EARTH'S MAGNETIC FIELD *

Harold L. Stolov **
Goddard Institute for Space Studies
National Aeronautics and Space Administration
New York, New York

* Prepared for inclusion in the Encyclopedia of Earth Sciences, R.W. Fairbridge (ed.), Reinhold Press

** On leave from Department of Physics of the City College of the City University of New York on a National Academy of Sciences - National Research Council senior post-doctoral research associateship.

Introduction. The earth's magnetic field is demonstrated most simply by the forces exerted on a compass needle. The first man to appreciate the global character of the geomagnetic field seems to have been William Gilbert. He determined that the magnetic forces are guided from within the earth, and described his experiments in a treatise "De Magnete" published in 1600. By observing the magnetic forces in the vicinity of a spherical lodestone and comparing them with what was known of the earth's field, he concluded that the earth itself is a great magnet. A small bar magnet (magnetic dipole) of appropriate strength placed at the center of the earth would have the same external field as a uniformly magnetized sphere. Every schoolboy has mapped a dipole field by sprinkling iron filings in the vicinity of a bar magnet. About 90 per cent of the main geomagnetic field can be represented by a short earth-centered dipole inclined at an angle of about 11.5° to the axis of rotation.

Although the compass was used in navigation during the fifteenth century, the earliest measurements of the deviation of the compass from true north were not made until the first half of the sixteenth century. The first world chart of the variation of compass direction (declination) was constructed by Halley in 1701, with the knowledge that it would soon be obsolete.

[redacted]

The earth's magnetic field is ever changing and its variations are recorded continuously at magnetic observatories over the globe. Nonmagnetic ships, aircraft, rockets and now earth satellites contribute their geomagnetic measurements to complete the description. Magnetic charts are currently revised every five or ten years to monitor the secular changes arising from fluid motions generating electric currents within the molten conducting core of the earth (see volume 5 for dynamo theory of the origin of earth's magnetic field). A World Magnetic Survey has been undertaken during the years 1964-1965 and will lead to improved world magnetic charts for the epoch 1965.0. This project continues the highest traditions of international scientific cooperation established during the IGY.

Measurements. In order to measure the vector geomagnetic field intensity it is necessary to determine a set of three independent quantities. Surface observatories usually measure the horizontal intensity H, the vertical intensity Z and the magnetic declination D. With the introduction of extremely accurate precession magnetometers to measure the magnitude of the total field B, the quantities determined are often B, D and the dip angle or inclination I. It is sometimes convenient to use the set given by the north component $X = H \cos D$, the east component $Y = H \sin D$, and the vertical component $Z = H \tan I$, where $B^2 = X^2 + Y^2 + Z^2$.

Figures 1 to 5 are reproductions of world magnetic charts of the surface field describing D, H, Z, B, and I respectively. The epoch and source are given for each isomagnetic chart. The isomagnetic lines of declination are called isogonic lines, and the zero isogonic line, along which the compass points to geographic north, is the agonic line. For the field intensity components the lines are called isodynamic lines, and on the inclination chart the lines are isoclinic lines. The secular variation, which amounts to about 0.1 per cent of the total field per year, can be found on world isoporic maps prepared by the U.S. Navy Hydrographic Office in the 1700 series.

Recent evaluations of the main geomagnetic field (Cain et al., 1965) have succeeded in reducing the errors in the field description to a fraction of 1% in regions of good data coverage. High speed computers are handling the data directly, thus eliminating the errors that may appear in the construction of intermediate charts. Surface anomalies on the order of a 100 km in extent do not appear on the charts, but at times may be a few per cent of the total field. Fortunately, the effects of these magnetic sources in the earth's crust disappear rapidly with altitude, and present no problem in describing the geomagnetic field in space.

Dipole Field. The first approximation of the geomagnetic field given by a uniformly magnetized sphere is equivalent to a centered dipole aligned parallel to the magnetic axis.

