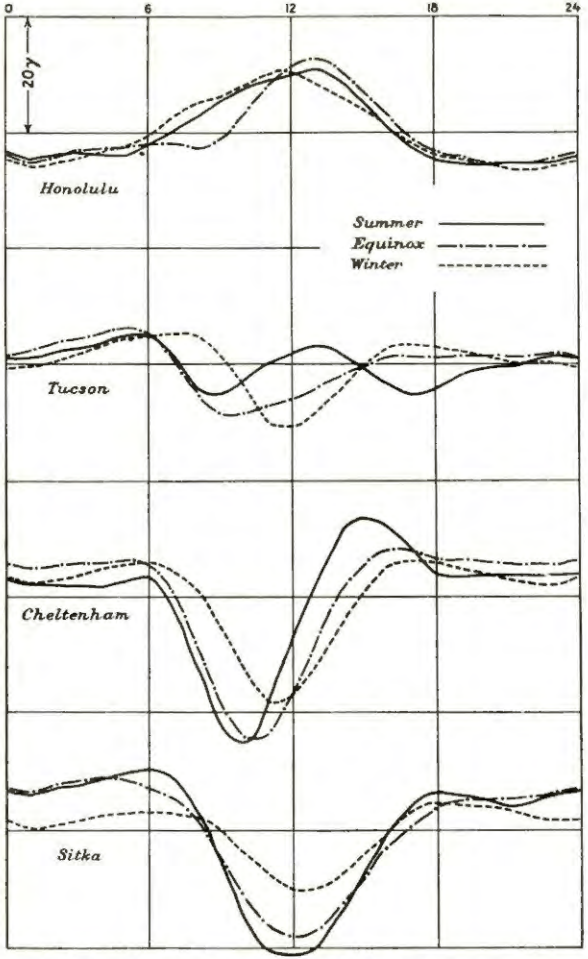

Figure 11.—Daily variation of horizontal intensity.

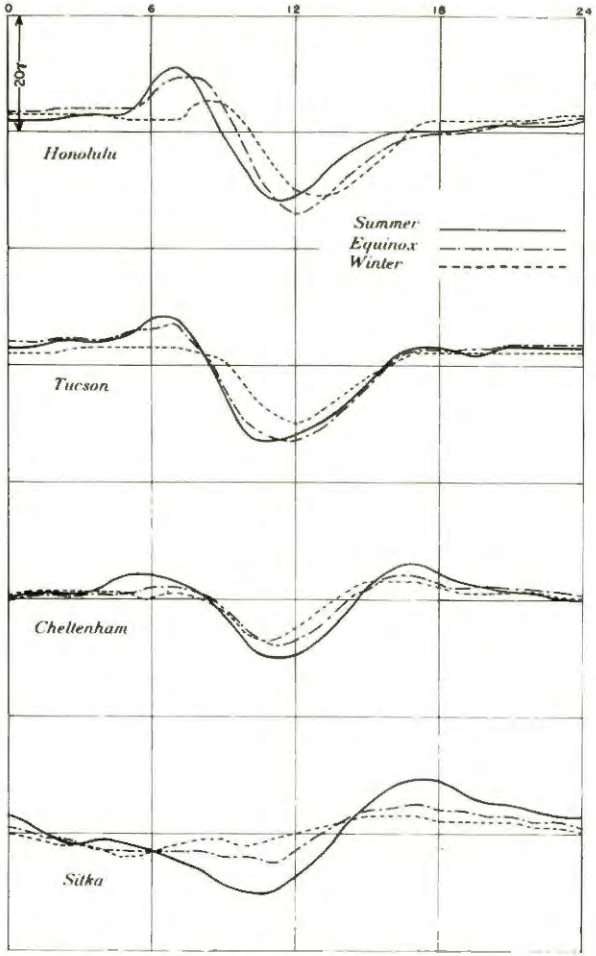

Figure 12.—Daily variation of vertical intensity.

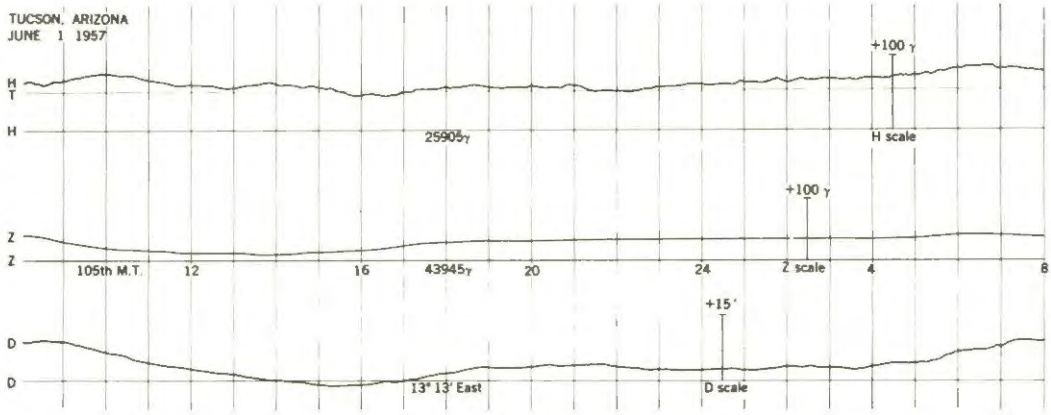

Figure 13.—Magnetogram for a magnetically quiet day.

It is believed that the difference results from the enhancement of the solar semidiurnal tide by resonance. Solar heating of the atmosphere also plays a part in producing the ionospheric tides.

Stewart-Schuster dynamo theory.—Since the ionosphere contains free ions, it behaves somewhat like an electrical conductor. When a conductor moves across a magnetic field, effects are produced which may give rise to electric currents (p. 5); likewise, when, for any reason, the ions of the ionosphere move, the earth's magnetic field deflects them from their initial course, and the result may be equivalent to an electric current, producing for example the daily-variation magnetic field.

This dynamo action is the essence of the theory advanced by Balfour Stewart in 1882 to explain the magnetic solar daily variation. The required primary motion of the ions is ascribed to mass tidal and heating action, with resonance, the geomagnetic effect being attributed to resulting current systems in regions of shorter free paths—say below 100 km. The currents are chiefly generated by horizontal motions across the vertical component of the magnetic field. This theory, first put in quantitative form by Arthur Schuster, is accepted as the explanation of most of the solar daily variation and is the basis of the current system shown in figure 16. The lunar daily variation is explained in the same way.

On this theory small increments in conductivity of the ionosphere, such as occur during solar flares, primarily enhance the already flowing current. The magnetic effect observed on

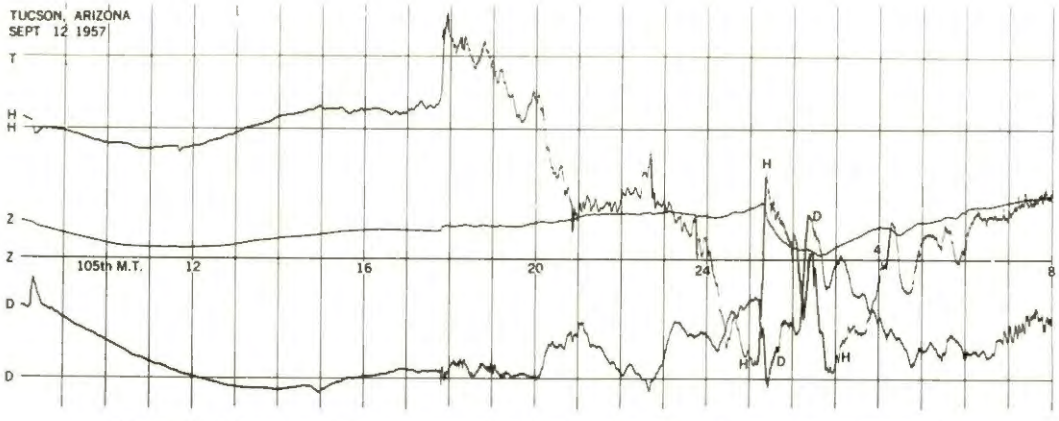

Figure 14.—Magnetogram for a magnetically disturbed day with a "sudden commencement."

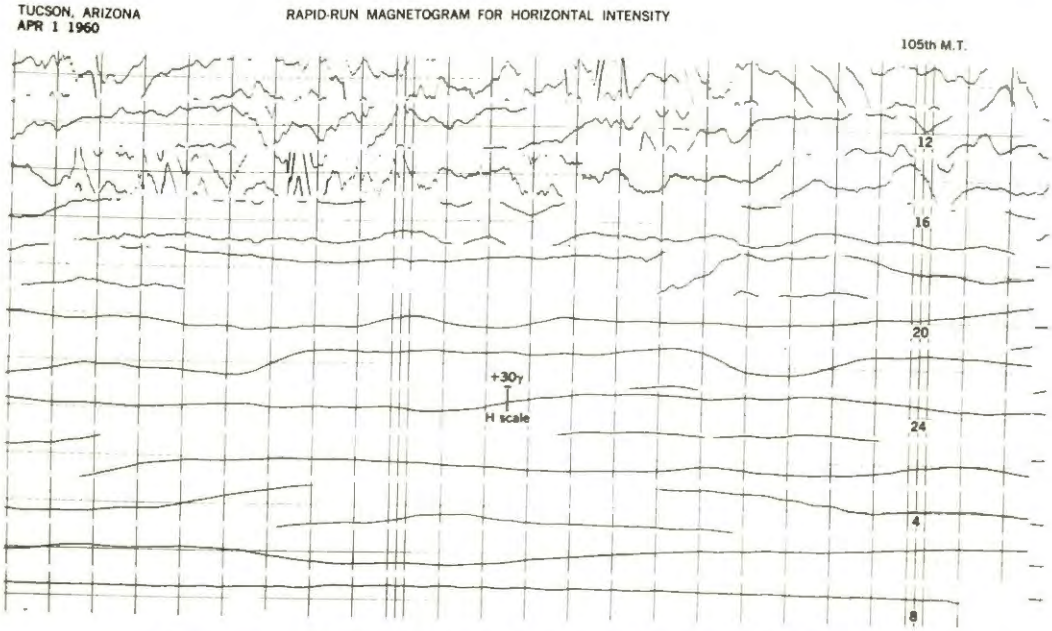

Figure 15.—Rapid-run magnetogram for horizontal intensity, moderately disturbed day.

the ground is therefore an augmentation of the daily variation departure prevailing at this time.

Magnetic Disturbances and Magnetic Storms

Quiet-day daily variation is normal and should not be classed as disturbance. However, from time to time the records show disturbance in great variety, from moderate fluctuations to those which can be completely recorded only by insensitive instruments. Any marked degree of natural disturbance is classed as a magnetic storm.

Though the name comes from analogy with the meteorological storm, the magnetic storm is not perceptible to the senses and has no established correlation with the weather. Obviously no direct association is possible between magnetic storms, which are widespread phenomena, and detailed weather conditions, which depend so much on local effects.

Description of Magnetic Disturbances

A magnetogram illustrating a magnetic storm is reproduced as figure 14. It should be understood, however, that magnetic storms differ greatly in the extent and character of the disturbance which they show; also, that storms are much more intense in higher latitudes than at Tucson.

Though the records of individual storms differ greatly among themselves, the change in the field at the earth's surface during a magnetic storm may be analyzed into three main parts: (1) a part proceeding according to time measured from the commencement of the storm, known as the *storm-time variation;* (2) a daily variation additional to that present on quiet days, but much greater in intensity and markedly different in type, known as the *disturbance-daily variation;* and (3) an irregular part, most marked in the high latitudes.

In separating the storm-time portion of the record, it is often difficult to fix the time of beginning. This uncertainty is frequently so great that any reckoning of storm-time variation is futile. On the other hand, many storms begin with abrupt changes in all the elements, especially marked in horizontal intensity. Such occurrences are known as *sudden commencements.* (See fig. 14.) These take place almost simultaneously all over the earth.

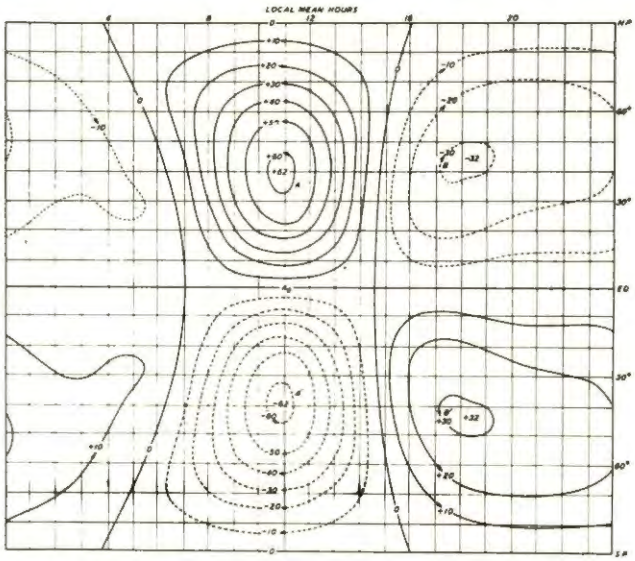

Figure 16.—Postulated current system in the ionosphere, deduced from the average daily variation observed for quiet days. In the space enclosed by each pair of adjacent lines, a current of 10,000 amperes flows in the indicated direction. The total current around each main focus is 62,000 amperes. (Courtesy of Department of Terrestrial Magnetism, Carnegie Institution of Washington.)

In middle or lower latitudes, the storm-time part of horizontal intensity rises to a maximum within an hour or two after the start. Then there is a steady drop to a value considerably below normal, the minimum coming on the average within two-thirds of a day. This is followed by gradual recovery, usually for several days, until the normal value is reached. The greater the storm, the more rapid is the development of these phases.

The detailed aspects of individual magnetic storms, while more prominent than the other features, are less amenable to systematic study and analysis. Chree [50] has stressed the fact that individual storms vary widely and display marked asymmetrical features. Chapman [51, 52] discusses various studies in this field, such as Birkeland's classification of magnetic storms into different types.

There are a number of special forms of magnetic disturbance, the most important of which is the *bay*. This is a departure from an otherwise undisturbed record, in the form of a V or of a bay of the sea, from which it gets its name. Most bays have no apparent relation to radio communication; but a special kind of bay (magnetic crochet or solar-flare effect) is closely associated with solar flares and with radio fade-outs (p. 32). Other special forms of magnetic disturbance are cusped bays occurring during storms, micropulsations registered in otherwise quiet intervals, sudden commencements preceded by small oscillations, and giant pulsations [53].

Magnetic storms are correlated with solar conditions and the solar rotation, with conditions in the upper atmosphere, with the aurora, with phenomena of radio communication, with cosmic-ray intensity changes and with changes in the Van Allen belts.

In the United States, exclusive of Alaska, the change in declination in the course of a magnetic storm may, on rare occasions, be more than 4 degrees, and the change in intensity may be as great as 5 percent. For example, at the magnetic observatory at Cheltenham, Md., the ranges on September 18 and 19, 1941, were: declination, 4.4°; horizontal intensity, 2,500 gammas; vertical intensity 1,400 gammas. (The mean values of horizontal and vertical intensity at Cheltenham are about 18,200 and 54,000 gammas, respectively.)

On the average, the intensity of a magnetic

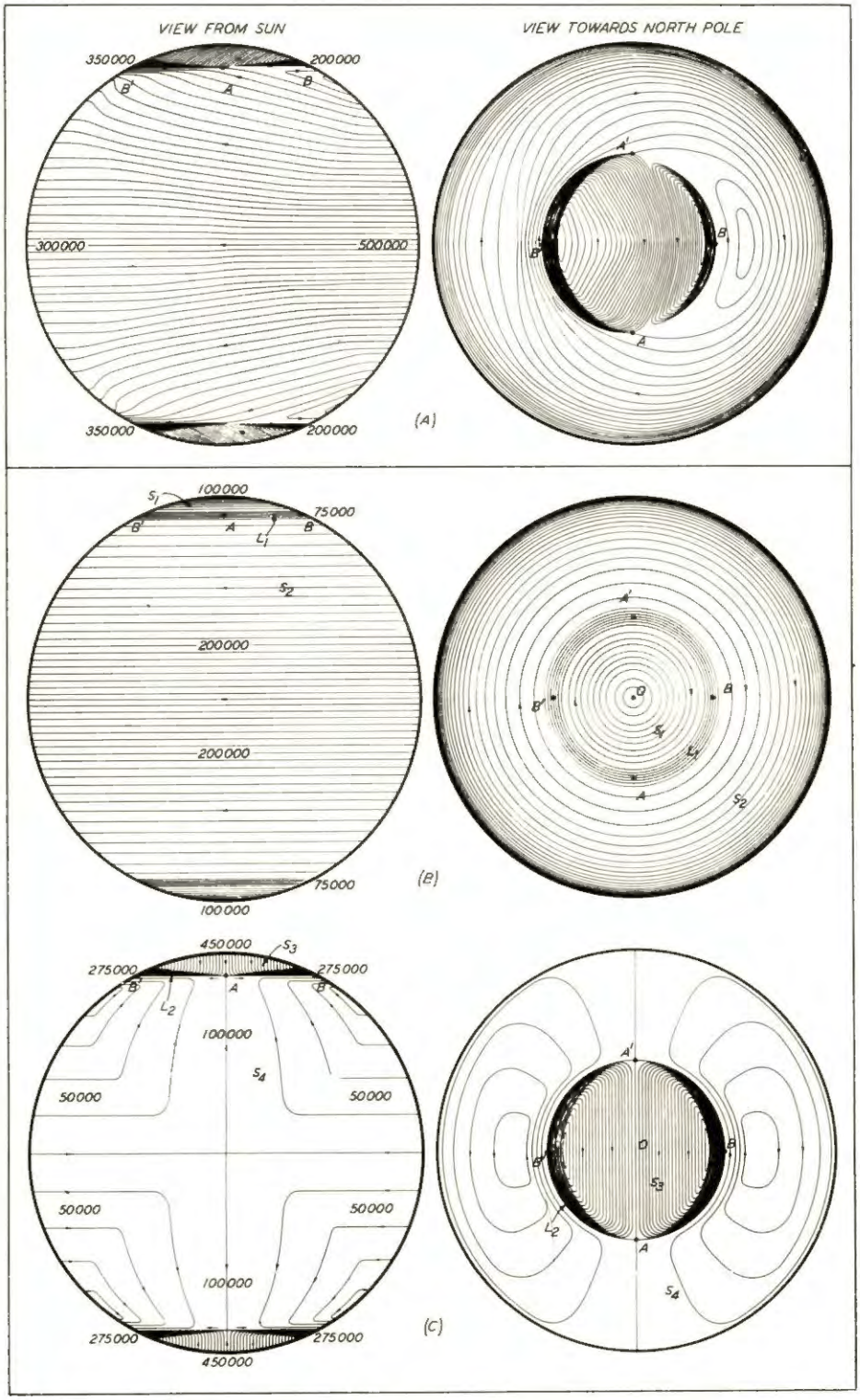

Figure 17.—Postulated average current system in the ionosphere for a magnetic storm. (B) gives the storm-time field (which, by definition, is independent of longitude); (C) gives the disturbance-daily variation, while (A) is the sum of these two. Note intense currents in auroral zone. (Courtesy of Department of Terrestrial Magnetism, Carnegie Institution of Washington.)

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storm increases up to about 67° magnetic latitude, and then decreases somewhat toward the poles. An extreme example of this increase with latitude is the storm of April 2, 1944; the total range in declination at Cheltenham, Md., was less than 1°, whereas at Sitka, Alaska, it was over 9°.