In Figure 6 let the magnetic axis be NS where N is the north geomagnetic pole and S the south geomagnetic pole, the radius of the sphere is a, the magnetic colatitude is θ, then at a distance r from the earth's center the magnetic potential $V = -M\cos\theta/r^2$ where M is the magnetic moment. The intensity B of the field is given by $B = -\text{grad } V$. The inward radial component of the field is $Z = \frac{\partial V}{\partial r} = \frac{2M\cos\theta}{r^3}$ and the component perpendicular to r, in the direction of decreasing θ is $H = \frac{\partial V}{r\partial\theta} = \frac{M\sin\theta}{r^3}$. Therefore $B = (H^2+Z^2)^{\frac{1}{2}} = \frac{M}{r^3}\left[1+3\cos^2\theta\right]^{\frac{1}{2}}$ and since at the surface of the sphere at the equator $M = a^3 Bo$, this yields $B = Bo\left(\frac{a}{r}\right)^3\left[1+3\cos^2\theta\right]^{\frac{1}{2}}$ and $\tan I = \frac{Z}{H} = 2\cot\theta$. The dip in a dipole field is seen to be the same at all points along the radius OP. The geomagnetic equator is the dip isoline I=0 for the centered dipole field. The observed curve I=0 for the actual main field is the magnetic equator. The polar equation of a dipole line of force is $r = c \sin^2\theta$, where c is the distance at which the line crosses the equatorial plane. Clearly a field line that is at the surface at $\theta = 30^\circ$ crosses the equatorial plane at 4 earth radii from the center (see Figure 6).

Spherical harmonic analysis. The first spherical harmonic analysis of the main field was made by Gauss in 1838. Several investigators using improved data and varying numbers of coefficients have continued the work. The early studies are discussed in Chapman and Bartels (1940). References to the recent work of Vestine, Finch and Leaton, and Cain may be found in Cain et al. (1965).

With the assumptions of internal origin of the main magnetic field and negligible electric currents within the magnetosphere, Laplace's equation $\nabla^2 V=0$ is satisfied and the magnetic field is derivable from a magnetic potential of the form

$$V = a \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^{n+1} \left[g_n^m \cos m\lambda + h_n^m \sin m\lambda \right] P_n^m(\cos\theta)$$

where θ and λ are here the geographic colatitude and east longitude, $P_n^m(\cos\theta)$ are the Schmidt normalized associated Legendre polynomials of degree n and order m and g_n^m and h_n^m are the Gauss coefficients determined from the surface magnetic data. The potential function is not a measured quantity, but the gradient of the potential function gives the magnetic field components that are observed at the earth's surface:

$$X = \frac{1}{r} \frac{\partial V}{\partial \theta} \qquad Y = -\frac{1}{r\sin\theta} \frac{\partial V}{\partial \lambda} \qquad Z = \frac{\partial V}{\partial r}$$

In recent years, the most widely used coefficients have been those derived by Finch and Leaton, however the coefficients of Cain and collaborators, determined by fitting the measured data rather than the data read from magnetic charts, are likely to be used more extensively in the future.

The first approximation of the earth's magnetic field as a dipole can be represented mathematically by taking terms in the potential function with n=1 (3 Gauss coefficients). This is the earth-centered dipole inclined at an angle of 11.5°

to the axis of rotation. The axis of the dipole intersecting the surface of the earth defines the geomagnetic poles and consequently the geomagnetic coordinate system. Figure 7 indicates the geomagnetic coordinate system superimposed on a Mercator projection in geographic coordinates after Vestine. The geomagnetic poles are not the magnetic poles indicated on the surface magnetic field maps. The latter are the dip poles, which are points on the surface of the earth where the magnetic field is vertical. The dip poles are not antipodal.

A second approximation to the observed geomagnetic field is provided by taking terms through $n=2$ (8 Gauss coefficients). This is the eccentric dipole approximation and is provided by a suitable magnetic dipole parallel to the original central dipole, but displaced from the center of the earth about 436 km towards a point at latitude 15.6° N, longitude 150.9° E for epoch 1955. The axis of the eccentric dipole intersects the earth's surface at points which represent another pair of magnetic poles. The approximate geographic location of the various magnetic poles discussed above are shown in Table 1, with source and epoch given.

Table 1

Geographic Latitude and Longitude of Various Magnetic Poles

Observed Field (Dip Poles)	75.5°N, 259.5°E 66.5°S, 139.9°E	Epoch 1965 Watford et al.(1965)
Centered dipole (geomagnetic poles)	78.5°N, 291.0°E 78.5°S, 111.0°E	Epoch 1955 Finch and Leaton(1957)
eccentric dipole	81.0°N, 275.3°E 75.0°S, 120.4°E	Epoch 1955 Parkinson & Cleary(1958)

More accurate approximations to the observed field can be made by taking additional terms in the potential expansion. The analysis by Cain et al. for the epoch 1965 in Figures 4 and 5 takes potential terms through $n=7$ (63 Gauss coefficients).

Main field above the earth. At least 99 per cent of the main magnetic field on the surface of the earth originates from sources within the earth. When the magnetic field is known at all points on a closed surface which encompasses the sources of the field, the field is completely determined at all points outside the surface. The potential of the main field given above may be expressed in the form

$$V = \sum_{n=1}^{\infty} \frac{a^{n+2}}{r^{n+1}} \, T_n$$

where

$$T_n = \sum_{m=0}^{n} (g_n^m \cos m\lambda + h_n^m \sin m\lambda) \, P_n^m (\cos\theta)$$

and g_n^m and h_n^m determine the surface field. In order to compute the field at height h above the earth, let $a_1 = a+h$; then V may be written in the convenient form

$$V = \sum_{n=1}^{\infty} \frac{a_1^{n+2}}{r^{n+1}} \, T_n \left(\frac{a}{a_1}\right)^{n+2}$$

It is seen that the Gauss coefficients of degree n are diminished in the ratio $\left(\frac{a}{a_1}\right)^{n+2}$ at height h. Local anomalies which correspond to harmonics of a considerably higher degree than 7 are thus reduced effectively with elevation. The intensity of the dipole field and its components decreases outward as the cube of the distance from the center of the earth. The contributions to the geomagnetic field of harmonic terms of n=2, 3, 4, 5....decrease outward proportional to r^{-4}, r^{-5}, r^{-6}, r^{-7}......., respectively. Consequently, the greater the distance from the earth, the more like a dipole is the permanent field; provided that current sheets and ring currents are excluded from consideration. It may be expected that the fit between computed and observed values of the permanent field will be better at altitude than at the surface, since the use of a limited number of harmonics cannot represent accurately the complex character of the anomalies in the surface field.

Magnetosphere. For many years the region far above the earth's atmosphere was thought to be a vacuum and consequently the earth's magnetic field was thought to extend outward in a completely predictable fashion. However, with the observations of comet tails by Biermann, theoretical studies by Chapman, and the magnetohydrodynamic theory of the solar plasma flux by Parker (see Solar Wind, volume 1), the permanent presence of streaming corpuscular radiation in space was established and verified by satellite observations, The conducting solar plasma confines the geomagnetic field within a cavity known as the magnetosphere, having a boundary called the magnetopause (see Magnetosphere, volume 1). Since the solar plasma is highly supersonic in the magnetohydrodynamic sense (velocity higher than the Alfvén velocity in the medium), a detached shock wave is produced in the medium ahead of the boundary. Viscous forces acting along the sides of the magnetopause are likely to be responsible for pulling out the magnetic field lines into an extended geomagnetic tail on the night side. (See Figure 3 of Geomagnetic Disturbances, volume 1 for view of magnetosphere).

Quiet day geomagnetic variations. Examination of magnetograms during geomagnetically quiet periods will readily reveal characteristic magnetic variations that proceed according to local solar time and have amplitudes of approximately 20 to 50 gammas (gamma = 10^{-5} gauss). This is the solar quiet day variation Sq. However, careful statistical analysis of the record is necessary to reveal another much weaker variation (L) related to the lunar day and having an amplitude about one order of magnitude less than Sq. Analysis of both Sq and L reveal that about two-thirds of the magnetic variation is due to external sources, and one-third to sources within the earth. The internal contribution is likely produced by electric currents induced in the earth by the varying external magnetic field.