The following list shows the dates of some of the great magnetic storms:

October 23, 1847	April 16, 1938
August 28, 1859	March 24, 1940
February 4, 1872	March 1, 1941
November 17, 1882	September 18, 1941
October 31, 1903	March 28, 1946
September 25, 1909	September 13, 1957
August 11, 1919	February 11, 1958
March 22, 1920	July 15, 1959
May 13–16, 1921	April 30, 1960
July 8, 1928	November 12–13, 1960

Measures of intensity of magnetic disturbance.—It has been considered desirable to assign to each day or shorter interval a letter or figure indicating whether the magnetic field is quiet or disturbed, and to what extent. In fact, research of any kind on magnetic storms would be almost impossible without such lists. The simplest method would be to divide days into "quiet" and "disturbed." In view of the fact that most days are somewhat disturbed and only a few are greatly disturbed, it is preferable to use a greater number of classes, and to use intervals as small as 3 hours or even 15 minutes.

Many different measures have been proposed and used. The reason for so many criteria is that there are many features of a magnetic storm (such as length of storm, rapidity of change at time of greatest rate, total range, average of the ranges during each hour of storm, etc.), and there is no general agreement in the selection of those aspects which should be regarded as most significant. With the discovery of the relation of magnetic storms to radio communication, to auroras, and to the incidence of radiation and energetic particles from the sun, characterization of magnetic conditions has attained practical, as well as scientific, importance.

Of the many measures which have been tried out, only a few survive. The one with the longest life has been the *international character figure, C*. Each magnetic observatory assigns the number 0 (quiet), 1 (moderately disturbed), or 2 (greatly disturbed) to each Greenwich day. The criterion for distinguishing them was left to each observatory, with the expectation that different criteria would be used, and the mean of all observatories would give a better measure of disturbance than would any one criterion.

To evaluate changes in standard for the character figure *C*, Bartels proposed the *interdiurnal variability, u*, which is a measure of average disturbance over an extended period, such as a month or a year, and affords a fairly satisfactory means of comparing the magnetic activity of two periods. First, a number is determined for each day, namely the difference of the mean value of horizontal intensity for that day and the value for the preceding day, without regard to sign. The mean of these figures for a month is reduced to an "equatorial value" by multiplying by an appropriate constant depending upon the observatory. Monthly means of *u* have been derived for the period 1872–1937, and annual means for 1835–1937.

A more recent measure is the *three-hour-range index, K*. A figure ranging from 0 to 9 is assigned for each interval of 3 hours (Greenwich time). Each number indicates that the range of the most disturbed element (usually horizontal intensity) during the interval was between certain limits. (For example, a number 3 for Fredericksburg means that the range was between 20 and 40 gammas.) Each observatory has a different scale, so chosen that during a representative period each observatory had approximately the same number of *K*-figures greater than 4. However, the "range" used is not strictly the extreme range during the interval; rather, it is the range when the "normal daily variation" is subtracted. Since this normal daily variation is different for different days, the measure is in part subjective. It appears to be the most satisfactory measure yet proposed; it is free from the weakness of a widely changing standard such as applies to purely subjective measures (see discussion of *C* above), and yet is a more accurate measure of

disturbance than the purely objective measures thus far proposed [54].

For some purposes the K-index covers too long an interval. The 15-minute Q-index was therefore recently introduced to supplement K. It is however not merely a K-type index for a shorter interval. The Q-index reflects the sum of the magnitudes of the largest positive and negative departures, from an objective normal curve, during each 15-minute interval. The Q-index is intended for use at polar magnetic observatories and is designed to facilitate correlation with auroral and ionospheric records.

Causes of Magnetic Storms

Current systems.—As in the case of daily variation, current systems in the upper atmosphere can be postulated which account for the phenomena of an average storm. For example, the disturbance-daily variation and part of the storm-time variation can be attributed to the combined effect of two current systems, which will be briefly described.

According to this representation, the storm-time portion is ascribed chiefly to a ring current around the Equator some thousands of miles away. It offers an explanation for the first increase in horizontal intensity, followed by the decrease over many hours and the final recovery. It also fits in with the effects on the different elements and the relative unimportance of storm-time in polar regions. As an alternate, or perhaps supplemental, description, the storm-time effect can be attributed to a simple current system in the ionosphere. (See fig. 17(B).)

The disturbance-daily variation can be explained only by a much more complex system of currents. These currents are very strong in the auroral zone, half east-west and half west-east, the return circuits being across the polar cap with a smaller portion in middle and lower latitudes. (See fig. 17(C).) An analysis of 32 stations at which observations were made during the Second Polar Year (p. 41) conformed with this type of current system. This typical current system may be a statistical artifact compounded of current systems with individual characteristics differing more or less from the average. Furthermore there is no satisfactory quantitative theory explaining the origin of these currents. To see how such current systems might arise, one must turn to the sun, its sunspots and solar flares.

Sunspots.—It has been known since the time of Galileo that relatively dark spots appear from time to time on the face of the sun. They are familiar to many people who have seen them through smoked glass. They are carefully photographed and examined by astronomers.

By means of the Zeeman effect (splitting of spectrum lines in a magnetic field), Hale found that sunspots have intense magnetic fields, with flux density of the order of 4000 gauss. The sun as a whole seems to possess a much weaker magnetic field, comparable with that of the earth but having much more more complex local features. None of these solar fields can be effective at the distance of the earth except by a process of plasma transport, which may play an important part in some kinds of geomagnetic phenomena.

Sunspots appear to travel across the sun from east to west at a fairly regular rate. Although the rate of rotation varies with latitude, the mean synodic period is about 27.4 days. The spots vary in size, but may have diameters of 50,000 kilometers or more. Probably the largest on record was seen in 1858, with a diameter of 230,000 kilometers (18 times the diameter of the earth).

The life of sunspots varies a great deal. They change in size and shape, and their reappearance after one or more rotations of the sun cannot be reliably predicted. The spots may be single or they may occur in a group. In many cases they appear as bipolar pairs, with opposite magnetic polarity in the spots comprising the pair. The average number of visible spots varies greatly from year to year but with a rough regularity of increase and decrease between years of sunspot minimum and sunspot maximum. The time from one minimum to another is called the sunspot cycle. The sunspot cycle in the past has ranged from 8 to 17 years with an average of 11.2 years. The average time from minimum to maximum is 4.6 years, and from maximum to

minimum 6.6 years. The degree of sunspottedness at the maximum epoch varies from one cycle to another.

At the beginning of a sunspot cycle, the sun s surface is relatively free from spots; then a few appear in the middle latitudes of the sun on both sides of the sun's equator. As the cycle advances, the spots become more numerous and their average latitude is less than that for the earlier spots. At the end of the cycle, most of the spots are near the equator. Before the last spots of one cycle disappear near the equator, new spots of the succeeding cycle are seen in the middle latitudes.

Solar flares.—If the sun is studied by using the light of a particular line of the hydrogen spectrum, there is observed at infrequent intervals an outburst of greatly intensified emission from a very small area of the sun's chromosphere.

By means of simultaneous spectroheliograph, radio, geomagnetic, and rocket observations it has been found that a chromospheric eruption on the sun may be accompanied by a radio fade-out, ultraviolet and X-rays, magnetic disturbance (magnetic crochets or solar-flare effects). These effects are usually of short duration, lasting less than 1 hour, and 60 percent of them less than 15 minutes. They occur only in the sunlit hemisphere, and are intense only where the sun is within 30° of the zenith. Analysis shows that the magnetic effect can be accounted for in the same manner as the daily variation; that is, by ultraviolet radiation or X-rays from the sun. The ionization of the F_1 and F_2 regions usually remains unchanged after the fade-out is over, but there is some change in the E region.

There is good evidence then that the magnetic crochet is a phenomenon like the daily variation and that both are due to current systems in the E region, or perhaps below it, somewhere between 60 and 100 km.

Certain studies suggest that some of these "solar flares," as they are called, are followed after the lapse of about 1 day by magnetic storms.

Correlation of magnetic storms and solar conditions.—It has long been known that magnetic storms tend to be associated with the passage of large sunspots across the sun s central meridian. A much stronger correlation is obtained, however, when only those central-zone sunspots are considered that generate solar flares. If a sunspot generates a strong solar flare, the radiation effects will be observed simultaneously on the earth. If moreover the solar flare occurs near the central zone of the sun (within about 45° of the center) particle effects will be observed at a later time, depending on how long it takes the particles blown off by the solar flare to reach the earth. Sometimes energetic protons reach the earth in about 1 hour, being recorded as sudden cosmic ray increases; more generally the slower particles reach the earth in from 20 to 26 hours or more, giving rise to suddenly commencing great magnetic storms.

Although the sunspots last long enough to have one or more 27-day recurrences of central meridian passage, the great storms do not show this 27-day recurrence.

There is, however, a 27-day recurrence tendency for moderate magnetic storms, and many of these storms do not have sudden commencements. It is inferred that there are regions (called M-regions) on the sun that emit continuous streams of particles lasting for several rotations. These rotating solar jets overtake the earth about once a month (more exactly every 27 days), as long as the jet continues to stream outward into space. Moderate magnetic activity occurs while the jet is passing over the orbiting earth, and for some time thereafter. Recurrence of moderate magnetic activity for as many as 17 rotations has been noted.

The M-regions have not yet been identified.

Current concepts.—The discovery of the Van Allen radiation belts and the development of hydromagnetic theory [55] contribute to currently-held concepts in connection with magnetic storms, such as: The wind of solar protons blowing against the geomagnetic field thus distorting the shape of the field; hydromagnetic waves resulting from instabilities in the flow of the solar wind past the geomagnetic field; propagation of magnetic disturbance to the earth's surface in the form of hydromagnetic shock waves; spiraling and drift of the particles in the Van Allen

radiation belt; mirror points; leakage of particles from the Van Allen radiation belts into contiguous regions of the atmosphere; and tangled magnetic fields [56].

Aeronomic Phenomena Related to Magnetic Storms

Auroras.—World-wide magnetic storms are generally accompanied by outstanding auroral displays. According to the theory described above, when the charged particles which cause magnetic storms reach the outer atmosphere, they produce the aurora by collisions with the atmospheric particles. There is as yet no agreement as to just how the particles get to the auroral zones.

The aurora constitutes the best evidence of the existence of the stream of corpuscles. Additional evidence is afforded by the simultaneous occurrence of auroras in north and south latitudes, sometimes extending nearly to the Equator, and by spectographic studies of absorption of light passing through the streams.

The jet of particles apparently does not reach the surface of the earth. The height of the aurora has been measured many times by means of photographs taken simultaneously from different points of view. The method of triangulation is applied to details that are common to the different photographs. The lower limit found in this way is about 80 km. Although there are many reports that auroras have been seen much closer to the ground, it seems likely that these are based on misleading appearances.

The northern lights, seen in the Northern Hemisphere, are called "aurora borealis," while the southern lights are called the "aurora australis." The total illumination of the aurora is rarely greater than that of the full moon.

The aurora is very impressive because of its ever changing form, intensity, and color, and its constant apparent motion. Many of the forms have been given standard names, such as "quiet and moving arcs," "luminous bands," "draperies," and "rays." One striking form is the "corona." In this and other forms, there are rays which appear to diverge from a point. This is merely a perspective effect, caused by the travel of the particles along the magnetic lines of force (the spirals being of such small radius that from a distance they appear to be straight lines). The point of divergence lies nearly in the direction of the line of force passing through the point of observation; thus, if the dip is 70°, as in the central United States, the point of divergence will be some 20° south of the zenith. (This relation was discovered by Wilcke in 1770.) More accurately, the point of divergence is perhaps 1° south of the point determined by the lines of force at the place of observation.

The frequency of visibility of the auroras depends on geomagnetic latitude, reaching a maximum in narrow zones (the auroral zones) at about 23° from each geomagnetic pole.

Effect of magnetic storms on radio communication.—Magnetic storms have great practical importance in connection with radio communication, especially for the higher frequencies that are useful in long-distance transmission. While solar daily variation on quiet days has no disrupting effect on the ionosphere, a magnetic storm may completely disrupt normal conditions, especially toward the polar regions. In lesser storms the ionosphere is disturbed enough to change the reflection of radio waves, and sometimes abnormal ionization below the *E* region (p. 23) may interfere with transmission. It has been found that the power required to transmit signals received at different times with the same intensity at the receiving station varies with the *K*-figure, and when *K* exceeds 7, increase of power will not suffice for transmission across the North Atlantic Ocean.

It is important to identify the cause of poor reception, as there are several causes not at all related to magnetic conditions, such as faulty receiving equipment, man-made "static," interfering signals on approximately the same frequency as the desired signal, intentional "jamming" so as to block a whole band of frequencies, and natural "static" or "atmospherics." Magnetic storm effects are greater in high latitudes; for example, messages can often be sent across the North Atlantic by relaying through a low-latitude station when direct communication is impossible.

Prediction of radio-communication conditions is of great importance. It is provided regularly by the Central Radio Propagation Laboratory of the National Bureau of Standards. The predictions are based, in part, on 27-day recurrence of similar conditions. If the disturbed regions on the sun remained active for 6 months or more, and if it were certain that the emanations from them would consistently sweep over the earth for several rotations, fairly accurate prediction of magnetic activity would be less difficult. However, these conditions do not obtain, and great magnetic storms have little tendency to recur. Old disturbances weaken and disappear and new disturbances develop, especially during a sunspot maximum. At such times, there is more interference with radio communication by magnetic storms, and prediction is more uncertain.

It has been found that the ion-density in the outermost or F_2 region of the ionosphere shows considerable fluctuation which is correlated with magnetic disturbance, and that it likewise shows an extraordinary change in different parts of the sunspot cycle. It may be that this is the most sensitive indicator we have of the kind of solar activity that results in magnetic storms and disturbance.

Cosmic Rays

Primary cosmic rays are chiefly protons of enormous energies (10^8 to over 10^{19} electron-volts) approaching the earth from outer space. When they encounter the earth's magnetic field it acts as a crude filter. The magnetic field acting on particles approaching in the geomagnetic equatorial plane prevents those with energies of less than about 10^{10} electron-volts from reaching the outer atmosphere. Less energetic particles are able to reach the atmosphere at higher geomagnetic latitudes. The primary particles that reach the atmosphere produce hosts of secondaries.

The intensity of cosmic rays at the surface of the earth varies with geomagnetic latitude. (See p. 9.) The values at the geomagnetic equator are about 10 percent less than at 50° geomagnetic latitude, above which there is apparently no further decrease. The intensity is nearly independent of longitude, but there is a difference in intensity between cosmic rays coming from the east and those coming from the west.

Continuous recording of secondary cosmic rays at the surface of the earth has revealed several occurrences of large changes in cosmic-ray intensity associated with intense solar flares and great magnetic storms. The cosmic-ray intensity increases lagged behind the maximum solar-flare intensity by about 1 hour, on the average. The cosmic-ray intensity decreases coincided with the onset of suddenly commencing great magnetic storms, lagging behind the solar flare by about 1 day.

During the course of some great storms, there has been recorded an enhancement of a daily variation of cosmic-ray intensity.

In some magnetic storms, the intensity of cosmic rays recorded at the surface of the earth is not changed. It has been claimed that the behavior of cosmic rays may be used to decide the question of the existence of the equatorial ring current.

It is of interest that one of the proofs that cosmic rays originate in outer space is that the effect of at least 15,000 kilometers of the earth's magnetic field is needed to explain the behavior of the rays.

Earth Currents[1]

Sir Humphrey Davy suggested as long ago as 1821 that electric currents flow in the earth, but early attempts to detect such currents proved fruitless. However, the establishment and operation of telegraph lines utilizing the ground for the return circuit soon disclosed the reality of the phenomenon. Sometimes it was possible to signal with the aid of the spontaneous currents thus generated in the wires; on the other hand, there were occasional instances of irregular currents which prevented use of the circuits, as they were much more intense than the currents normally used for signaling. These outstanding occurrences were found to coincide with magnetic storms and auroras, sharing with the phenomena

[1] This discussion has been condensed from the one by W. J. Rooney in reference [14].

of geomagnetism several characteristics such as world-wide appearance, relation to sunspots, 27-day recurrence tendency, etc. Occasional measurements on telegraph circuits established the existence of currents in the earth not only at the time of magnetic storms but also during times of quiet magnetic conditions.

These currents are called *earth currents,* and the term is meant to include only those natural currents which flow in the crust of the earth in great circuits, and not local currents even if they are of natural origin. This would exclude local currents generated by chemical processes or by temperature differences in the earth; those generated by surges due to lightning discharges; and those generated by the movement of water in the earth's magnetic field, as in strong tides and oceanic currents. It would also exclude artificial or man-made currents due to leakage from power systems or electric railway systems. If all these local currents, artificial and natural alike, are allowed for, there is still positive evidence of electric currents circulating in the earth's crust.

Because of various observational problems, especially the elimination of contact potentials, no information is available with regard to any constant (direct) earth currents. The study has of necessity been confined to the fluctuations.

There is so much difference between land and sea in conductivity that it is difficult to arrive at a satisfactory general picture of the great-circuit earth currents. However, it has been determined that they flow in both the Northern and Southern Hemispheres, and are subject not only to irregular and spasmodic disturbances, but also to regular and periodic variations. Both the regular variations and the disturbances show a consistent relationship to the changes found in other cosmic phenomena. At a number of places where earth-current potentials have been measured, the resultant current flow is practically confined to a single azimuth and acts as an alternating current with long period. Although this feature is absent at some stations, including Tucson, it is striking that it should be found in so many widely separated localities.

Like the magnetic elements, the potential gradients of earth currents show daily variation. With data now available from polar and equatorial stations as well as from those in middle latitudes, it is possible to map out in a general way the circulation represented by and responsible for these daily-variation records. There appear to he eight current-whorls rather symmetrically spaced with reference to the Equator, and a secondary series of similar whorls near the poles. The whorls on the daylight side of the earth are large and well defined, while those on the dark side are less definite. These current whorls should be considered as fixed; that is, as the earth rotates on its axis, any selected point on the earth occupies successive positions with respect to the whorls.

Earth-current storms vary widely in type and intensity just as magnetic storms do. Potential gradients in the earth's crust of several volts per kilometer have been found in extreme cases. World-wide storms, often characterized by sudden commencements, are recorded in conjunction with similar magnetic storms. Although an exact correspondence is not apparent, the connection between earth-current and magnetic disturbances is not merely one of coincidence of time. Examination of a large number of records shows a consistent agreement in the nature of the disturbances in the two: for example, fluctuations appearing in the earth-current records when the same type of disturbance is found in the magnetic records. At middle-latitude stations the successive fluctuations in earth-current records follow closely the changes in magnetic vertical intensity and declination, while at Huancayo, near the Equator, the agreement is closer between changes in earth currents and changes in magnetic horizontal intensity.

Although the practical effects of earth currents are usually confined to telegraphic communication, there has been interference with power transmission on at least one occasion. On March 24, 1940, the rate of change of the magnetic field was so great that the direct currents induced in transmission lines caused them to be thrown out of service through the functioning of protective devices. An inquiry among 22 power companies in various parts of the United States and Canada by W. F. Davidson of the Consoli-

dated Edison Company of New York revealed that the disturbances were experienced in the New England States, New York, eastern Pennsylvania, Minnesota, Quebec, and Ontario. No trouble was reported in the southern and western parts of the United States.

The fluctuations of the currents flowing in the ionosphere (pp. 31–32) induce currents in the surface layers of the earth. These induced currents produce a magnetic field, which combines with that of the external currents to modify the field observed at the surface. In the deeper layers of the earth, the field of the induced currents tends to oppose that of the external current; thus the surface layers partially shield the interior of the earth from the effect of the external currents.