The quiet day solar variation of the horizontal intensity has an amplitude that is greater during the day than at night, and changes phase at a latitude somewhat below 40°. The amplitude of Sq is greater in summer than in winter and is greater in years of sunspot maximum than in years of sunspot minimum. The lunar daily magnetic variation L also has a greater amplitude during daylight hours and in summer. The summer to winter ratio of L (2.6 to 1) is much greater than for Sq. However, L increases only slightly with sunspot number, while Sq increases by about a factor of two from years of small to large sunspot number.

The nature of the ionospheric current system that might produce the observed Sq variation or the observed L variation can be computed independently of any theory indicating the precise mechanism by which the current system is produced. Illustrations of such current systems may be seen in Chapman and Bartels (1940).

Dynamo Theory-Ionosphere. The most widely held theory to explain the origin of the ionospheric current systems that would produce the Sq and L variations is the dynamo theory suggested in 1882 by Balfour Stewart. Tidal oscillations in the E region of the ionosphere move conducting air across the geomagnetic field inducing currents by dynamo action. The conducting air is the armature of the atmospheric dynamo and the geomagnetic field is the permanent field magnet in the analogy. The observed magnetic variations Sq and L are supposed to be caused by the magnetic fields of these ionospheric currents (often called dynamo currents). The analogy is far from exact, since in the presence of a magnetic field the conductivity of a partially ionized gas is anistropic. The mathematical development of the dynamo theory is given in Chapter 23 of Chapman and Bartels (1940) with recent developments and references in a review by Fejer (1964).

Two lines of investigation contribute supporting evidence for the dynamo theory. In one approach the wind velocities and the conductivities are assumed and the resulting current systems with their magnetic variations are calculated. In the second approach the observed magnetic variations are taken as a starting point and with conductivity assumptions, the electric current systems and then the wind velocities are calculated. The internal consistency of these calculations lend broad support to the dynamo theory.

Even during magnetically quiet days the ever-present solar wind interacting with the magnetosphere will increase the magnetic field on the day side relative to the night side. The rotation of the earth under this pattern will provide the observer on the ground with a quiet day magnetic variation related to currents flowing at the boundary of the magnetosphere. Investigations along these lines are almost nonexistent, and current explanations for the quiet day magnetic variation look toward the ionosphere and the dynamo theory.

<u>Some relationships of the geomagnetic field</u>. 1) In association with activity on the sun, enhanced solar plasma interacting with the earth's magnetosphere causes geomagnetic disturbance and a host of related phenomena (see Geomagnetic Disturbances, volume 1). 2) The earth's magnetic field acts

on cosmic rays like a huge magnetic spectrometer. The various particles are sorted with low energy particles reaching the polar regions, while only high energy particles are detected near the equator (see Cosmic Radiation, volume 1). 3) Within the earth's magnetic field, trapped electrons and protons spiral along the lines of force and drift around the earth to populate the radiation belts (see Van Allen Radiation Belts, volume 1).

References

* Cain, J.C., W.E. Daniels, S.J. Hendricks, and D.C. Jensen, 1965. An evaluation of the main geomagnetic field, 1940-1962. J. Geophys. Res., vol. 70, 3647-3674.

* Chapman, S., and J. Bartels, 1940. Geomagnetism. vols. 1 and 2, Oxford Univ. Press, Oxford.

* Fejer, J.A., 1964. Atmospheric tides and associated magnetic effects. Rev. Geophys., vol. 2, 275-309.

Finch, H.F., and B.R. Leaton, 1957. The earth's main magnetic field - epoch 1955. Monthly notices Roy. Astron. Soc., Geophys. Suppl., vol. 7, 314-317.

Parkinson, W.D., and J. Cleary, 1958. The eccentric geomagnetic dipole. Geophys. J., vol. 1, 346.

Watford, O.B., W.A. Francis, G.B. Walker, and E.B. Fabiano, 1965. Isomagnetic patterns in the regions of the 1965 dip poles. Trans. Am. Geophys. Union, vol. 46, 661-664.

Figure Captions

Figure 1. World magnetic chart of the surface field: declination (D), epoch 1960 (Geomagnetism and Aeronomy, vol. 4(1964), p.602)

Figure 2. World magnetic chart of the surface field: horizontal intensity (H), epoch 1960 (Geomagnetism and Aeronomy, vol. 4 (1964), p.603)

Figure 3. World magnetic chart of the surface field: vertical intensity (Z), epoch 1960 (Geomagnetism and Aeronomy, vol. 4 (1964), p.604)

Figure 4. World magnetic chart of the surface field: total intensity (B), epoch 1965, after Cain et al. (JGR, vol. 70 (1965), p.3659)

Figure 5. World magnetic chart of the surface field: inclination (I), epoch 1965, after Cain et al. (JGR, vol. 70 (1965), p.3661)

Figure 6. Dipole Field

Figure 7. Geomagnetic coordinates (curved lines) superimposed on a Mercator projector of the world. (Handbook of Geophysics, Revised Edition 1960, p.10-9)

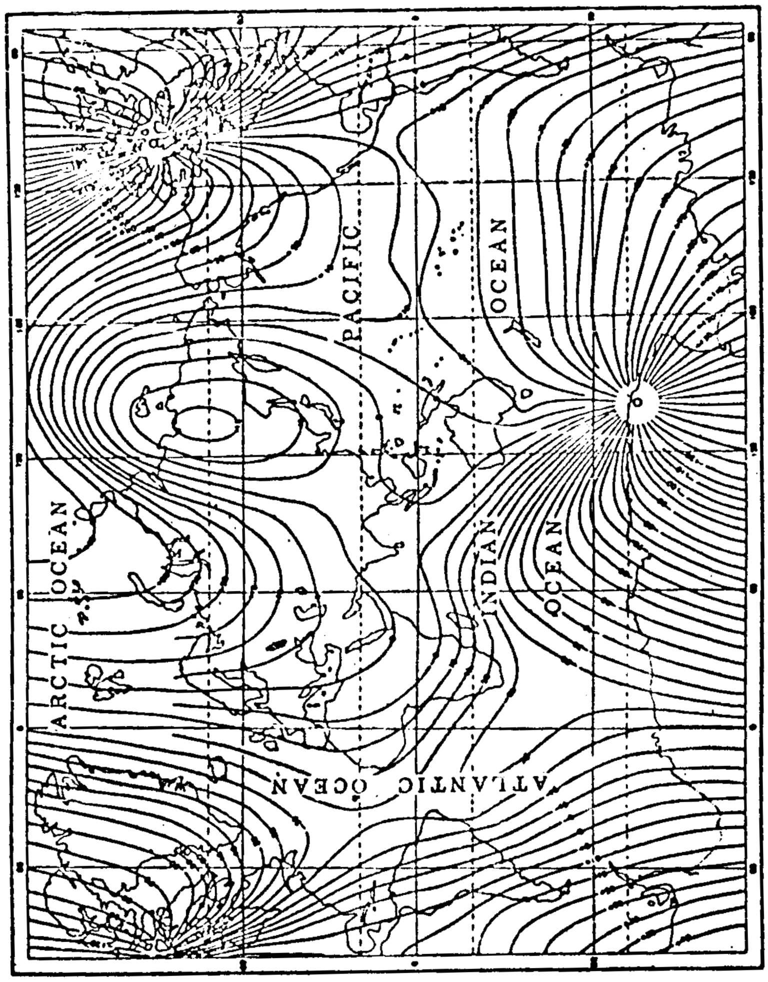


Fig. 1

Fig 1

data used were 250 determinations in Argentina during the period 1951-1954 [21, 22], 70 determinations in Colombia in 1958 and 60 determinations in Mexico [23].