Chapter IV. Magnetic Surveys

The information given in chapters II and III is derived from magnetic surveys, which have been made over most of the earth's surface, both land and sea. A magnetic survey is conducted by measuring one or more of the magnetic elements at numerous points of observation, called magnetic stations. The term *magnetic station* is construed to include unmarked points; it is loosely applied even to a geographic position at which an observation has been made from a moving craft.

In using the term "magnetic surveys" we shall be here concerned only with the measurement of absolute values of intensity and/or direction of the magnetic field for use in the compilation of generalized, or smoothed, magnetic charts and for the determination of secular change in the field over a period of years. We thus exclude the magnetic measurements of relative values of field intensity (vertical component or total-field values) widely used in geophysical exploration work, much of which is done by private organizations in connection with mining and petroleum operations.

A majority of magnetic surveys (in the sense here considered) have been carried out by governments. (See p. 76.) Since about 1905, the chief nongovernmental surveys have been those of the Carnegie Institution of Washington, which made observations in regions not otherwise cared for, primarily for the purpose of providing data needed for studies of the nature and origin of the earth's magnetism. In some cases, that institution established the importance of the work so successfully that the governments concerned took it over.

Problems of the Magnetic Survey

An ideal description of the main field would specify a temporal and spatial average for any locality. As to time, the average would be a monthly mean about a specified epoch. As to space, the average would be a mean value for a sizable area, say 100 miles on a side. The ideal description is not achieved in practice; nevertheless, it does serve as a guide to the observing and processing programs.

Among the many points to be considered in conducting a magnetic survey are the following: Instrumental quality, station recoverability, reduction to monthly mean, local anomaly, and artificial disturbance. If observations are made in a moving craft (sea or air observations) the effect of the motion and magnetism of the craft must also be considered.

Overcoming contamination from local anomaly.—The degree to which the observations are affected by local irregularity is an important consideration. By careful selection of the station sites, the grosser effects may be avoided; but moderate irregularity is so widespread that this device cannot be relied upon to yield a smooth distribution. It is therefore desirable to make the density of stations high enougb so that the local anomalies can be practically averaged out. The density need not be as high as that needed for geophysical exploration.

Reduction to monthly mean.—The necessity for applying corrections to observations made at magnetic stations may be explained as follows: The observer at a magnetic station actually determines the intensity and direction of the field at a specific time. Such values, however, cannot be related directly to a previous or subsequent value observed at the same place because the field changes in a more or less irregular way each day. This difficulty may he overcome by "reducing" the observed values to a mean value for the month. This reduction can be made from the continuous record of a nearby permanent magnetic observatory or temporary recording station. When the nearest observatory or recording station is not very close it is necessary to make a series of obeservations over a

and in their subsequent use the same vigilance must be maintained.

An observatory must be well removed from all sources of artificial disturbance, particularly electric railways. There have been many cases where it was necssary to move an observatory to a new site because of the construction of electric railways in the vicinity. An electric railway running out from the District of Columbia had a faintly perceptible (though not deleterious) effect on the instruments of the Cheltenham Observatory even at a distance of more than 19 kilometers.

For the same reason, anyone entering the variation building must be careful first to divest himself of all articles of iron or steel, such as knives and keys. The sole of a shoe may contain a piece of steel sufficient to produce an appreciable effect on the sensitive magnets of the variometers. In one case, it was found that a prospectve magnetic observer could deflect a suspended magnet by holding his hand near it, and before he could make satisfactory observations, it was necessary to remove surgically a small piece of iron from his hand.

The variation building should be well insulated, so that the daily range of temperature inside will not be more than a few tenths of a degree. Otherwise, the temperature corrections (p. 52) become large and uncertain, since there is uncertainty as to whether the observed temperature truly represents the temperature of all relevant parts of the instruments.

Two methods used to secure the desired uniformity of temperature are: (1) to build above ground, depending entirely upon thick layers of sawdust, glass wool, or similar insulating material; (2) to build below ground, depending upon the surrounding earth. The variation building at Tucson is partly underground, the ground level being about a foot below the top of the sidewalls. The insulating walls are made of concrete blocks enclosing about 3 feet of sawdust or wood shavings. Although at most places underground observatories have had much trouble with damage to instruments from moisture, no such trouble is experienced at Tucson because of the dry climate.

Since observatories are constructed chiefly of wood, it is necessary in some regions to take precautions to protect them from termites.

Magnetic Surveys on Land

Distribution.—Existing magnetic stations are most closely distributed in the most accessible regions of the earth. Hence, transportation is partly the key to their distribution. In settled areas, the surveys have tended to follow established lines of communication by road and rail. In remote areas, where such means proved inadequate, the surveys have been conducted by boat, pack train, dog sled, and camel train. In recent surveys in Alaska and in Central and South America, the equipment was reduced in weight sufficiently to make air transportation feasible, the greater cost of travel being offset by the time saved. As might be expected, the density of magnetic stations has always been greatest in Europe.

Polar expeditions.—Since one-twelfth of the earth's surface lies within the Arctic and Antarctic Circles, and since great changes occur within those regions, the world magnetic survey cannot be considered even approximately complete without polar surveys. Because of climatic conditions, large portions of the polar areas are uninhabited, and there are few permanent magnetic observatories beyond the Circles.

There have been numerous exploring expeditions to polar regions, under both governmental and private auspices. Most of these have included magnetic surveys as an important feature of their work. Consequently, only the areas untouched by these explorations are wholly devoid of magnetic observations. However, the value of older data for giving the present-day magnetic field is small, because of lack of adequate repeat observations.

In the Arctic, observations have been made on the sea ice as well as on land. The most novel of these expeditions was that of the Soviet party headed by Ivan Papanin, which landed on the ice at the north geographic pole and drifted to the vicinity of Greenland, making observations en route.

In addition to such isolated observations, there have been numerous cases in which a magnetic observatory was operated in polar regions for limited periods. Most noteworthy are the three occasions on which, by international cooperation, many observatories were operated during the same interval. These are known as the First International Polar Year (1882–83) with 14 special observatories, the Second International Polar Year (1932–33) with 35 special observatories and the IGY (International Geophysical Year 1957–58) with 50 or 60 observatories. During the Second Polar Year many of these observatories made observations of other geophysical phenomena, such as ionospheric changes, auroras, and earth currents, and during the IGY the geophysical programs included many other disciplines as well.

Magnetic stations.—In selecting the site for a magnetic station, care must be taken to avoid natural disturbance (unless the purpose is to investigate the disturbance), and as far as possible to avoid regions in which artificial disturbance is present or likely to occur in the future. At repeat stations, where observations are repeated at intervals of 5 or 10 years, freedom from artificial disturbance is especially important. Since, however, it is usually impossible to foresee industrial developments for many years ahead, an undesirably large number of magnetic stations become unusable because of artificial disturbance, caused by magnetic materials or electric currents. Many stations established in cemeteries, which were formerly considered ideal sites for the purpose, have been affected in recent years by the steel burial vaults now used.

In some regions, the magnetic field near the ground varies significantly for a change of only a few centimeters in altitude. Consequently, whenever there is possibility that a station will be reoccupied later, the height of the instrument should be recorded, so that the instrument may be put in the same place next time.

Clearly, magnetic stations are subject to special hazards, as well as those common to all survey monuments, arising from construction work, wind- and water-erosion, earthquakes, and military activities.

Figure 19.—Magnetic-station marker. The disk is made of bronze, and is put into a concrete post. (About one-third actual size.)

When observations are made for mapping purposes only, the stations are sometimes not permanently marked. However, because of the many uses to which they are put, it is often better to mark them. The standard marker of the Coast and Geodetic Survey is a concrete post with a bronze disk in the top. (See fig. 19.)

When three elements are observed from which the entire field may be computed, the observations are said to be "complete." Sometimes only one element (usually declination) is observed.

To obtain declination, the true azimuth of one or more marks must be determined. (See p. 46.) Triangulation stations are sometimes used as magnetic stations, since the azimuth is available without special observations; but many of them are so near highways as to be magnetically disturbed by iron fences and passing automobiles.

Magnetic Surveys at Sea

Since three-fourths of the earth's surface is covered with water, the land surveys are inadequate for a complete description of the main fields. The land survey must be supplemented by sea or air observations.

For many years, the most difficult problem involved in making magnetic observations at sea was the instability of the moving support. So far as declination is concerned, the problems were solved in a reasonably satisfactory manner several centuries ago, as discussed on pages 64–65.

About 1900, the Coast and Geodetic Survey undertook on one of its wooden steamers, the *Blake,* the development of magnetic surveys at sea. The program had some success, but there was too much iron and steel in the vessels of

the Survey, and after a few years the effort was relinquished.

L. A. Bauer, who was in immediate charge of the Survey's magnetic work during this period, gained much valuable experience which he utilized when he became the first Director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. Under his supervision the department made many sea observations, first with the brig *Galilee,* and (after 1910) with the nonmagnetic yacht *Carnegie.* The latter ship was equipped with a specially designed marine compass, a collimating compass for measuring declination, a simple deflection apparatus for measuring horizontal intensity, a special type of dip circle, and a modified earth inductor. All of these were designed to give accurate results in spite of the movements of the vessel. Secular change was determined by use of observations made near points where different cruises crossed. Methods and instruments had been perfected and the program had been broadened to include allied geophysical phenomena when the *Carnegie* was destroyed by explosion and fire at Apia, Samoa, in 1929.

Since the loss of the *Carnegie,* magnetic observations at sea have been made by a small nonmagnetic vessel operated in the Baltic Sea, and more recently by the Russian nonmagnetic vessel *Zarya,* which began operating at the time of the International Geophysical Year, 1957–58.

Compass deviation.—The oustanding nautical problem of the 19th century was the difficulty of navigating an iron or steel vessel with a magnetic compass. The iron not only causes the compass to deviate from the magnetic north, by a different amount on each heading; it also makes the compass more sluggish. (An ordinary compass is almost useless in a submarine, because the mean directive force of the earth's field may be reduced as much as 80%.)

When making magnetic observations on board ship or on an aircraft the magnetic fields produced by the magnetic iron and steel and by the direct-current circuitry of the craft contaminate the observed values. Special observations are needed to measure the parameters of the contaminating field so that corrections may be made therefor.

Magnetic Observations in the Air

Improved airborne measuring equipment has opened the way to fast, reliable surveys. Rapid advances are also being made in magnetic surveying by rocket- and satellite-borne equipment.

The airborne survey is primarily a survey of the magnetic field at altitude. The measurement of the vector field (and its gradients) at altitude permits reduction to ground level; hence, the airborne survey is also an adjunct of land and sea surveys. This second function is important for filling in the large gaps in the ocean and polar regions where observations have not been made or where the observations are so old that they cannot be reliably brought up to date by secular change corrections.

In spite of the ability of the airplane to reach otherwise inaccessible regions, the Antarctic remains a region poorly surveyed, because of the long stretches without suitable aircraft base locations.

In 1949, the Coast and Geodetic Survey, working cooperatively with the U.S. Air Force, began making airborne magnetic observations using a vector airborne magnetometer. Mounted inboard in a large, suitably modified aircraft, the magnetometer was capable of measuring magnetic total intensity, magnetic dip and declination. The data were recorded continuously while the aircraft was in flight, thus yielding relatively large quantities of data over long distances in short intervals of time. In the process of averaging out the effect of aircraft pitch, roll and yaw, the continuity of dip and declination is lost and instead average values are obtained every 5 minutes of time (about every 20 miles). This project had to be relinquished after covering a very small portion of the northern part of the Western Hemisphere.

In 1953 the U.S. Navy Hydrographic Office, using essentially the same magnetic instrumentation—the vector airborne magnetometer was developed primarily through the ef-

forts of the U.S. Naval Ordnance Laboratory—began its Project Magnet, and at this writing has flown hundreds of thousands of miles of magnetic survey track, including a large number of round-the-world trips [57].

For the airborne surveys the problem of contamination by the magnetism of the craft is similar to that for the observations at sea. The details of compensation are quite different, but the essential principles are the same [12, 30].

vations can be reduced to monthly mean values more accurately than would be possible by using the records from remote observatories.

Comparison and Standardization of Instruments

The older absolute instruments often did not agree to the desired accuracy (1 gamma or 0′.1 for observatory instruments). There was no way to tell which instrument gave results most nearly correct. The *International Magnetic Standard* (IMS) of the Carnegie Institution of Washington was derived by comparing many instruments throughout the world, and then assuming that the best standard was the mean of them all, the differences between the individual instruments and the mean being used as instrumental corrections necessary to reduce to the IMS. One unavoidable uncertainty in such a standard arises from the tendency of instrumental corrections to change, either gradually or abruptly, so that the standard is somewhat elusive. Nevertheless, the widespread use of the IMS has served to make results of different surveys more homogeneous.

In later years, because of its constancy and precision, the sine galvanometer designed and built by the Carnegie Institution of Washington was informally accepted throughout a large part of the world as representing the IMS for intensity measurements. It measured only the horizontal component; there was no reliable instrument of corresponding accuracy and precision for measuring the vertical component or the total field intensity.

The Committee on Comparisons, of the Association of Geomagnetism and Aeronomy, International Union of Geodesy and Geophysics, is charged with the responsibility of carrying on an international program of comparison of instrumental standards among the magnetic observatories of the world. For these comparisons the QHM is most commonly used, for it is very stable, it is light in weight and easily transported by air, and the technique of using it and obtaining satisfactory results is relatively simple. This procedure provides a comparison of measurements of only the horizontal component of the earth's field. No extensive comparisons of other components have been made with this or similar technique.

Within the past few years the proton-precession magnetometer has been used at quite a number of places for measurement of the scalar intensity. Because of the accuracy and precision of the proton-precession magnetometer, its use as an international magnetic standard is now being considered by the Association of Geomagnetism and Aeronomy, of the International Union of Geodesy and Geophysics. (See p. 56.)

Corrections for instruments of lesser accuracy are obtained by comparison with an observatory instrument. In the fieldwork of the Coast and Geodetic Survey, instruments are thus standardized before and after each field trip.

Method and Problems of Measuring Each Magnetic Element

For many years the available instrumentation has been such that the measurement of H, Z, or F was more difficult than the measurement of D or I. This has been changed by the introduction of the proton-precession magnetometer and the proton vector magnetometer.

Declination.—Since magnetic declination is the angle between the true and the magnetic meridians, both of these directions must be determined. The direction of the true meridian is established by observations on the sun or on a star (the North Star is most often used). The azimuth of some prominent object, called the *mark*, is determined and azimuths of other objects are obtained by measuring the horizontal angles between them and the mark. The prominent objects should be at least 300 feet from the observer and should be sharply defined. Sometimes two stones or concrete posts are set, one due north of the other, and suitable scribings or points on the posts thus delineate a *meridian line*.

The magnetic meridian is determined by a magnet free to turn in a horizontal plane. If the magnet is supported on a pivot, mechanical friction must be reduced to a minimum; if the magnet is suspended by a fiber, care must be

taken to see that there is no torsion in the fiber or that acceptable corrections are made for the torsion. There must be a means of determining the direction of the magnetic axis of the magnet, so that this direction may be compared with the direction of the true meridian. In the most accurate instruments the magnet is designed to be inverted, so that the difference between the mechanical or geometric axis and the magnetic axis is eliminated from the result.

The magnet of a surveyor's compass or similar instrument is usually supported by a jewelled bearing resting on a finely made pivot of very short radius—not a "sharp" point. It is balanced to prevent excessive dipping by an adjustable counterweight. It must be handled with great care and always lifted off the pivot when the compass is to be moved, for one careless lowering of the magnet on the pivot may easily damage the bearing surfaces and seriously impair all subsequent performance.

In marine compasses the magnets are usually attached to a float and immersed in a liquid so that the weight supported by the pivot is relatively small.

The marine gyro-compass is not, of course, a magnetic instrument and has no relationship with the earth's magnetic field. No further discussion of this device will be given here, except to say that it is a complicated piece of equipment subject to mechanical and electrical failure, so that all ships carry magnetic compasses as standby instruments even though most of their navigation may be done with reference to the true directions indicated by the gyro-compass.

Inclination.—Magnetic inclination is the vertical angle between the plane of the horizon and the direction of the magnetic field. The dip circle is an obsolete instrument, and direct measurements of magnetic dip are now made with the earth inductor.

Horizontal intensity.—The conventional absolute magnetometer employs the method of Gauss, or the "oscillations and deflections" method. A suspended magnet is permitted to oscillate in a horizontal plane about the magnetic meridian, and the oscillation period T is measured. Then it is replaced by a second magnet and the first magnet is used, at a preset distance r, to deflect the second magnet. Adjustment is made for equilibrium with the two magnets horizontal and mutually perpendicular, then the deflection angle u is measured. The moment of inertia K of the oscillated magnet is separately determined. The measured values of T, u, r, and K give the horizontal intensity (H) and the magnetic moment (M) of the first magnet.

A method somewhat simpler in principle is to suspend a small bar magnet horizontally on a fine quartz fiber. The sine of the angle through which the magnet is turned when a predetermined amount of torsion is put in the fiber (by twisting its upper end) is inversely proportional to the intensity of the horizontal field. The quartz horizontal magnetometer (QHM) works on this principle; it is a relative instrument requiring calibration against a standard.

The proton-precession magnetometer, which is non-directional and therefore measures the total intensity of the field in which its sensing head lies, can be used to measure the horizontal component if the unwanted vertical component is approximately nulled by means of a coil field. (See p. 57.)

Vertical intensity.—Until the introduction of the proton vector magnetometer, there was no absolute instrument in use in the United States that provided satisfactory measurements of the vertical component of the field. The method of computing Z from observed H and I ($Z = H \tan I$) leads to great uncertainty in the value of Z in polar regions. Even as far south as the United States, this method of deriving Z is not adequate for all purposes.

Relative measurements of the vertical component have been made with the magnetic field balance and with the magnetometric zero balance (BMZ), but both instruments require periodic recalibration by comparison measurements made in fields of known vertical intensity.

Total intensity.—Because of the difficulty of making satisfactory measurements of total intensity, or of the changes in total intensity, very little work was done with this element for many years. During the past decade, entirely new concepts in magnetometry have appeared in the form

of the nuclear or atomic instruments, such as the proton magnetometer, the rubidium-vapor magnetometer (developed at the Fredericksburg Magnetic Observatory in cooperation with the National Bureau of Standards), and the metastable helium magnetometer. All of these are nondirectional and measure the magnitude of the total field in which they are operating. A measurement of intensity with such an instrument requires only the determination of the frequency of an alternating current or voltage. The proton instrument is at this time (1962) the most widely used, being employed in magnetic observatories, in magnetic field surveys, as an airborne magnetometer for geophysical exploration work, and as a marine magnetometer with the sensing head towed on a cable behind oceanographic research and survey vessels.

The saturable-core (fluxgate) magnetometer is also widely used for airborne and seaborne survey operations. When mounted inboard it can be combined with angle-measuring equipment so that the direction as well as the magnitude of the total intensity is determined. When towed in a "bird" (or in a "fish" behind a ship) the fluxgate magnetometer measures the magnitude of the total intensity only.

Other components.—Although some magnetic observatories located in or near the polar zones have oriented their recording equipment so that measurements are made of the fluctuations in the north component (X) and the east component (Y), as well as the vertical component (Z), the absolute calibration of such recorders is usually derived from measurements of the magnetic declination (D), inclination (I), and one or more of the intensity components H, Z, and F.

Descriptions of Individual Instruments

Although there is extensive international cooperation in geomagnetic work, there is a great variety in the instruments used in different countries. The instruments selected for description in this chapter are chiefly those used by the Coast and Geodetic Survey. Somewhat similar instruments are used by all countries making magnetic surveys, but in many cases they may differ in significant respects.

Figures 20–29 illustrate some of these instruments.

Transit magnetometer.—This instrument, sometimes called a transit declinometer, is used primarily for the observation of magnetic declination. Essentially it is a surveyor's transit built to specifications that insure freedom from magnetic impurities in its construction and that provide a more sensitive compass needle than normally available. There is also a reading microscope for observing the precise position of the compass needle. It is a relative instrument, for its magnetic index correction must be determined by comparison with a standard. Two of these transit magnetometers have been equipped with auxiliary deflecting magnets, a modification that enables measurements of the horizontal-intensity component to be made. However, this feature has not been widely used.

Earth inductor.—The heart of this instrument, sometimes called an inductor inclinometer, is a multi-turn coil of copper or aluminum wire wound on a circular coil form carried in a frame. The coil can be rapidly and continuously rotated about a coil diameter (rotation axis) by means of a hand-powered flexible shaft. It is connected to a sensitive galvanometer through a commutator and brushes. A voltage is induced in the coil when it is rotated in the earth's magnetic field; the galvanometer indicates the rectified current.

When the rotation axis is in line with the direction of the earth's magnetic field the galvanometer reading will be zero. The commutator is so adjusted that the galvanometer current is most sensitive to change in the inclination of the axis and least sensitive to change in the azimuth of the axis.

In operation the coil axis is placed approximately in the magnetic meridian. The coil is spun while the inclination of the axis is adjusted until the galvanometer reading is zero. The inclination of the rotation axis is then read from a vertical circle.

Magnetic field balance.—This instrument is known by various names, a common one among exploration geophysicists and geologists

Figure 20.—Transit magnetometer, a specially modified engineers' transit equipped with a very fine compass and a reading microscope (mounted just under the main telescope) for precisely reading the position of the compass needle. Used primarily for measurements of magnetic declination, but can be used to observe horizontal intensity when equipped with an auxiliary deflector magnet.

being "magnetometer," but that name has the disadvantage of permitting confusion with other types of magnetometers. A permanent magnet, equipped with delicate knife edges and a plane mirror, is so mounted that the magnetic axis of the magnet is approximately horizontal and in the magnetic east-west direction. The position of the magnet is observed with a telescope so placed that an image of the scale in the telescope is reflected by the mirror on the magnet. Counterpoises are provided on the magnet for balancing it, and for adjusting the sensitivity and the temperature compensation of the instrument. The instrument is in a condition of balance when the couple due to the action of the vertical component of the field on the horizontally mounted magnet is just equal to the couple resulting from gravitational force acting on the center of mass that is laterally displaced very slightly from the line of the two knife edges.

To convert the changes of scale reading (in divisions) to field changes (gammas) it is necessary to know the sensitivity of the instrument; this can be measured by means of a Helmholtz coil arrangement. To convert scale readings to absolute values, it is necessary to read the scale at a point where Z is known. The field balance is quite reliable for measuring changes of Z at the same place or at different places over a short period of time. To measure large differences the BMZ may be used.

Occasionally the field balance is made to sense

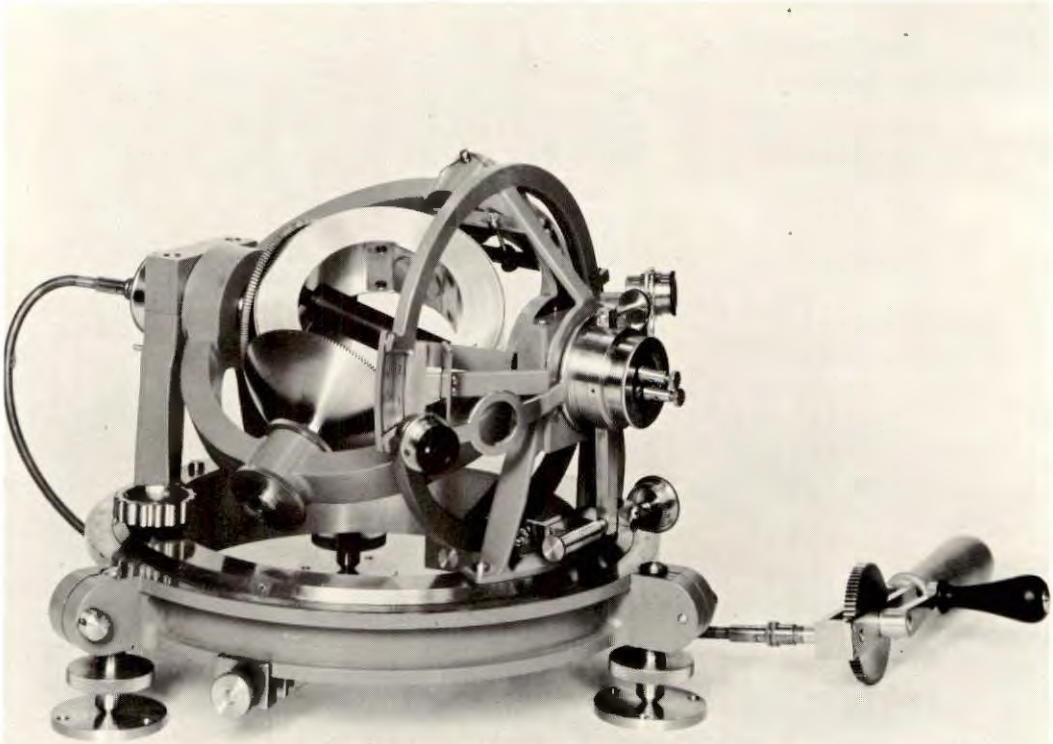

Figure 21.—Earth inductor or inclinometer for measuring dip.

the horizontal field instead of the vertical. With the magnetic axis of the magnet in a vertical position when balanced, the instrument becomes sensitive to small differences in the horizontal component of the field. However, care must be taken to see that the plane of rotation of the balanced magnet is accurately in the magnetic meridian.

Orientation with respect to the meridian is much less critical for the vertical field balance.

BMZ (*Magnetometric zero balance*).—This is a Danish-built, highly dependable magnetic balance that overcomes to a considerable extent the shortcomings of the ordinary field balance. Its magnet, knife edges, and mirror are ground from one piece of steel, so that it is mechanically very stable. All readings are made with the balanced magnet in a precisely horizontal position, this being accomplished by adjusting a "turn" magnet mounted below the housing of the balanced magnet. A calibrated dial controlling the turn magnet indicates the amount of auxiliary field being utilized and thus indicates the reading that constitutes the magnetic measurement of the vertical component.

QHM (*Quartz horizontal magnetometer*).—This is another very dependable and very simple magnetic instrument of Danish origin; it uses a small permanent bar magnet suspended from a fine quartz fiber in such a way that the horizontally placed magnet will turn in a horizontal plane. When there is no twist in the fiber the magnet assumes a position exactly in the magnetic meridian, and its position is read through a telescope that sees a plane mirror mounted with the magnet. If the whole instrument is turned in azimuth the magnet, restrained by the earth's magnetic field, will lag. The turning of the instrument is continued through an angle somewhat more than 2π, until the position of the magnet as seen in the telescope is the same as before. The magnet has turned through an angle φ, the instrument has turned through an angle $2\pi+\varphi$ and the twist in the fiber is

2π radians. The couple due to the action of H on M balances that due to the twist in the fiber. Then

$$HM \sin \varphi = 2\pi k'$$

where k' is the couple per unit (radian) twist. The parameter $C = 2\pi k'/M$ is determined by calibration where H is known rather than from the separate measurement of k' and M. Then if the deflection φ is measured at other places, H is computed from

$$H = C/\sin \varphi$$

The instrument has a considerable temperature coefficient, however, and care must be used to see that adequate corrections for temperature effects are applied to the results. The relative sizes of the fiber and magnets are so chosen that the twist (usually 2π radians) can be introduced without difficulty.

Sine galvanometer.—The sine galvanometer is an electromagnetic instrument for measuring H. It consists essentially of equipment for producing a calibrated field, and a small detector magnet. The detector magnet is acted on by the horizontal intensity H of the earth's magnetic field and by the horizontal coil field, and the resulting deflection angle u of the magnet is measured. H is computed from the coil field and deflection angle.

The sine galvanometer measurements agree with measurements of H with the proton vector magnetometer (p. 57).

Magnetograph.—A magnetograph consists of one or more (usually 3) variometers, one for each element recorded, and a recorder. The record produced is called a magnetogram. Most magnetographs utilize photographic recording because of its simplicity and dependability. For special purposes, however, some equipment is made with electronic sensing and amplifying devices that have sufficient power output to drive a pen-and-ink recorder.

The conventional or classical variometer contains a recording magnet free to turn about a specified axis. The magnet turns in response to changes in intensity normal to the axis of rotation and to the magnetic axis of the magnet. In the D and H variometers, the recording magnets are suspended from quartz fibers. The D variometer magnet is practically in the magnetic meridian, so that it responds to changes in declination (changes of the east intensity). The H variometer uses a fiber of sufficient stiffness

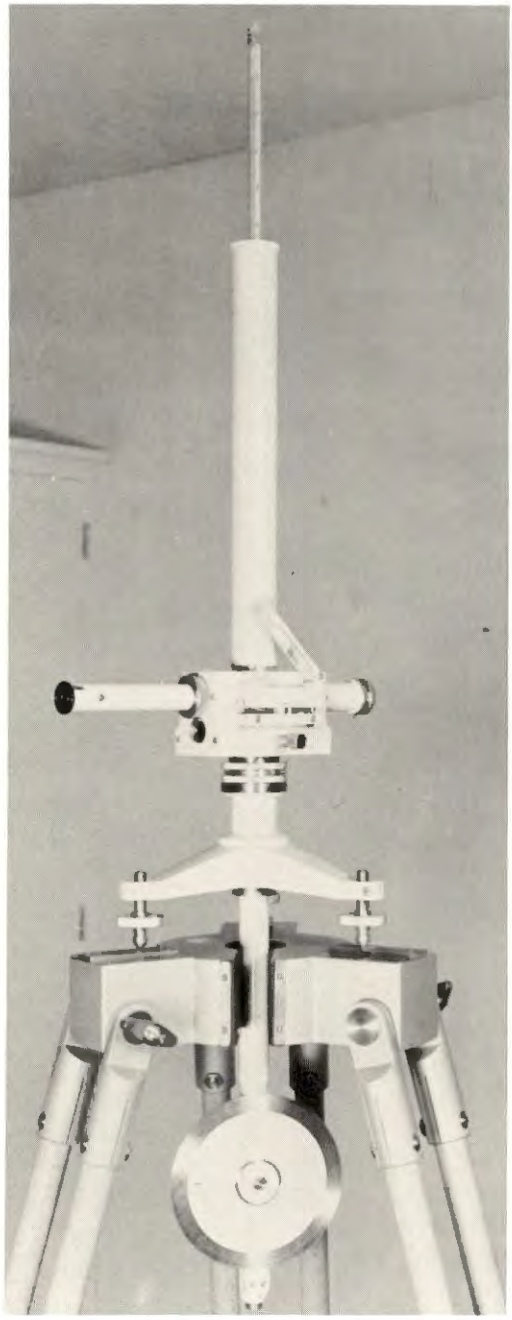

Figure 22.—Magnetometric zero balance (BMZ), used for measuring vertical intensity.

Figure 23.—Quartz horizontal magnetometer (QHM); used for accurate measurement of horizontal intensity.

so that the suspended H magnet can be turned into a magnetic east-west position by introducing twist in the fiber; this orientation permits it to respond to changes in the north-south (horizontal) component of the field. The Z (vertical component) variometer uses a magnet balanced horizontally on knife edges of the highest quality. It will operate with the magnet in any azimuth, responding to changes of Z. Each variometer magnet has a plane mirror which reflects a beam of light. Through a suitable optical system, the light is focused to a point at the surface of the recording drum on which the photographic paper is mounted. Normal recording speed is 20 mm per hour, with the drum turning once in 24 hours. Time lines are put on the magnetograms by flashing a line of light across the record once each hour.

The standard magnetogram ordinarily has all three components recorded simultaneously on one sheet of paper. (See figs. 13 and 14.) In addition to the traces of the 3 magnetic elements, reference lines (base lines) are recorded by means of light reflected from fixed mirrors. The base lines are used in the absolute calibration of the magnetograph. Often there is a temperature (T) trace which records the temperature in the magnetograph building. On many standard magnetographs "reserve traces" are provided. They appear at one edge of the gram just before the regular trace goes off the other edge; this occurs during times of severe magnetic disturbance.

Variometer magnets differ greatly in size. In the first observatory Gauss used magnets some 93 cm long. The magnets now used by the Coast and Geodetic Survey in D and H variometers are

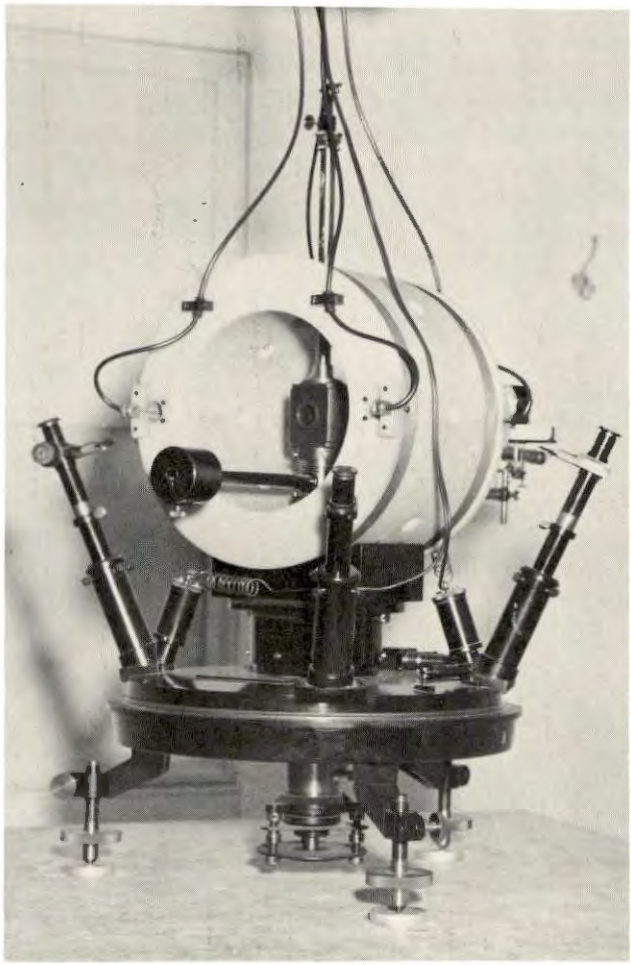

Figure 24.—Sine galvanometer No. 1 of the Department of Terrestrial Magnetism, Carnegie Institution of Washington; used for accurate measurement of horizontal intensity by means of an electric current. The current is measured with a potentiometer and standard resistance.

about 1 cm long, in Z variometers some 8 cm in length. The smaller magnets permit the variometers to be placed relatively close together (about 50 cm) without serious interaction among them.

On the magnetograms shown in figures 13 and 14, the time axis is horizontal. Changes in vertical ordinate of a curve indicate changes of D, H, or Z.

Rapid-run magnetographs used by the Coast and Geodetic Survey have a recording speed of 4 mm per minute—12 times the normal recording speed. The variometers are essentially the same, but with slightly modified suspension systems to reduce the mechanical moments of inertia. A triple-drum motor-driven recorder is used, and each of the three magnetic elements is recorded on a separate sheet of paper. The drums turn once in 2 hours, or 12 times per day, and are shifted laterally hy 22 mm at the end of each revolution. Each recording "track" is thus 22 mm wide. An array of reserve-trace mirrors for each element prevents the loss of record when the changes in the field cause the main trace to move outside the limits of the track. A rapid-run H magnetogram from Tucson is shown in figure 15.

A standard magnetograph must be calibrated at frequent intervals (usually once or twice a week) by observations with absolute instruments.

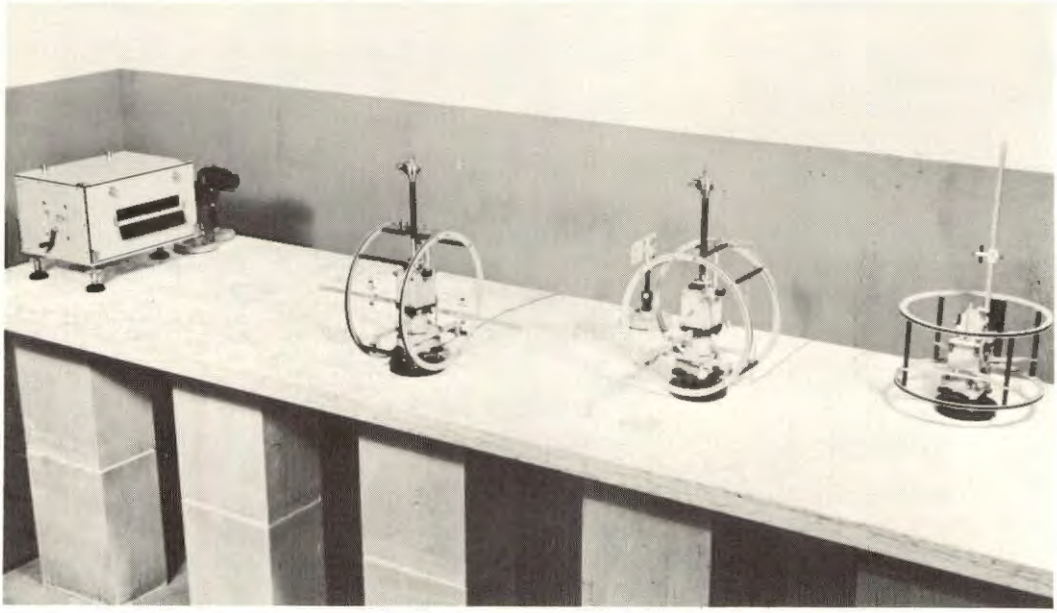

Figure 25.—Typical magnetograph at the Fredericksburg Magnetic Observatory. At the right is the Z variometer; next is the *D* variometer; and next, the *H* variometer. All are equipped with Helmholtz coils for sensitivity calibration. The small stand near the *D* variometer supports a mirror for putting time lines on the record. At the far end of the pier is the enclosed recording drum; the two lamp holders are for the recording lamp and the time-flash lamp.

The calibration consists of the determination of the scale value (reciprocal of sensitivity) and of the base-line value of each of the three recording variometers. With this information the absolute value (relative to zero) of any magnetic element can be determined from the recorded traces for any instant or interval of time.

More complete descriptions and discussions of variometers and magnetographs are given in Coast and Geodetic Survey Special Publication 283 [24].

Magnetometer.—The classical magnetometer was used almost exclusively by the Coast and Geodetic Survey for many years in measuring *D* and *H*, for it was a "self-checking" absolute magnetometer. Its fundamental constants depend on physical characteristics that can reasonably be expected to remain fixed for years at a time, such as length of the deflection bar, temperature coefficients of magnets and other parts, and mechanical moment of inertia of the suspended magnet. Using the method of Gauss, the magnetic moment or strength of its principal magnet is redetermined at the time of each observation for *H* and if this figure remains constant (after correction for temperature) the self-checking is accomplished. The principle of operation is briefly outlined on page 47, and discussed more thoroughly in Coast and Geodetic Survey Serial No. 166 [19].