Asia. Recent observations of a high accuracy were used in Japan and the near-lying islands for 1951-1955 at more than 1000 stations [24, 23], in India for 1957-1958 and in the Philippines for 1954-1955 [29] at 100 stations. We had no new data for the remaining territory of Asia.

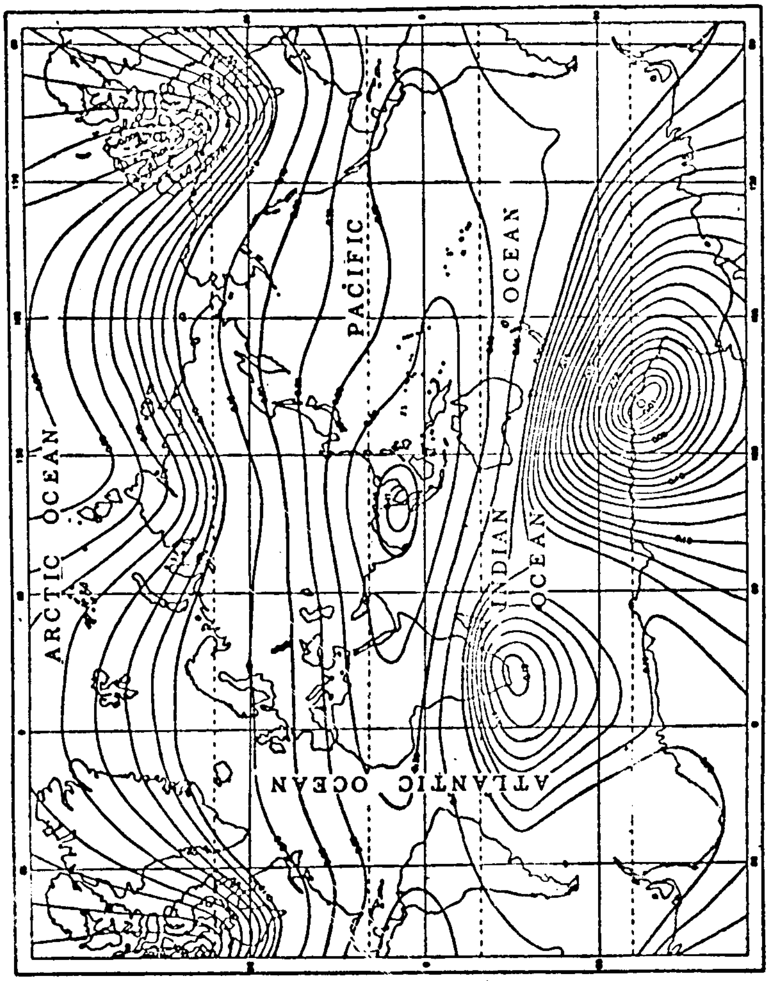
Africa. New determinations at 650 stations were used in North Africa [30, 31], in the Sahara [32-36] and in the Madagascar area [40] for 1947-1957.

Australia. We used determinations made from 1927 through 1958 at 775 stations [41]. Their distribution over the territory of Australia is uneven. Its eastern part is covered better. These data supplemented information on the magnetic field of Australia considerably. In the case of New Zealand we used 237 determinations for the period 1941-1951 [43].

Oceans. The magnetic determinations of the scientific expeditions aboard the schooner Zarya were a considerable contribution to the study of the magnetic field of the oceans. These expeditions during the period from 1957 through 1961 made a survey in the Atlantic, Indian and Pacific Oceans, covering them with a thin but reliable network of magnetic determinations. The total length of the track followed by the Zarya was approximately 160,000 nautical miles. The accuracy of determinations of declination was $\sim 0^\circ.5$; accuracy of the horizontal and vertical components was ~ 0.001 oe.

About 250 determinations of recent years [45, 46] were used for the islands situated in the Atlantic, Indian and Pacific Oceans.