Nuclear magnetometer.—The use of some kind of nuclear magnetometer both for field work and in observatories is on the increase. The advantages are two-fold: first, the accuracy of the measurements is much higher (for example, the error of a single measurement of intensity is reduced by a factor of 5, 10, or even 20); second, the time required for a single measurement is reduced by a factor of ten to a hundred. The disadvantage of the nuclear instruments is the complicated electronic circuity and their dependence on expert electronics technicians for maintenance and repair.

The simplest and most direct instrument of the new category is probably the proton-precession magnetometer [60]. A cupful of ordinary water furnishes the protons. The water sample is "magnetized" by being subjected to a strong electromagnetic field (perhaps 100 gauss) applied roughly at right angles to the earth's field for

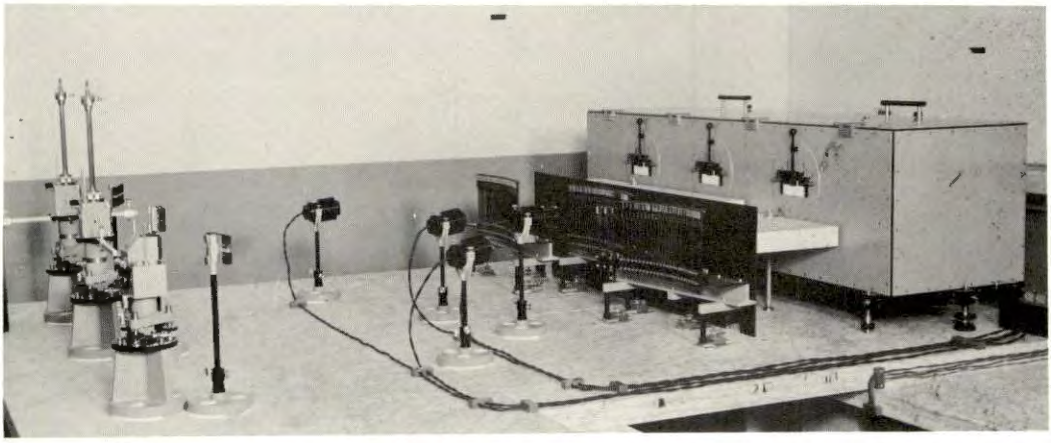

Figure 26.—Rapid-run magnetograph at Fredericksburg. The *Z*, *D*, and *H* variometers are at the left; the triple-drum recorder is at the right. In front of the recorder are three curved racks supporting arrays of front-surface mirrors that serve as multiple sources of light for the three variometers. Each variometer has its own recording lamp, and there is a fourth lamp for time marks, which are put on the record every 5 minutes.

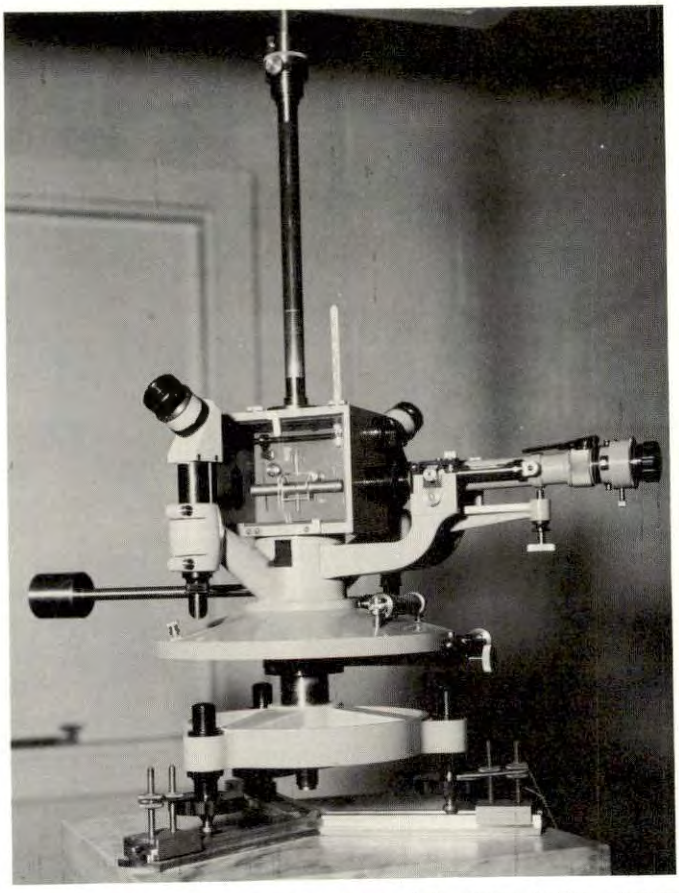

Figure 27.—Observatory-type magnetometer, designed for absolute measurements of magnetic declination and horizontal intensity.

Figure 28.—Coils and sensing head of proton vector magnetometer. The water sample and polarizing coil are at the center. The inner set of four coaxial coils, with axis vertical, is a Braunbek system for nulling Z during the measurement of H. The outer pair of coaxial coils, with axis horizontal, is a Helmholtz system for nulling H during the Z measurement. In the F measurement, neither coil system is energized.

a period of a second or two. This polarizes the sample so that a significant percentage of the protons have their magnetic axes aligned parallel to the polarizing field. When the polarizing field is suddenly removed, the spinning protons precess about the direction of the remaining (earth's) field, and the angular velocity of precession is precisely proportional to the intensity of the remaining field. Such a precession will induce a weak alternating voltage in a suitably placed coil. The frequency of the signal can be accurately measured, and the field intensity is a function of the frequency alone, not of the amplitude of the generated signal. The electronic components of the magnetometer are concerned exclusively with the measurement of the frequency. The physical constant, known as the gyromagnetic ratio of the proton, which relates the angular frequency of precession to the intensity of the magnetic field has been determined to an accuracy of about 1 part in 100,000 [61] hy the National Bureau of Standards, and measurements made in other countries agree substantially with the *NBS* value. In 1960 the Association of Geomagnetism and Aeronomy, International Union of Geodesy and Geophysics, adopted the following resolution:

The International Association of Geomagnetism and Aeronomy, considering the need for a universal agreement regarding the value of the gyromagnetic ratio of the proton for measurements of the geomagnetic field, strongly recommends that, pending the agreement and specification by an appropriate international scientific organization of a final value, all measurements of the geo-

magnetic field with a proton free-precession magnetometer, using pure water as a proton sample, shall be based on the following value of the gyromagnetic ratio: $2 \cdot 67513 \times 10^4$ radians/gauss second.

Expressed in other units, the magnetic field intensity in gammas is equal to 23.4874 multiplied by the frequency in cycles per second of the induced a-c. signal.

Nuclear total-intensity magnetometers have been adapted to the measurement of the vector field by the addition of bias fields and conventional equipment for measuring angles. The Coast and Geodetic Survey has developed two such vector devices. One is the proton vector magnetometer (PVM) [58] shown in figures 28 and 29. With this instrument it is possible to measure H and Z as well as F. From these measurements dip can be computed; declination is not obtained. The second type of vector magnetometer records in digital form, once each minute, five measurements of field intensity, four of which are made with biasing fields. From these measurements the complete vector field is computed by automatic data-processing techniques [62].

Recent intercomparisons between the sine galvanometer and the PVM, for measurement of H, covering a period of several months, showed average agreement within 0.3 gamma [63]. This difference is within the accuracy of determination of pier differences at the observatory where the tests were made.

Field Control Equipment

An important auxiliary installation at the Fredericksburg Magnetic Observatory consists of three sets of coils for producing controlled and nearly uniform fields within a large working space. With this equipment it is possible to simulate the vector field that would be encountered at any point on the earth or in cosmic space. Not only is the desired vector field established, but the troublesome daily and irregular fluctuations are largely canceled. It is thus possible, for example, to pre-adjust an instrument intended for use in the Antarctic, or to test a new magnetometer designed to operate on the moon, where the magnetic field is believed to be less than one-tenth of 1 percent as strong as on the earth.

Figure 29.—Control console for the proton vector magnetometer, includes (a) switching and electronic gear for supplying polarizing current and for precise measurements of the proton-precession frequency of the hydrogen nuclei, and (b) switching and measuring circuits for the currents in the nulling coils.

The three sets of coils have mutually perpendicular axes. Their common center is just over the pier in the working space. One set of four coils is a Braunbek system [64] with vertical axis, a second set of four coils is a Braunbek system with horizontal axis in the magnetic

meridian, and the third set is a Helmholtz pair (p. 4) with horizontal axis in the magnetic east-west direction. In the Braunbek arrays, each coil has two independent windings—one for producing the desired steady field and the other for producing a field in opposition to the temporal variation field. The currents for the fields that cancel the ambient variations are automatically monitored by a magnetograph.

The large coils are about 5.5 meters in diameter, so that the useful working region is about one meter across.

Chapter VI. Origins of Geomagnetic Science

Second Revision by David G. Knapp

Medieval lore surrounding the mariner's compass, with its seeming evidence of fearful unseen powers and influences, must have been colored with a superstitious awe that can scarcely be appreciated by the present-day student. Such irrational attitudes may well account for the meagerness of contemporary references to the beginnings of compass art, and the unfortunate resulting obscurities in later writings. The labors of a host of scholars have erected a considerable body of literature on which to draw, though discrimination is needed in handling a number of unsettled points, as remarked in the predecessor to this publication. Though a fresh approach to the subject is not attempted here, some points in the earlier treatment are modified to reflect more recent scholarship. For fuller information see works by Crichton Mitchell [65] and by Balmer [5].

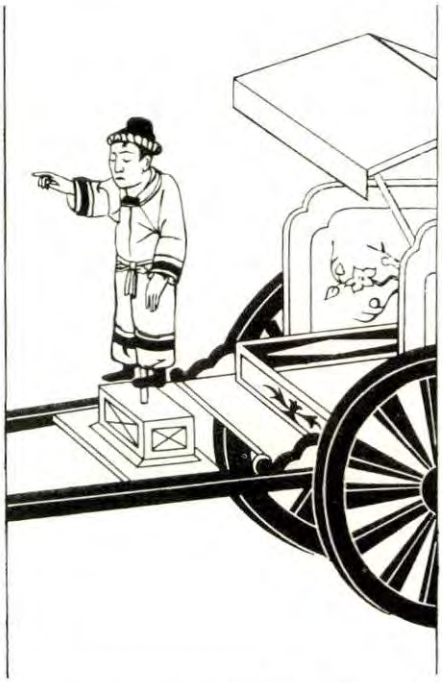

Figure 30.—A version of the "south-pointing chariot," believed to be of Chinese origin. The principle of its operation is obscure. From Urbanitzky, "Electricität und Magnetismus im Alterthume." (Original was in the Japanese encyclopedia *Wa zi si*, compiled by Kaï bara Tok sin.)

The Lodestone and its Properties

At what date the properties of the lodestone first became known to man has not been definitely determined. Its property of attracting iron was certainly known to the Greeks toward the close of the seventh century B.C., as it is mentioned by Thales, who lived from 640 to 546 B.C. The origin of the word "magnet" is not well established, but it may have come from the place where the lodestone was first found (in the hills of Magnesia).[1]

The names given to the lodestone, magnet, and compass form an interesting study and afford important clues to the diffusion of the concepts involved. Crichton Mitchell cites several writings in which this topic is explored. The terms for "magnet" in various languages tend to be suggestive of one or other of its properties. However, this does not establish whether a given term was first linked with magnetic action before or after its use with analogous meaning in another domain. Some properties of the magnet and its names in several languages are: Attraction for iron (French, aimant; Spanish, iman; Sanskrit, thoumbaka); directive property (English, lodestone; Icelandic, leidersteen; Swedish, segelsteen); hardness (Roman, adamas; Old English, adamant). The Italian form, calamita, may be derived from the method of supporting the magnet in the early form of compass, namely, on

[1] Of the three ancient places that bore this name, the one usually cited is a district of Macedonia adjoining the Gulf of Vólos. The other two Magnesias were in what is now Turkey—one the present city of Manisa, the other a town on the Büyük Menderes River, an important archeological site about 45 miles southeast of Smyrna. Alternative derivations of the word "magnet" have related it to "magnis" (strong), to Sanskrit "mahaji" (the great or wise—cf. the Maji), and to the name of its legendary discoverer, whose iron-tipped staff is supposed to have adhered to outcrops of the ore.

a bit of reed (calamo) floating in a vessel of water.

The nature of the attraction for iron by the magnet was variously explained by the writers of antiquity: "Iron gives it life and nourishes it"; "A certain appetite or desire of nutriment that makes the lodestone snatch the iron"; "Humidity in iron which the dryness of the magnet feeds upon." One theory of considerable standing held that some sort of exhalation or emanation streamed from one to another of the bodies concerned, and was able to produce the observed attraction.

In addition to the physical properties of the lodestone recognized at the present day, curative properties for all sorts of maladies were ascribed to it in the Middle Ages, just as such properties were later ascribed to electricity. Toothache, gout, dropsy, hemorrhage, and convulsions were among the many complaints which it was said to relieve, and even disputes between husband and wife came within the scope of its magic powers.

On the other hand, a common belief which prevailed for many centuries was that a magnet would lose its directive property if rubbed with garlic, and mariners were charged not to eat onions or garlic lest the odor "deprive the stone of its virtue by weakening it and prevent them from perceiving their correct course."

The ancient myths about magnetic rocks and hills, typified by the fatal mountain of lodestone that broke up ships by drawing the nails out (in "The Arabian Nights"), were the precursors of equally fantastic ideas in later times, attributing the action of the compass to a supposed magnetic mountain or island in the Arctic regions, the China Sea, or some equally remote place.

Some writers have credited the Greeks with the use of the lodestone to direct navigation at the time of the siege of Troy, on the basis of a passage in Homer's Odyssey; but this interpretation seems not at all warranted by the wording of the original passage. According to Bertelli, a careful examination of the writings of more than 70 Greek and Latin authors, covering the period from the 6th century B.C. to the

Figure 31.—Medieval floating compass, as shown by Athanasius Kircher, "Magnes sive de arte Magnetica" (1643).

10th century A.D., failed to disclose any mention of the directive property of the lodestone, or any suggestion from which one might conclude that this directive property found any use whatever in navigation, astronomy, or surveying during that long period of time, though there are numerous descriptions of voyages and storms at sea where mention of the compass would be expected, if it had been in general use at the time.

Apparently the only facts about the lodestone which were known before the 10th century were its property of attracting iron and of communicating that attractive power to iron. The property of polarity was unknown, as indicated by the fact that Pliny and subsequent writers attributed the phenomena of attraction, repulsion, and neutralization of magnetic action to three supposedly different minerals, magnete, teamede, and adamas.

Chinese application doubtful.—There has been a persistent belief that the directive property of the magnet was known to the Chinese before the beginning of the Christian era. Some writers go so far as to say that it was known as early as 2634 B.C. According to Klaproth a quaint legend relates that in the reign of Huang-ti the Emperor's troops attacked some rebels led by Tchi-yeou, on the plains of Tchou-lou. Finding that he was getting the worst of the conflict, Tchi-yeou raised a great smoke in order to throw the ranks of his adversary into confusion. Huang-ti was equal to the occasion, however, and constructed a chariot which indicated the south and thus was enabled to pursue the rebels and take Tchi-yeou prisoner. Modern scholars

consider this legend as clearly mythical. Huang-ti was probably the outstanding figure of Chinese antiquity, the legendary founder of the Chinese Empire, and it would not be surprising if knowledge and acts were ascribed to him which really belonged to a much later epoch.

The chih-nan-ch'ê or so-called south pointing cart, a recurrent curiosity in Oriental literature since the third or fourth century, has been claimed to have been in use in China as late as the 15th century and to have been introduced into Japan in the 7th century. (See fig. 30.) A pivoted figure with outstretched arm was mounted in front of the cart. Certain 17th-century missionaries supposed that a magnet had actuated the figure to keep it pointing south. It is now considered more likely that the cart was set in a place where the directions were known and that the figure was connected to the two wheels so that on rounding a bend the differential effect kept the figure pointing in the original direction.[2]

It must be recognized that a knowledge of the directive property of magnetized needles may have preceded by a long interval the embodiment of the principle in the form of a useful instrument, particularly if the secret was known only to a select class and carefully guarded. A remarkable passage in a work entitled "Mêng-ch'i-pi-t'an," which appeared toward the end of the 11th century A.D., seems to establish that the directive property was known in China at that period. This passage is as follows:

> A geomancer rubs the point of a needle with the lodestone to make it point to the south, but it will always deviate a little to the east, and not show the south; that to use the needle, it may be put on water, but it would not be steady; and also it may be put on the nail of a finger or on the lip of a bowl, but it is too apt to drop, because its motion is very brisk; that the best method is to hang it by a thread, and to prepare the contrivance, one has to single out a fine thread from a new skein of floss silk and fix it with a piece of beeswax on the middle of the needle, the latter to be hung up where there is no wind; that the needle would then always point to the south; that, on rubbing a needle with a lodestone, it may happen by chance to point to the north, and he (the author) owned needles of both sorts, and that no one could as yet find the principle of it.[3]

This passage was repeated in several later Chinese works without essential revision, but we have no trustworthy evidence of any application of this knowledge until quite some time later.

Medieval Origin of the Magnetic Compass

The earliest definite mention of the use of the compass in Europe occurs in a Latin treatise entitled "De Utensilibus," written about A.D. 1187 by an English monk, Alexander Neckam. In another book, "De Naturis Rerum," he writes: "Mariners at sea, when through cloudy weather in the day, which hides the sun, or through the darkness of the night they lose knowledge of the quarter of the world to which they are sailing, touch a needle with a magnet which will turn around until, on its own motion ceasing, its point will be directed toward the north."[4] Whether the first type was a floating lodestone (fig. 31) remains in doubt.

At about the same date Guyot de Provins, minstrel at the French court, in a politico-satirical poem entitled "La Bible," refers to the use by sailors of the compass with floating needle. Other writers of the 13th century who speak of the use of the compass are Jacobus de Vitry, Cardinal of Ptolemais in Syria; Raymond Lully, of Majorca; Vincent de Beauvais, a crusader; Roger Bacon, the English philosopher (p. 62); Brunetto Latini, a celebrated Florentine encyclopedist; and the poet Dante. Brunetto supposes that the lodestone directs the needle toward the mariner's star. He dwells on the distinction between the polarities of the opposite faces of the stone, and the effect each part has on the needle.

References to the compass in Chinese literature are fairly well authenticated after the 11th or 12th century, with some indication that Arabian navigators were the first to use a compass in Chinese waters. Klaproth found "no indubi-

[2] M. Hashimoto, Origin of the compass, in *Memoirs of the Research Department of the Toyo Bunko* (the Oriental Library), Tokyo, 1926, No. 1, pp. 69–92. For an excellent description of geared mechanisms for accomplishing the result stated above without resorting to differential gears, see A. C. Moule, The Chinese South-pointing Carriage in *T'oung Pao*, Leyden 23, 83, 1924. Note, however, that the device there described would not maintain a true indication unless the inside wheel were locked for each turn. Gradual turns would not register at all.

[3] Discussed by Friedrich Hirth, Ancient History of China, New York, 1908, p. 132. The translation above is that given by Crichton Mitchell.

[4] Neckham's statements are nowadays believed to refer to a floating compass; see W. E. May, J. Inst. Navig., 8: 283, 1955.

table use" of the compass in navigation by the Chinese until toward the end of the 13th century. A primitive floating needle seems to have been in use in China in the 16th century.[5]

European origin probable.—The conclusions of Crichton Mitchell with respect to the invention of the compass are as follows:

"(I) That while it is possible that the Chinese were acquainted with the directive property of a magnet by 1093 A.D., they made no further use of that property for at least two hundred years thereafter.

"(II) That there is no evidence of the origin of any such knowledge among the Arabs, and it is improbable that they transmitted any information on the matter to Europe, their earliest mention of the compass being nearly half a century after its first mention in Europe.

"(III) That the compass was in use in western Europe by 1187 A.D., and taking into consideration the fact that the directive property must have been discovered much earlier, it is most probable that a knowledge of that property and its application in western Europe were of independent origin and as early as, if not earlier than, [the same developments] in China."

A view more favorable to Chinese priority is advanced by Needham,[6] but his supporting arguments have not yet become available.

Petrus Peregrinus and the pivoted compass.—It is to Pierre Pelerin de Maricourt, usually referred to as Petrus Peregrinus, that we owe what is probably the first European treatise on the magnet and the earliest known work on experimental physics. Pierre was a native of Maricourt, a little village in Picardy, France, and his appellation Peregrinus indicates that he had taken part in the Crusades. He was a partisan of Charles of Anjou and was with him at the seige of Lucera in southern Italy and the time (August, 1269) of writing his famous letter to his friend and neighbor, Sygerus de Foucaucourt—"Epistola Petri Peregrini de Maricourt ad Sygerum de Foucaucourt, Miletem, de Magnete." [7]

In this epistle he gave a clear and concise statement about what was then known regarding the magnet and its properties, which he had evidently tested experimentally. He conceived and made use of a spherical lodestone "in the likeness of the heavens," the precursor of Gilbert's terrella. He devised methods for locating the axis of such a magnet, finding that at the axis poles a short piece of a needle would stand perpendicular to the surface of the stone. He must also be credited with discovering the fact that when a magnet is broken into a number of pieces each piece will be a magnet, and with devising the methods of touch and rubbing for reversing the polarity of a needle (p. 3).

In the second part of the discourse he described important improvements of the compass, which were attained (1) by floating the lodestone in a circular bowl with graduated rim, (2) by replacing the floating lodestone with a pivoted needle, turning between upper and lower bearings, and (3) by supplying an azimuth bar, having sighting pins, so that the azimuth of an object in any part of the horizon might be measured (fig. 32).

It will be noticed that Peregrinus had in his improved compass the features needed to ascertain whether or not the magnetic needle pointed precisely to the north. He noted (Part I, Chapter X) that the direction of the magnet is not toward the mariner's star, for that star is always out of the meridian except twice in each complete revolution of the firmament. Since he reached the conclusion that the poles of the magnet receive their power from the poles of the heavens, it seems safe to assume that the needle did not at that time point far from true north at the place where he made his experiments.

His work has further significance as a rare exemplar, for medieval times, of the experimental approach to Nature's laws. Small wonder, then, that he was hailed with the greatest enthusiasm by his advocate, the philosopher Roger Bacon,

[5] Some of the Chinese references are reviewed in the article "Compass" in the 11th and subsequent editions of the Encyclopedia Britannica. The article likewise quotes the passages from Cardinal de Vitry and from the "Livres dou Trésor" of Brunetto Latini.

[6] J. Needham, Science and Civilisation in China, vol. 4, in press, 1962.

[7] See item [66] of Bibliography, and S. P. Thompson, *Proc. Brit. Acad.*, 2, 377–408 (1906).

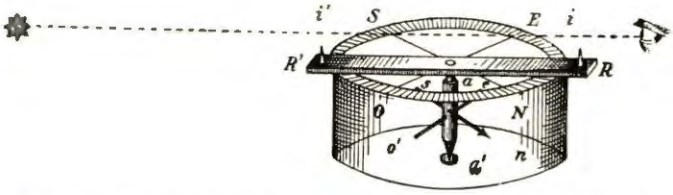

Figure 32.—Peregrinus' compass with a pivoted needle and a graduated rim (after Bertelli).

whose bold attack on the prevailing authoritarian basis of physical knowledge was a harbinger for the teachings of Copernicus, Galileo, Francis Bacon, Gilbert, and Newton, with their varying contributions to the emergence of experimental science. Roger Bacon characterized Peregrinus as the only man, besides Master John of London, who at that period could be deemed a perfect mathematician; and as one who understood the business of experimenting in natural philosophy, alchemy, and medicine better than anyone else in western Europe.

The Amalfi tradition.—The letter of Peregrinus tells us that the invention of a pivoted nautical compass took place no later than 1269. Once the instrument was put in service, its use in navigation must have spread rapidly, giving rise to inevitable refinements and improvements of the basic device. Any such change could lend color to a claim on behalf of a particular person or group to have invented the compass. For some 350 years a tradition persisted to the effect that the mariner's compass was invented by one Flavio Gioja, of Amalfi, Italy, about the year 1302. Bertelli made a very thorough investigation of the origin of this tradition and found nothing to indicate that it was founded on fact. The first writer to attribute a special knowledge of the compass to the Amalfians was Flavio Biondo, who, about 1450, made a first attempt at a history of Italy. The passage was quoted, with Flavio credited as its author, in a later work, whence it was carelessly requoted with the invention itself attributed to Flavio, who finally acquired the fictitious surname Gioja and the associated date.

It may be that the Amalfians should be credited with improving the compass by the substitution of a pivoted needle for the floating one and by the addition of the graduated compass card or "rose of the winds" attached to the needle and moving with it.

The Mariner's Compass After Peregrinus

Early Developments

Cap-and-pivot suspension.—The arrangement outlined by Peregrinus, with a needle on a staff confined between upper and lower bearings, did not afford the best solution to the difficulties imposed by the weakly magnetized needles then available, since the effects of friction in such a mounting are so largely dependent on dynamic conditions that are difficult to control. The introduction of the cap-and-pivot design constitutes another of the lost milestones in the evolution of the compass. In the modern version of this mounting, a very hard metallic pivot is solidly supported from below, and the movable card with its needles hangs from a jeweled cap which turns on the pivot. In this type of bearing the friction is small and uniform if the surfaces are properly shaped.

Compass cards and the rose of the winds.—It has been conjectured that the Amalfians introduced the movable "fly" or card attached to the needle; at all events, we are told by Da Buti, writing in about 1380, that the sailors of his day used a compass at the middle of which was pivoted a wheel of light paper—an indication that this feature was developed within a century of the time when Peregrinus wrote.

The remarkably accurate early charts of the Mediterranean Sea, contained in "Portolani" or handbooks of sailing directions, were usually embellished with an eight-pointed star or "rose," the same figure which served for the fly of the early compasses (possibly at first a by-product

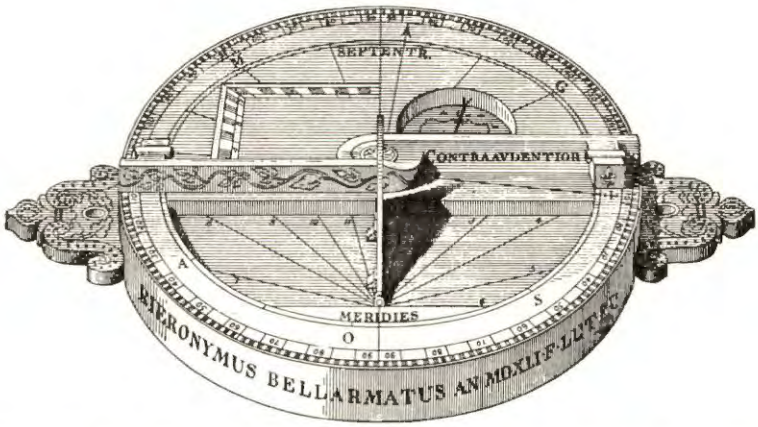

Figure 33.—A traveller's sundial with compass, made about 1541 and marked to show the magnetic declination. From G. Hellmann, "Die Anfänge der Magnetischen Beobachtungen."

of the pattern of rhumb-lines that criss-crossed the charts). Initials at the several vertices of the figure stood for the Italian names of the eight principal winds. An alternative system of marking the cardinal points utilized the Latin names of the corresponding quarters of the heavens—*septentriones, oriens, meridies,* and *occidens.* (See fig. 33.) Both systems ultimately fell out of use, though a vestige of the former is said to survive in the fleur-de-lis at the north point (supposedly derived as a combination of a spear-head with a "T" for *tramontano,* the north wind).[8]

The demands of accuracy led to the subdivision of each of the eight "winds" into four "quarters of the wind" (points) separated by $11\frac{1}{4}°$; this 32-point division is still in wide use, and it was mentioned by Chaucer as early as 1391. In modern times, the improved accuracy with which steam-powered vessels can be steered has resulted in the addition of a scale of degrees, and curiously enough the ensuing subordination of the older pattern of points has led in some cases to a reversion to the eight-point division, like the ancient wind roses, the intermediate points being then superseded by the degree markings.

Multiple needles.—In connection with the introduction of a movable card, trouble must have been experienced so long as only a single straight needle was used, for the motions of the ship would be apt to impart to the card a "wobbling" motion of its unweighted east and west edges. It is interesting to note that the early compasses often had an assembly of two needles, joined at their ends and spread apart in the middle; this tended to mitigate the difficulty just mentioned, as did the later use of an arrangement of parallel needles. It was finally shown that an arrangement should be used which would result in a card having approximately equal moments of inertia about all diameters, and such an arrangement is one feature of the Thomson compass.[9]

Gimbal rings.—It was an obvious desideratum to provide a special mounting for the compass so that the bowl as well as the card would remain horizontal despite the rolling and pitching of the ship. This was the purpose of the gimbal rings or so-called cardan suspension; this form of universal joint, now in such general use, made possible greater accuracy in measuring the compass bearing on any object, whether terrestrial or celestial, and paved the way for the introduction of the azimuth circle and other aids to the use of the compass.

Summarizing, the four chief improvements applied to Peregrinus' compass in late medieval times were: the cap-and-pivot support, the movable fly, the divided needle, and the gimbal sus-

[8] Silvanus P. Thompson, The Rose of the Winds: The Origin and Development of the Compass-card, *Proceedings of the British Academy,* 6, 179–209, 1914. Other authorities have advanced different and equally plausible explanations.

[9] See W. J. Peters: The distribution of mass in marine compasses, *Terr. Mag.* 37, 317–320, 1932.

pension. All these were apparently in use by 1551, the date of a treatise on navigation by Martin Cortes, in which a compass having these features is described.[10]

Modern Improvements

The development of the compass in modern times has proceeded hand in hand with the treatment of the troublesome deviations caused by the ship's magnetism (p. 42). It is a certainty that from the first beginnings of compass navigation there have been unexplained errors from the effects of iron fittings near the compass. However, the deviation as a systematic phenomenon seems to have attracted particular attention in the course of Captain James Cook's exploration in the southern oceans, during the period 1772–79. The wide-ranging explorations of Cook and others (especially in the Arctic) brought out the fact that deviations become more pronounced in high latitudes, where the horizontal intensity of the earth's field is small and the compass is more readily influenced by extraneous forces. Outstanding advances in the study of deviation and compensation were due to Matthew Flinders, Peter Barlow, and (as to high-latitude aspects) William Scoresby, Jr.

With the increasing use of iron in naval vessels, accelerated by the introduction of steam, the problem of compensating the compass came to the fore and engaged the attention of some of the ablest scientific minds of the 19th century. We owe to Poisson's insight the underlying principles of magnetic induction, which came to fruition in important advances by Airy and in the mathematical achievements of Archibald Smith; finally, Kelvin showed how to construct a compass to which the theory could be applied with complete satisfaction.

During rough weather, violent motions of the ship may cause the compass card to oscillate severely despite careful design of the card and the use of gimbals. In the time when Cortes wrote his treatise on navigation, he could only counsel blunting the pivot if the card was too unsteady. In modern practice, two methods of damping have proved useful. One is to use heavy copper for the compass bowl, so that rapid oscillations of the card will be restrained through the agency of the Foucault currents generated in the copper by the magnetic field of the moving needles. The other and older method (proposed in 1813) is to fill the compass bowl with liquid; this has the further advantage of reducing the weight on the pivot. It is said that the idea of using liquid in the bowl originated when a heavy sea, breaking over a vessel during a storm, accidentally filled the compass bowl with sea water, whereupon the violent swinging of the card ceased, yet the card continued to show directions correctly. For war vessels, the stability of the liquid compass under the shock imposed by the firing of heavy weapons proved to be a decided advantage, though it did not afford a solution to all the problems involved.

Early Knowledge of the Magnetic Declination

Discovery of the Effect

Possibly a Chinese discovery.—The isolated passage from "Mêng-ch'i-pi-t'an" quoted on page 61 has often been cited as indicating that the Chinese were aware of the magnetic declination before its discovery in Europe. The words "will always deviate a little to the east" certainly suggest such an interpretation to the modern reader. However, the passage contains the further statement that when suspended by the "best" method the needle would "always point to the south." Translators are not agreed as to the proper rendering of the passage, and the version given above is not altogether clear on this point, so that some doubt remains as to the original author's meaning. Furthermore, there is no elaboration of the matter; the whole emphasis is on the remarkable fact of the directional behavior, rather than on any precise measure of the phenomenon.

If the Chinese had known of the magnetic declination as early as the 12th century, it is reasonable to presume (as Bertelli points out) that the knowledge would have been handed down

[10] "Breve compendio de la sphera y de la arte de navegar" (Seville). The portion germane to the present discussion is translated by H. D. Harradon [66]. **48**, 79.

from generation to generation. However, at the beginning of the 17th century, when the Jesuit mathematician and astronomer Matteo Ricci and some of his fellow missionaries were allowed by the Emperor of China to take part in the Tribunal of Mathematicians, it was with great difficulty and only by ocular demonstration that they were able to convince the Chinese scientists that the magnetic and astronomic meridians were not coincident. At that time the declination at Peking was about 2° W., as determined by Ricci. Nearly 2 centuries later Amiot found that the Chinese still used that value of declination in placing their sundials, indicating that the knowledge of the fact was preserved for 2 centuries after its demonstration by Ricci.

Observations by Columbus not significant here.—Columbus is frequently credited with the discovery of the fact that the compass needle does not in general point true to the pole and that it changes it direction as it is carried from place to place. This viewpoint is based on certain obscure statements found in the journal kept by Columbus, or rather in documents prepared by subsequent writers who made abstracts of his journal. One passage, however, shows that one of the compasses carried on the second voyage was constructed with the needles set away from the north point of the card, so as to allow for the declination prevailing at some place (presumably the locality where the compass was made). Columbus appears to have been troubled by the diurnal revolution of Polaris, a confusing factor in the method he followed for checking the indications of the compass. Furthermore, all his epochal voyages were made in regions where the magnetic declination and its space changes were relatively small. (See fig. 37.) The whole matter has been further obscured by errors of long standing in various editions and translations of the relevant documents.

While the discoverer probably had no opportunity to gain a comprehensive view of the space changes in declination, nevertheless he seems to have been the first navigator of Western civilization to penetrate a region of west declination and to remark on the behavior of the compass therein. In any event, the chief reliance of Columbus, as of all navigators of that day, was on dead reckoning, not on celestial observation; and the successful completion of his voyages, with all their consequences to civilization, attest to an opportune skill in that art, coupled with the indomitable spirit that proved decisive, completely overshadowing any defects that might be singled out from his speculations on the behavior of the compass.

Evidence of compass charts.—Returning now to an earlier day, we find that the compass played an important role in the medieval phases of cartographic development. This instrument came into use during an era when geographic knowledge was at a low ebb, but as soon as compasses of the requisite precision became generally available so that mariners might determine with reasonable accuracy the direction from one port to another, chart construction was established on a much surer footing.

The early charts of the Mediterranean coasts of the 14th and 15th centuries were thus oriented by compass, in disregard of the (perhaps unrecognized) fact that the compass needle does not in general point true to the pole. The earliest of these charts were by Marino Sanuto, between 1306 and 1324; the best, however, are those in the atlas of Andrea Bianco of Venice, which bears the date 1436. This atlas was subjected to a critical comparison with modern charts by Oscar Peschel. He found that in spite of the crude appliances in use at that date, the distances from place to place harmonized in a most remarkable manner with later, more accurate, determinations; but the places were not always in their proper relations as regards latitude and longitude, the departures therefrom being quite systematic. This was more noticeable in the latitudes because of the greater distances involved, places at the west end of the Mediterranean being shown too far south with reference to those at the east end.

As the charts were based on compass directions, this systematic departure from the true directions indicates that the direction shown by the compass at that time differed by an appreciable amount from true north. By measuring the angle through which one of these charts had

to be turned in order that the places would fall in their proper geographic relations, L. A. Bauer found that the magnetic declination attributed to Rome was 5° E. in 1436 (or more probably before that date as the charts were undoubtedly constructed from data obtained during many years prior to the date of publication).

In later years, after the fact of the magnetic declination came to be generally known, it became the practice in some localities to place the needles at such an angle on the compass card that the compass would give true bearings instead of magnetic bearings in the particular locality in which it is to be used. Thus Norman, in his book, "The Newe Attractive," published in London in 1581, says that he finds in Europe five sorts of compasses, depending upon the locality in which they were used. Those made in Italy gave the correct magnetic bearings, as a rule, presumably because the magnetic declination was small in the Mediterranean; in Holland and Denmark the wires were set three-quarters of a point or sometimes a whole point "to the eastward of the north of the compass." (See p. 64 regarding "points.") In compasses for use in France, Spain, Portugal, and England, the wires were most commonly set at half a point. Thus, differing compasses were used in charting the coasts of different parts of Europe and the East and West Indies as well. In Russia still another angle was used.

Norman goes on to say:

> . . . And the Mayster or Maryner Sayling by these Compasses of sundry sorts may thereby fall into great perill, and the reason is, because that of long time these Compasses haue been used, by them the Marine Plats haue bene described of sundry sortes, every one according to the Compasse of that Countrey.
>
> If then he take not the Compasse of the same setts or making that the Plat was made by, then his Carde or Plat will showe him one Course and the Compasse when he thinketh he goeth well, will carry him another way.

This difficulty is discussed at length by the Dutch cartographer Willem Barentsz in a navigator's atlas published in 1595. Overlapping sets of convergent rhumb lines were provided on some of his charts to facilitate their use with either Flemish or Italian compasses as desired. As Heathcote points out, these lines show that in that period the Flemish compasses were set to allow for 6 degrees of east declination. A discrepancy between Dutch and Genoese compasses was also noted by Columbus. (See p. 66.)

The earliest known maps on which magnetic declination was graphically depicted are probably certain German road maps by Etzlaub, dating from about the time of Columbus' first voyage.. On these maps there appears a figure of a compass with its needle pointing about 11¼° east of north. Again, a map of the coast of Palestine, which was included in a work published in 1532, contained a figure which similarly seems to represent the declination as 25° west (apparently an excessive value).[12] Such maps were the precursors of the isogonic charts discussed on pages 9–12 and 74.

Evidence in sundial compasses of first knowledge of the declination.—The investigations of Hellmann indicate that it was the construction of sundials that first required a definite recognition of the magnetic declination, so far as can be established from the available records. Besides fixed sundials, the use of which may be traced back into the Babylonian-Chaldean period, there were also in olden times portable sundials for travelers, the distinctive feature being a small compass, to be used no doubt for the purpose of orientation. Samples of these portable sundials are preserved in many museums of Europe. The majority of them are of German origin, and it appears that as early as the middle of the 15th century Nuremberg was a recognized center for the manufacture of sundials provided with magnetic needles.

Thanks to the searching investigations of W. Wolkenhauer there have been brought to light three compass sundials constructed prior to 1500. The most important of these was preserved in the Museum Ferdinandeum at Innsbruck. This is a pocket sundial not much larger than a watch. It bears the date 1451, and is made of copper (or bronze), gilded and decorated with a black enameled imperial eagle. According to Hellmann, there appears to be no question that this sundial was made in Nuremberg, probably for Emperor Frederick III.