Arctic. In the Arctic in recent years magnetic determinations have been made by expeditions on drifting stations and other high-latitude expeditions. We used the results of these determinations for 1955-1960. (Earlier observations on drifting stations were used when compiling maps of the epoch 1955.) These determinations covered a considerable part of the north polar zone and were the basic data for map compilation. In addition, observational data for Spitzbergen for 1951-1953 and earlier were used [47]. We had no other data based on foreign observations and therefore the western sector of the Arctic was mapped solely on the basis of old very modest and inexact data.



H

Fig 2

Fig. 2

Antarctica. This region, virtually unstudied in magnetic respects, was supplemented by magnetic observations of very great importance for compilation of maps. These observations were made by Soviet antarctic expeditions on sea and land; in the Indian Ocean determinations were made aboard the diesel-electric ship Lena in 1956. In the Pacific Ocean magnetic observations were made aboard the diesel-electric ship Ob' in 1957-1958 [48, 49]. These observations were made along the tracks of the vessels to Antarctica. Their accuracy was low, but they were useful for such magnetically unstudied regions.

Soviet investigators made determinations along the coast of Antarctica and in the interior of the continent. Although the number of determinations in Antarctica was not great each reconnaissance and each determination for that continent is of great value. The first traverse into the antarctic interior was made by P.K. Sen'ko in 1956 [50]. He followed a route about 400 km in length from Mirny station to Pionerskaya station. In 1957 N.D. Medvedev made a traverse 1,400 km in length from the Pravda Coast to the earth's South Geomagnetic Pole. Then, in 1958, determinations were made along the traverse Pionerskaya - Vostok I - Komsomolskaya - Sovetskaya - Pole of Relative Inaccessability [51]. In 1959-1960 determinations were made along the traverse Vostok-South Geographic Pole, and in 1960-1961 along the traverse Mirny - Komsomolskaya - Vostok and in the area of the Shackleton and West Ice Shelves. In addition, certain observational data of foreign expeditions were used. Among these were a survey of 1957 in the area of Prince Harald Land [52], observations of American expeditions of 1951-1956 in the area of the Palmer Peninsula and at Little America and Little Rockford stations, French observations in Adelie Land [53] and at the stations Charcot and Dumont D'Urville in 1951-1952 and Australian observations of 1953-1954 at Mawson station and to the south of it [54].

All the data used in compilation of the maps were reduced to the single epoch 1960. The reduction was accomplished using world maps of isopors of D, H and Z for the period 1954-1959