[12] G. Hellmann: The beginnings of magnetic observations, *Terr. Mag.*, 4, 73, 1899, p. 79. See also *Terr. Mag.*, 13, 97, 1908.

The cardinal points are indicated on the rim of the compass box. Across the bottom of the box there is a heavily engraved line, forked at one end, which it is believed indicates the direction of the compass needle at Nuremberg at the time the instrument was made—about 11° east of true north.

Hellmann has found that still another specimen, in the Bavarian National Museum, dating from the year 1456, and very probably by the same maker, likewise has engraved on the compass a line making an angle of about 11° with the true north-south line. As the making of compass sundials had evidently reached a high state of perfection in the middle of the 15th century, Hellmann argues that this angle of 11° E. may refer to an earlier date than 1451, as it is known that the same angle was used by Nuremberg compass makers well into the 16th century. However, it has been suggested that the endeavor may have been simply to allow one point as a sufficiently close approximation to the prevailing declination; one point of the nautical compass equals 11¼ degrees. The same amount of east declination is indicated on the early German road maps already mentioned.

One of the most famous of the compass makers, as they were called, was Georg Hartmann, who lived in Nuremberg from 1518 until his death, serving as vicar of the church of St. Sebaldus. He constructed such sundials in great numbers for persons of high rank, among others Duke Albert of Prussia, with whom he corresponded. In one letter Hartmann speaks of making eight compass sundials of ivory and four smaller ones of boxwood, most of them designed for use in latitude 55°.

We have no means of determining at what date the makers or users of compasses became convinced that the failure of the compass needle to point exactly north was not due to imperfection of construction or to the peculiarity of the lodestone with which the needle was rubbed, but it is to Hartmann that we owe the first recorded determination of the magnetic declination on land. Under date of March 4, 1544, he wrote to Duke Albert of Prussia that from his own observations he had found the declination to be about 6° E. at Rome and 10° E. at Nuremberg and more or less at other places.[14] As Hartmann was living in Rome in 1510, his observation must refer to that date.

Even before that date, as we have seen, the compass makers adopted the practice of placing a line on the sundial to indicate the angle between true north and the direction taken by the compass needle, and Wolkenhauer gives a valuable summary of the angles of the early compass sundials according to the country or place from which they originated. Thus it has been possible, from some of the old sundials which have been preserved, to derive values of the magnetic declination for the date of their construction. From the one shown in figure 33, for example, an ivory sundial made by Hieronymus Bellarmatus in 1541 and found in the collection of the Prince de Conti, it is concluded that the declination was about 7° E. in Paris in 1541.

Early Methods of Determining the Magnetic Declination

The first method was no doubt that of noting the magnetic bearing of the pole star (in practice, of a point beneath it on the horizon), and this was probably the one employed by Columbus. That no great accuracy could be attained in this way is self-evident, and it is doubtful whether at first the motion of the pole star about the pole was recognized and taken into account, though such motion was clearly explained by Peregrinus in 1269. (See p. 62.)

Felipe Guillen, a Sevillian apothecary, devised an instrument for a more accurate determination of the declination, which he called *brujula de variacion* and which he presented to the King of Portugal in 1525. With this instrument the magnetic bearing of the sun was noted at equal altitudes before and after noon, with the aid of the shadow from a stylus. Half the difference of the bearings was the declination.

The first book giving directions for determin-

[14] See item [66] of Bibliography on p. 78. The story that one Peter Adsiger determined the declination in 1269 was discredited by Wenckebach in 1836; it arose from a spurious passage in one of the manuscripts derived from the Peregrinus letter.

ing the declination appears to be one by Francisco Falero, published at Seville in 1535. He gave three methods, all making use of the sun: (1) magnetic bearing of the sun at apparent noon, when the shadow of the stylus falls to the north, (2) Guillen's method of equal altitudes, and (3) magnetic bearing of the sun at sunrise and sunset.

In 1537 Pedro Nunes improved Guillen's instrument by adding a device for measuring the sun's altitude and invented a new method for the determination of latitude at any time of day. Infante Dom Luis of Portugal, who had received instruction in mathematics and astronomy from Nunes and had shown great interest in all nautical problems, presented such an instrument to João de Castro, commander of one of the 11 ships that sailed to the East Indies in 1538, and charged him to give it and the new methods a thorough test. How completely Castro carried out his instructions is shown by the very full journals or log books in which he recorded all his nautical, magnetic, meteorologic, and hydrographic observations and notes on allied phenomena from 1538 to 1541. They include 43 determinations of the magnetic declination, notes regarding the instruments and methods, the deviation of the compass, magnetism of rocks, etc. After reading the journals, Hellmann did not hesitate to pronounce João de Castro to be the most noteworthy representative of scientific marine investigations up to the close of the epoch of discoveries. It is of interest that, on one occasion, the journal recorded serious errors owing to the proximity of the ship's armament. (See ref. [66].)

The methods thus given such a thorough trial came gradually into general use among navigators, and we find them described by writers in Spain, England, and Holland as late as the end of the 16th century, but without mention of Guillen, Falero, or Nunes.

Norman and the Magnetic Inclination

Although Hartmann, the Nuremberg maker of sundials, had noticed in 1544 that the north end of the compass needle tends to dip below the horizon, it was left for Robert Norman, of London, to devise an apparatus with a needle supported on a horizontal axis and actually measure the amount of dip. In his book "The Newe Attractive," published in 1581, Norman tells "by what means the rare and strange declining of the needle from the plane of the horizon was first found." Norman was an instrument maker who had had 18 to 20 years of practical experience as a seaman. In making compasses he noticed that it was always necesary to put small pieces of wax on the south end of the needle in order to balance it, although it had been perfectly balanced before magnetization. He paid little heed to this fact, however, until he had occasion to make an instrument with a needle 6 inches long and was constrained to cut away some of the north end to secure a balance. In doing this he cut it too short and spoiled the needle.

Vexed by the necessity of doing his work over again ("hereby being stroken in some choller" as he says), Norman devised an instrument to determine how much the needle touched with the stone would decline, or what greatest angle it would make with the plane of the horizon. With this instrument he measured the dip at London in 1576 and found it to be 71°50′. The general character of the instrument is indicated by the sketch in figure 34, copied from Norman's book.

Norman continued his investigations and proved experimentally that the force exerted on the needle by the earth's magnetism does not produce motion of translation but simply that of rotation. To do this he first stuck a steel wire through a piece of cork of such size as to support the needle on the surface of a vessel of water. Then he cut away the cork bit by bit until it would float the wire well beneath the surface. At the same time he adjusted the position of the cork with respect to the wire so that the wire would lie horizontal. After being rubbed by the stone, the north end of the wire dipped below the horizon as the needle had done in the dip circle, but the supporting cork still

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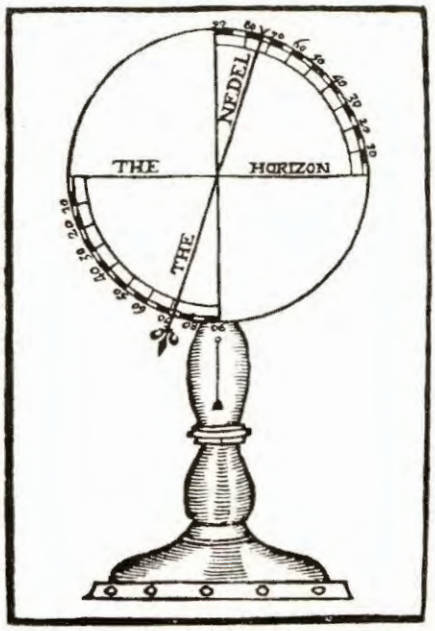

Figure 34.—First dip circle (after Norman, 1576).

held it in equilibrium, neither sinking nor rising to the surface. (See fig. 35.)

He also weighted several pieces of steel wire before and after magnetization, using a "fine gold balance," and showed that no change of weight occurred, thus disproving the assertion made by some that the act of rubbing one end of the needle by the stone added to its weight.

It should be remarked that the prevailing opinion of Norman's day regarded the compass as being drawn toward a "point attractive" usually identified with the celestial pole or with a supposed magnetic mountain or island (p. 60). Norman refuted this false idea, maintaining as a result of his experiments (a) that the supposed point toward which the north end of the needle tended to direct itself was not above the horizon but below it, and (b) that it was not a "point attractive" but a "point respective"—or in modern terms, that the needle was not attracted but merely directed toward the point, which he believed lay somewhere in the continuation of the line through the dipping needle, so that dip observations in other places would serve to fix the position of the point by intersections. He ventured the opinion that the angle of dip would be found to change according to the distance from the "point respective." The actual behavior of the dip needle at various distances from the earth's north magnetic pole is not at all in accord with Norman's hypothesis of a "point respective," yet his experiments and deductions constituted a large forward step and an undoubted stimulus to the next great advance in the science.

In his book Norman called attention to the common practice of adjusting the compass card to correspond with the declination in the region where it was to be used, and to the confusion which had resulted from the use of such compasses in making maps. (See p. 67.)

Annexed to later editions of Norman's book (if not to the first) appeared "A discourse of the variation of the compasse, or magneticall needle," by William Borough, which explained several methods of determining the magnetic declination and gave directions for its use in navigation. Borough called attention to the irregular distribution of the earth's magnetism, borne out by his own experience as a navigator, and showed that the observed compass variations cannot be explained by a magnetic north pole toward which the needle is directed, thereby

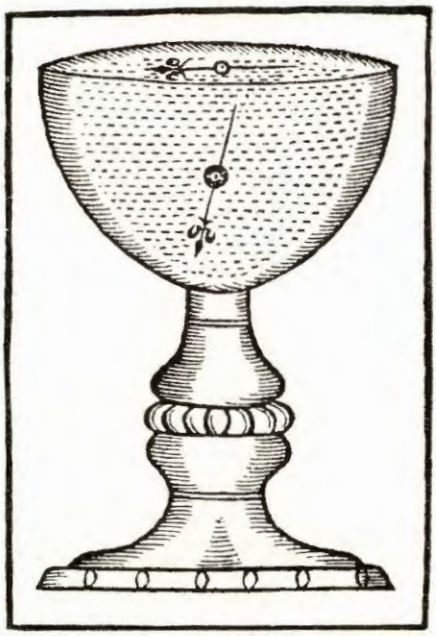

Figure 35.—Norman's experiment to show the absence of net force on a magnetized needle.

refuting a widespread belief which nevertheless persists in some quarters to the present time. (See p. 8.)

The Work of William Gilbert

The year 1600 is a memorable one in the history of the sciences of magnetism and electricity for in that year appeared Dr. William Gilbert's famous work "De Magnete," giving the most complete summary of the properties of magnetic bodies up to that time, and containing his theory that the earth itself is a great magnet.

Gilbert was born at Colchester, England, in 1540, and after graduating at St. Johns College and serving there as mathematical examiner, he took up the study of medicine and received his degree in 1569. He is said to have practiced as a physician with great success and applause. His skill attracted the attention of Queen Elizabeth, by whom he was appointed physician in ordinary, and who showed him many marks of her favor, besides settling upon him an annual pension to aid him in the prosecution of his philosophical studies.

Gilbert's early investigations were directed to the study of chemistry, but later he turned his attention to electricity and magnetism, his interest aroused perhaps by Norman's discovery of the magnetic dip and the publication of "The Newe Attractive" in 1581; for it is stated that Gilbert had been actively engaged in the study of magnetism for nearly 18 years before the appearance of "De Magnete" in 1600, so that he must have begun about 1582.

Gilbert went about his investigations in a thorough and systematic manner. The many citations in the book attest his familiarity with previous writings on the subject, and it is said that he spent £5,000 on his experiments, "examining very many matters taken out of lofty mountains or the depths of seas, or deepest caverns, or hidden mines, in order to discover the true substance of the earth and of magnetic forces." He evidently had a collection of lodestones of various kinds coming from a number of different localities. Gilbert, like Norman, was a thorough believer in the importance of experimentation, and he had no patience with the "conjectures and opinions of philosophical speculators of the common sort." Nearly every conclusion drawn rests on experiments made over and over under slightly varying conditions; in this lies the great value of Gilbert's work on the properties of magnetic bodies. He was not willing to accept the statements of others until he had satisfied himself experimentally that they were correct.

In connection with his conception of the earth as a great magnet, Gilbert paid particular attention to experiments with a terrella, or spherical lodestone, and a very small pivoted magnetized needle (versorium) as long as a barleycorn. His description of one terrella gives its diameter as 6 or 7 fingerbreadths, but he evidently had several terrellas.

"De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure," as the title indicates, was written in Latin, but an English translation by P. Fleury Mottelay was published in 1893, and it is from that translation that the information here given has been derived.[15] Unfortunately Gilbert frequently made use of what he terms "words new and unheard-of," besides attaching to many others a significance far different from that generally accepted at this day, so that the translator had difficulty in determining the exact meaning of some passages in the book.

The earth a great magnet.—Gilbert first discusses the sources and characteristics of various kinds of lodestone and iron ore, and their fundamental similarity. He then urges a comprehensive theory to the effect that the lodestone is the fundamental form of matter; that lodestone constitutes all but the outer shell of the earth and that the various forms of matter with which we are familiar are derived from lodestone by disintegration; that the earth, being a great lodestone, has poles and a magnetic equator, just as

[15] Mottelay translates the full title of Gilbert's work as follows: "On the loadstone and magnetic bodies and on the great magnet the earth, a new physiology, demonstrated with many arguments and experiments." Another translation was distributed by the Gilbert Club in 1901 and republished in 1958 with an introduction by Derek J. Price [17]. It is characterized by high scholarship and meticulous adherence to the style and format of the original. The reprint includes voluminous notes by the principal translator, S. P. Thompson, reflecting his painstaking researches on numerous facets of compass history and the rise of geomagnetism.

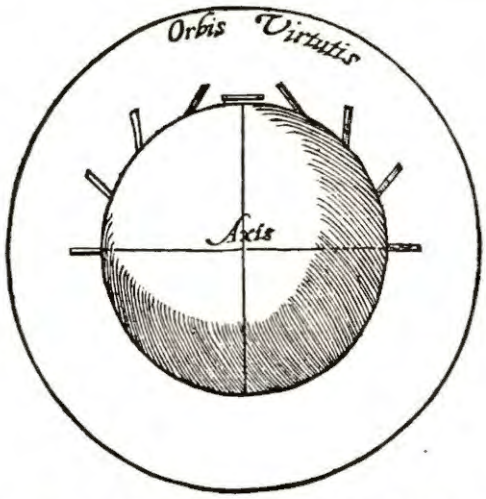

Figure 36.—Gilbert's representation of the field about a spherical magnet such as the earth.

the terrella has its magnetic poles and a neutral line between. And the earth takes a definite direction in space, just as the terrella takes a definite direction with reference to the earth; it rotates daily about its axis, thereby defining (so he believed) the direction in which a rotating terrella always tended to come to rest. Although most of Gilbert's reasons for considering the earth a great lodestone have since been discarded (see p. 20), his idea that the earth acts in much the same way as a spherical magnet was the starting point for the future development of the science of terrestrial magnetism. The renowned Galileo was captivated by Gilbert's treatise, which supported the Copernican view that the earth rotates about an axis.

According to Gilbert's theory the compass needle should everywhere point in the direction of the true meridian. Though he gave no table of values of the magnetic declination in "De Magnete," he was familiar with what was known of its distribution at that time and recognized the errors inherent in the instruments and methods then in use. He explained the fact that the needle does not in general point true north by saying that the north end of the needle is drawn toward the land in the northern hemisphere (the south end in the southern hemisphere) because of the greater amount of lodestone in the more elevated portions of the earth's crust. He supported this statement by experiments with a terrella on which irregular masses projected above the spherical surface. At that time the declination was small in the interior of Europe and he was able to find a spot near the center of the raised mass on the terrella where the versorium showed no variation. From this he concluded that declination was greatest near the borders of the land and decreased to zero in midocean and also in the middle of continents. Later observations showed the error of his conclusions. He was evidently familiar with the fact that the force directing the compass needle, the horizontal force, is greatest at the magnetic equator and decreases toward the magnetic poles, as he gives that as the reason why the observed declinations are greater in higher latitudes than near the equator, the needle being more susceptible to disturbing causes near the surface as the directive force becomes less.

Although Gilbert probably had no observed value of dip except the one determined by Norman at London, he was able with his terrella to obtain a very good idea of the distribution of dip on a uniformly magnetized sphere (fig. 36). Note that his diagram correctly shows how the dip on such a sphere would change from zero at the equator to 90° at either pole, the change being most rapid in crossing the equator. He devised an ingenious graphical method of finding the dip for any latitude, based on the assumption that the axis of magnetization coincided with the axis of rotation. This assumption would lead to a different construction in terms of modern theory (see p. 7), but Gilbert's was a remarkably close approximation and a radical improvement over Norman's "point respective." It yielded for the latitude of London approximately the value observed by Norman. A prompt confirmation of Gilbert's bold prediction regarding increase of dip with latitude was afforded by Hudson, on his voyage across the Barents Sea in 1608, when he made many dip observations giving values in excess of 84°.

Gilbert proposed to use dip observations as a means of determining latitude; he designed an instrument for measuring the dip, and showed how it might be mounted on board ship for the purpose. At the same time, he disparaged the analogous notion of finding longitude from the declination (a favorite project since the time of Columbus), holding that the needle "does not follow the rule of any meridian" and that the declination is "in divers ways ever uncertain." He anticipated that similar irregularities of dip might impair the usefulness of his method of finding latitude, and cautioned against relying on the method until the distribution of dip should be charted, though he seemed to think the irregularities would be small. It may be noted that

the existence of a considerable discrepancy between the earth's geographic and magnetic axes (of which he was skeptical or unaware) is an important factor in both propositions.

In Book II an explanation is given of the difference between the attraction exerted by electrified bodies, particularly amber, and that exerted by the lodestone and other magnetized bodies. The mutual action between lodestone and iron is examined in great detail.

Gilbert discusses in Book III the "verticity" or directive property of the lodestone. He notes that a bar of iron may be magnetized without being rubbed by the lodestone; that, for example, heated iron that is hammered while cooling acquires "verticity" dependent upon the direction it is held; also that an iron bar fixed in a north-and-south direction for many years will become magnetized. This latter fact was discovered on January 6, 1586. A piece of iron which for a long time had supported a terra-cotta ornament on the tower of the church of San Agostino at Rimini was bent by the force of the winds and so remained for 10 years. The friars, wishing to have it restored to its original shape, took it to a blacksmith, and in the smithy it was discovered that it resembled lodestone and attracted iron.

Impressed with the fact that the earth as well as the lodestone exerts an influence at a distance, in spite of intervening bodies, Gilbert used the term "orbis virtutis" (fig. 36) to denote the magnetic field of a magnet—the space surrounding a magnet through which its influence extends—apparently getting the idea from Norman, who spoke of the "vertue extending rounde about the stone in great compasse." [16]

An interesting sidelight on the times in which Gilbert lived is afforded by the following statement in his book: ". . . and as the planets and other heavenly bodies, according to their positions in the universe and according to their configuration with the horizon and the earth, do then impart to the newcomer (newborn infant) special peculiar qualites, so a piece of iron, while it is being wrought and lengthened, is affected by the general cause, the earth." Though derisive of astrologers, Gilbert could thus point up his insights in magnetism with a supporting argument drawn from astrological tenets, which were not wholly disavowed by philosophers until considerably after Gilbert's day.

Discovery of the Secular Change

The next noteworthy contribution to the science of terrestrial magnetism was Gellibrand's discovery in 1634 of the change of the magnetic declination with time. Up to that time it had been supposed that the declination, though different at different places, was fixed and invariable at any one place, except it might suffer a change "by the break up of a continent," as Gilbert put it.

Henry Gellibrand was a professor of mathematics at Gresham College. He made a careful determination of the magnetic declination at Diepford, about 3 miles southeast of London Bridge, on June 12, 1634, and got the value 4°06′ E. Now Edmund Gunter, another mathematician of Gresham College, had found it to be 5°56½′ E. on June 13, 1622, and Borough and Norman had found 11°15′ E. about 1580. Gellibrand repeated his observations and then examined carefully the published observations of Borough, without finding any material error. Clearly, therefore, the magnetic declination had changed by a considerable amount between 1580 and 1634.

Gellibrand announced his discovery in a book entitled "A Discourse Mathematical on the Variation of the Magneticall Needle, together with its Admirable Diminution Lately Discovered." He refrained from speculating as to the source of the change, "whether it may be imputed to the magnet or the earth, or both," saying that it must be left to future times to discover.

Gellibrand's discovery was of the greatest importance to all users of the compass. No longer could the mariner feel confident that on visiting a distant port he would find the same value of

[16] Some other possible sources for Gilbert's ideas are discussed by W. James King in a paper, "The natural philosophy of William Gilbert and his predecessors," U.S. National Museum Bul. 218, pp. 121–140, 1959.

declination as had been observed by previous navigators, nor could the land surveyor retrace the lines of an old compass survey without first finding out how much the declination had changed in the meantime.

Since Gellibrand's time, observations have shown that the dip and intensity of the earth's magnetic field also are changing with lapse of time, but the cause of the change is still not fully understood. The idea has been advanced repeatedly that the secular changes were due to shifting of the magnetic pole, but it has been long since established that they are too complex to be described in that simple fashion. (See p. 16.)

Much of our understanding of the main-field patterns as well as of the secular change is traceable to the persistent assaults on Arctic geomagnetism carried out by explorers during the 18th and 19th centuries.[17]

Historic Magnetic Charts

Methods of showing the value of the magnetic declination by means of compass roses, as on some of the medieval charts (p. 66), were ill adapted for use on general charts of the oceans and continents because of the changes of the declination from place to place. We are told that "magnetic charts" were prepared by Santa Cruz about 1536; it is not known what his mode of delineation was. As the record stands, however, it was not until the next century that a suitable method was devised—a method destined to find wide application in meteorology, topographic mapping, and other branches of physical geography. This invention was disclosed for the first time in a Latin work published in 1641 by Athanasius Kircher, who credits it to the Jesuit mathematician Christopher Borrus. The earliest extant example of the type, and probably the first such chart to have a firm foundation in observed data, was the work of the astronomer Edmond Halley, who published in 1701 a chart (fig. 38) showing lines of equal magnetic declination over the Atlantic Ocean, based upon his observations made between 1698 and 1701 on a "pink," the *Paramour,* at the expense of the British Government. His second chart, probably published a year later, gave the lines of equal variation over the Indian Ocean and the extreme western part of the Pacific as well as over the Atlantic. The name "isogonic lines" was applied to Halley's curves after they came into general use.

Van Bemmelen gives[18] an extensive collection of early values of the magnetic declination and a series of isogonic charts which he prepared for the years 1500, 1550, 1600, 1650, and 1700. The one for 1500 is shown in figure 37. Although any charts for these early epochs are necessarily only rough approximations because of the limited number of observations available, the series in question nevertheless brings out well the change in the distribution of the magnetic declination over the earth's surface from century to century.

Halley's example soon led the way to other uses of the scheme, and was the inspiration for the first dip chart, published in 1721 by William Whiston. Many of the early magnetic charts were prepared with the avowed objective of enabling the mariner to find his longitude by means of magnetic observations. (See p. 72.) Whiston expressed the hope that this might be accomplished with dip observations. His chart, however, was restricted to southeastern England, and it was not until 1768 that a world chart of inclination was published, the work of Johann Carl Wilcke of Sweden. This chart attested the general confirmation of Gilbert's prediction concerning the distribution of dip. The corresponding relation for intensity was discovered by Lamanon in 1787, and independently by Humboldt on his travels in America (1798–1803). The voyages of Duperrey in 1822–25 afforded further elucidation of the pattern of the earth's magnetism, particularly with regard to the magnetic equator.

[17] D. G. Knapp, Arctic aspects of geomagnetism, ch. 12 in The Dynamic North, bk. 1, Chief Naval Oper. for Polar Projects (OP-03A3), 65 pp., 1956.

[18] "Die Abweichung der Magnetnadel," in *Observations made at the Royal Magnetical and Meteorological Observatory at Batavia,* 21, supplement, 1899. Some of the charts of van Bemmelen, as well as those of Halley, are reproduced and discussed in S. Chapman's "Edmond Halley as physical geographer, and the story of his charts," *Roy. Astr. Soc.,* Occas. Notes, No. 9, London, 1941.

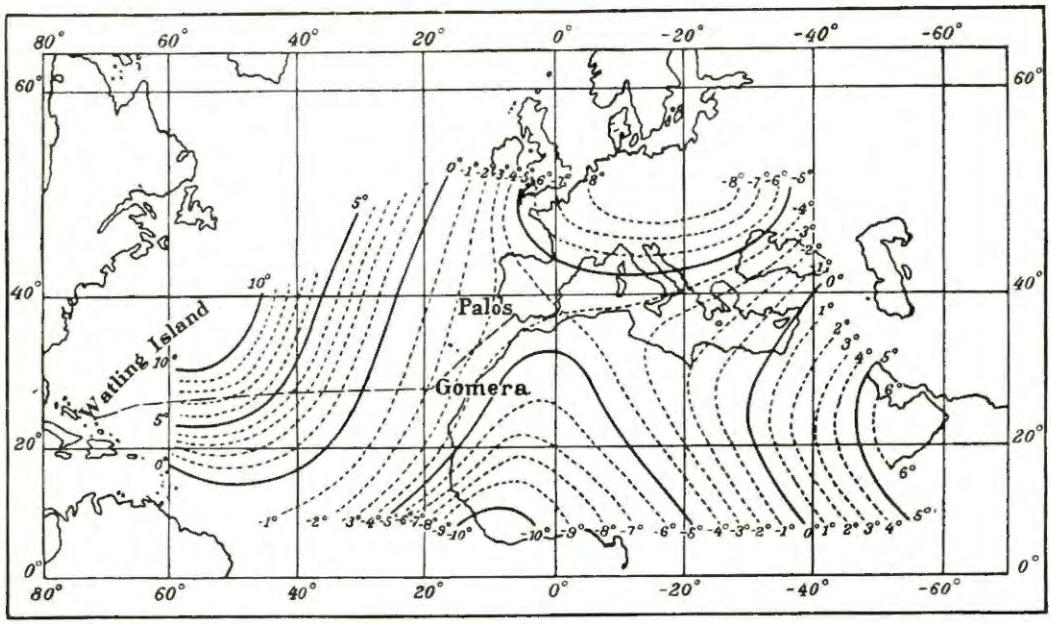

Figure 37.—Van Bemmelen's isogonic chart for 1500. Scale at Equator, 1:130,000,000. (Published in 1899. East declination shown with negative sign.) The approximate track of Columbus' Atlantic crossing of 1492 has been added.

Discovery of the Daily Variation of Declination

For half a century after the existence of secular change was well established, it was supposed that this was the only time-dependent feature of the earth's magnetism. However, in 1685 a party of French missionaries, guests of the Siamese king, recorded on December 9 and 10 a succession of determination of the declination which failed to agree; the reported results [19] of four observations showed a spread from 0°16′ W. to 0°38′ W. As all these observations were made at the same place (at Louvo, now Lop-buri, Thailand) they must be regarded as the pattern of early observations containing an intimation of the occurrence of transient changes in the direction of the compass needle.

The credit for the discovery of the daily variation must properly be given, however, to the noted London horologist George Graham, who, after many hundreds of observations of the declination at various times of the day, made in 1722 a definite announcement of his discovery. A few years later, with the aid of a needle made expressly for the purpose, the discovery was verified and amplified by the Swedish Astronomer Anders Celsius (whose name is perhaps better known in connection with the Centigrade temperature scale). He was followed in this by a host of other investigators; in fact, the daily variation, because of its complexity and periodic character, has afforded a fruitful and well-tilled field of investigation. Celsius, with his colleague and successor Hiorter, is likewise credited with discovering (1747) the relation between magnetic disturbance and the aurora. The seasonal change in the daily variation of declination was brought to light by Canton in 1759, and its inversion in southern latitudes by John MacDonald in 1795.

Developments Culminating in the Work of Gauss

Graham was probably the first to suggest that relative values of the intensity of the earth's

[19] "A relation of the voyage to Siam performed by six Jesuits sent by the French King to the Indies and China in the year 1685, with their astrological observations and their remarks of natural philosophy, geography, hydrography, and history." [By Father Gui Tachard.] London, 1688, pp. 231–2. See also P. S. Aab, Report on terrestrial magnetism in Siam, Internat. Assoc. Geomagnetism Aeronomy, Bul. 5, pp. 84–86, 1925. Tachard's results are noteworthy for the impetus they lent to further studies (see ref. [18], p. 407). They were scrutinized successively by Musschenbroek, by Swedenborg, and by Celsius, in their consideration of the evidence for transient fluctuations.

magnetism might be obtained by noting the time of vibration of a compass needle, but there is no record of observations by him. Frederick Mallet was the first one to make such observations, and in 1769 he found the times of vibration to be the same at St. Petersburg as at a place in China. In 1776 Jean Charles Borda, a French mathematician and astronomer, improved upon the work of Mallet and made observations with the needle of a dip circle mounted in the magnetic meridian, during an expedition to the Canary Islands. With the dip needle so mounted, relative values of the total intensity may be obtained, whereas the vibration of the compass needle would give relative values of the horizontal intensity. Considering the limitations of the instruments then in use, it is probable that greater accuracy was obtainable with the dip needle than with the compass. Upon the development of an instrument with a magnet supported by a silk fiber, probably due to Hansteen, much greater accuracy was possible with the horizontal magnet.

Poisson was no doubt the first (1828) to conceive a method for making absolute determinations of the intensity, but it was left for Gauss to devise the practical details of a complete procedure, a method still in widespread use (p. 47). His first paper on magnetism, published in 1832, was devoted to this subject, and a few months later, working with Weber at Göttingen, he developed a magnetometer with fiber suspension, for declination and absolute intensity observations. In the same year he established a magnetic observatory at Göttingen and later developed suitable instruments for measuring the variations of declination and horizontal intensity. It is interesting to compare Gauss' bifilar variometer, having a magnet more than 3 feet long that weighed 25 pounds, on a suspension 17 feet long, with a modern instrument having a magnet no longer than a carpet tack, suspended on a filament of quartz less than 6 inches long.

In 1838, Gauss published his famous paper "Allgemeine Theorie des Erdmagnetismus," in which he developed a potential formula in terms of spherical harmonics to represent the facts of the earth's magnetism as known at that time. This method has formed the basis for most of the mathematical discussions regarding the various alternative distributions of magnetism or electric current that might be postulated to account for the earth's magnetism. (See p. 9 and ref. [16].)

This study of the earth's magnetism as a whole directed attention to the need for more accurate and more extended information regarding the distribution of the earth's magnetism over the surface. With the assistance of Humboldt, Gauss succeeded in arousing the interest of scientists in other countries; the ensuing program constituted one of the earliest examples of international cooperation for the study of a world-embracing natural phenomenon. Magnetic surveys were undertaken on a broad scale, some of them encompassing regions where magnetic observations had not previously been made. One of the best-known outgrowths of the interest then aroused was the expedition of Ross to the vicinity of the magnetic south pole.

Soon after 1840, magnetic observatories were established at widely separated points to secure simultaneous data regarding the variations of the earth's magnetism. (See p. 38.) Some of them were discontinued at the close of the limited period for which international cooperation had been arranged, but others continued in operation much longer, some (as the one at Toronto, Canada) even to the present day. It is of interest to note that, thanks to the zeal of Alexander Dallas Bache, later superintendent of the Coast Survey, a magnetic observatory was operated at Girard College, Philadelphia, from 1840 to 1845, and that variation observations were made in Washington from 1840 to 1842. One of the meteorological and magnetic observatories established by Russia was at Sitka, Alaska, and was in operation from 1842 to 1864. In spite of the inferior instruments then available, the operation of these observatories served to establish the principal features of the short-period variations of the earth's magnetism.

Growth of magnetic surveys.—From that time onward the importance of a knowledge of the earth's magnetism was recognized more and more, and one after another the several nations

instituted magnetic surveys of their own possessions. Great Britain took the lead with a survey of the British Isles between 1836 and 1838. The work was later repeated and extended to India, Canada, Australia, New Zealand, Egypt, and South Africa. Nearly all European countries have now been surveyed magnetically in more or less detail, and the same is true of large regions in Asia and in the Western Hemisphere.

In the United States there were scattered observations by Long (1819), Nicollet (1832–36), Locke (1838–43), and Loomis (1838–41). The last named made the first general collection of results of magnetic observations in this country and prepared the first magnetic maps, covering the eastern part of the United States. Outstanding in this period was the magnetic survey of Pennsylvania and of parts of adjacent States by Bache in 1840–43.

When the Coast Survey was reorganized in 1843, the making of magnetic observations was included in its regular functions; and from that time forward many magnetic observations were made, at first confined to the coasts (to supply the necessary compass data for its charts) but later extended to the interior States.

Conclusion

Without endeavoring to relate the numerous and rapid advances in geomagnetism since the time of Gauss, it should be pointed out that they have been the fruit of a remarkable tradition of cooperation, informally manifested in many ways and formally implemented through such bodies as the International Meteorological Organization, the First and Second Polar Year Commissions, the International Association of Geomagnetism and Aeronomy, the Special Committee for the International Geophysical Year, and its successor the International Geophysical Committee. There has been excellent liaison among these organizations.

Summarizing briefly the early history of terrestrial magnetism, we note that it had its beginnings in the ancient lore of the lodestone, for many centuries a curiosity or mystery with no practical application. Eventually we find the mariner provided with a crude floating compass, suitable only as an expedient of last resort when other methods of finding direction failed. It nevertheless served to demonstrate the incalculable value of the basic principle in the service of a growing sea trade, and soon gave place to improved forms, leading to the discovery in succession of magnetic declination, of inclination or dip, of secular change, of the daily variation, and of other short-time changes; and to the invention of isogonic charts. Finally, we have noted the researches of Gauss and his contemporaries, which mark the culmination of all the older discoveries and the inception of the modern science of geomagnetism.

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The increased attention devoted to geomagnetism in recent years has led to the publication of a number of works that deal comprehensively with broad aspects of the subject, and a few devoted to the entire field. A number of classical works retain their historical significance, and certain current serial publications give special attention to geomagnetism. Items 1–36 in the list that follows are of these kinds. The remaining references cover specific points as cited in the text.

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Figure 38.—Halley's "Atlantic chart," the oldest extant isogonic chart (1701).

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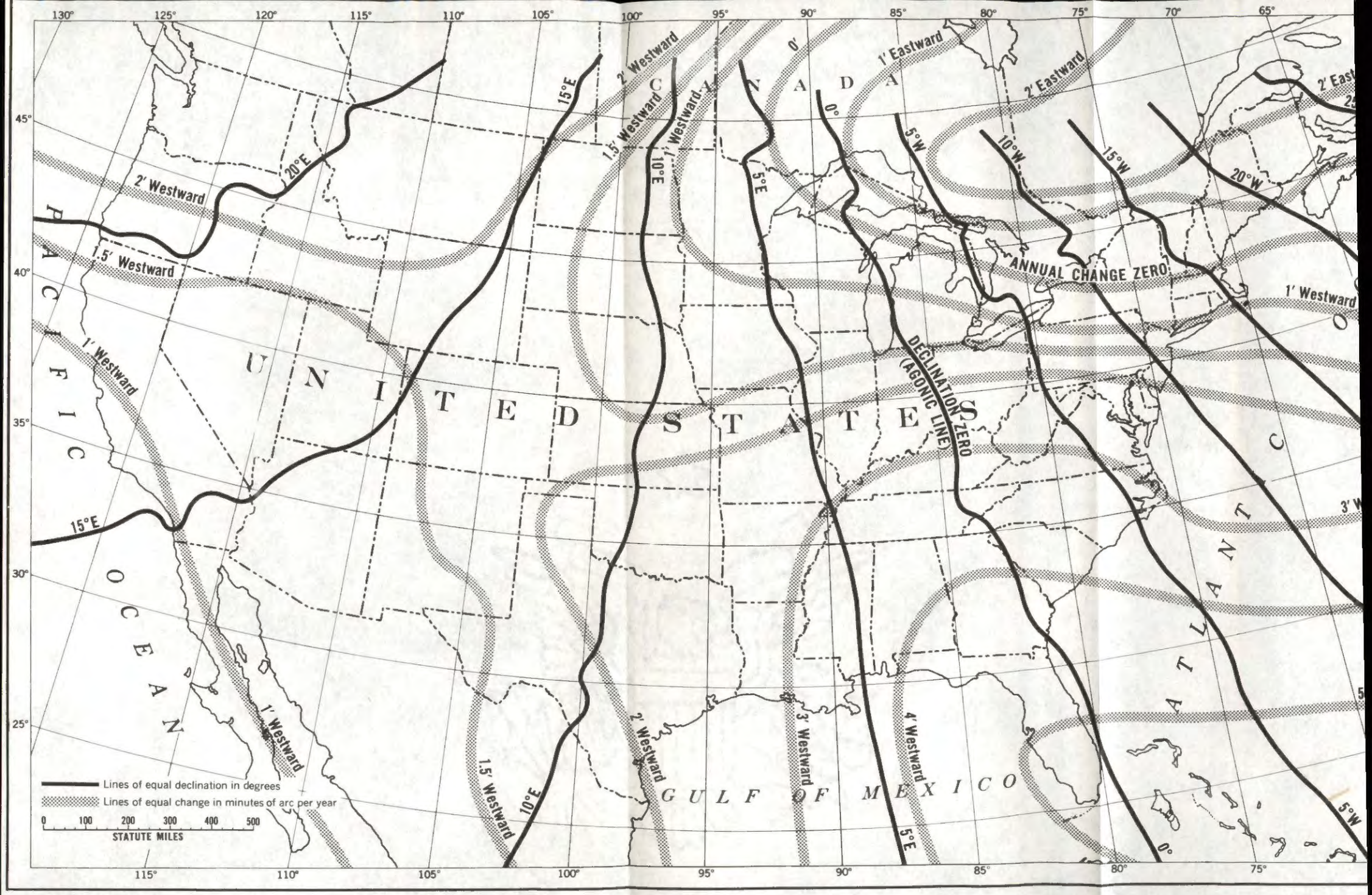

Figure 39.—Isogonic chart of the United States for 1960.

The isogonic lines or lines of equal magnetic declination are drawn for January 1960. East of the agonic line (line of zero declination) the north end of the compass needle points west of true north; west of the agonic line the compass points east of true north. The lines are drawn to show a smoothed distribution; sinuosities may be regarded only as an indication of irregularity and not as a close representation of the actual distribution.

Magnetic declination is subject to both rapid and gradual temporal changes. The gradual changes are indicated on this chart by stippled lines of equal annual change as estimated for 1960. Note that the legend *increasing* (or *decreasing*) means that the prevailing declination is numerically increasing (or decreasing). Where an isoporic line crosses the agonic line the legend changes from *increasing* to *decreasing*, or vice versa.

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