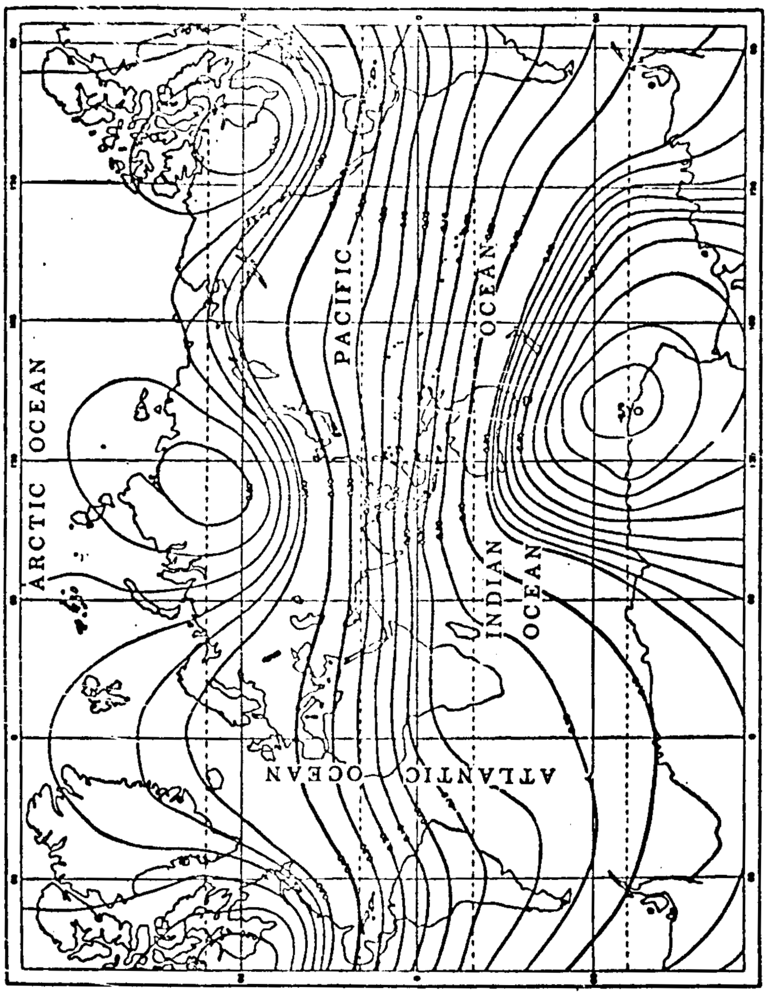


Fig. 3

2

Fig 3

[60], compiled by the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagatio

The cartographic base for compilation of maps for foreign areas was a grid at a scale of 1:10,000,000. The isolines were drawn by interpolation between the value of the magnetic elem at observation stations.

For the area of the USSR we used the above-mentioned magnetic maps, first subjected to s simplification.

The principal interval between isolines was 0.005 oe for H, 0.01 oe for Z and 1° for D. As a result of the nonuniform magnetic study of the earth it is extremely difficult to make an evaluat of the world maps, expecially for areas which include the European part of the USSR, western Europe, the United States, Japan, India, Australia and New Zealand, it will be ~ 0.002 oe for H and Z and 0°5 for D.

We have published maps obtained by replotting isolines from maps at a scale of 1:10,000,00 with the interval between isolines reduced to 0.01 oe for H and 0.002 oe for Z (Figs. 1-3). The world magnetic maps for the epoch 1960 were prepared using more extensive and up-to-date dat than the maps for the epoch 1955 and therefore now are the most reliable magnetic maps of the wor

On the oceans a great influence on the increase of quality of the maps was the result of rece observations on the schooner Zarya, whose contribution was great with respect to both quantity a quality. On all the world maps compiled earlier the magnetic field for ocean areas was represen for the most part on the basis of observations made on the yacht Carnegie, dating to the first hal of the 20th century. The reduction of these observations to the epoch of the map introduced appr able secular variation errors into the results and lowered the accuracy of the maps. The observa tions of the Zarya on the oceans are close to the epoch of the map and therefore are free from errors resulting from reduction to the epoch.

Observations in Antarctica yielded very valuable information concerning the distribution of

, we see only slight differences
poch being five years later and
e present charts use 63 instead
efficients. The reasons for this
entage changes in the field during
al are small and that the ampli-
ditional 15 coefficients are small
de of the lower terms.
smooth representation, it is of
ble to illustrate the many small-
that are found near the earth's
ntours are thus much smoother
standard world magnetic charts
ally constructed by other meth-
rity of standard charts, however,
empt to show as much detail as
with the result that there are
s around anomalies in isolated
d data coverage, but smooth
ere. It is likely that such maps
re 3 give a more realistic esti-
l averaged over the whole of the

feature of the secular change
in Table 4 is the fact that the
ot dominate the series as does
Even though there are fewer
terms determinable from the
ing secular change maps are at
x as those for the field itself.
nge in two of the components,
n in Figure 4. The characteristic
map is that the earth is almost
between positive and negative
s pattern of positive Z is equally
centers of negative change occur
and the positives are centered
itudes and over Asia. Since the
ences in the major secular change
maller than those for the coeffi-
in field (cf. Table 5), the details
illustrated are equally less likely

ith other models. To evaluate
ch the presently derived set of
ares with other models, we have
inations between the available
mputed field components at the
ation. Complete validation can
since it is not possible to make
regions that are void of data.
ata are accrued it should always

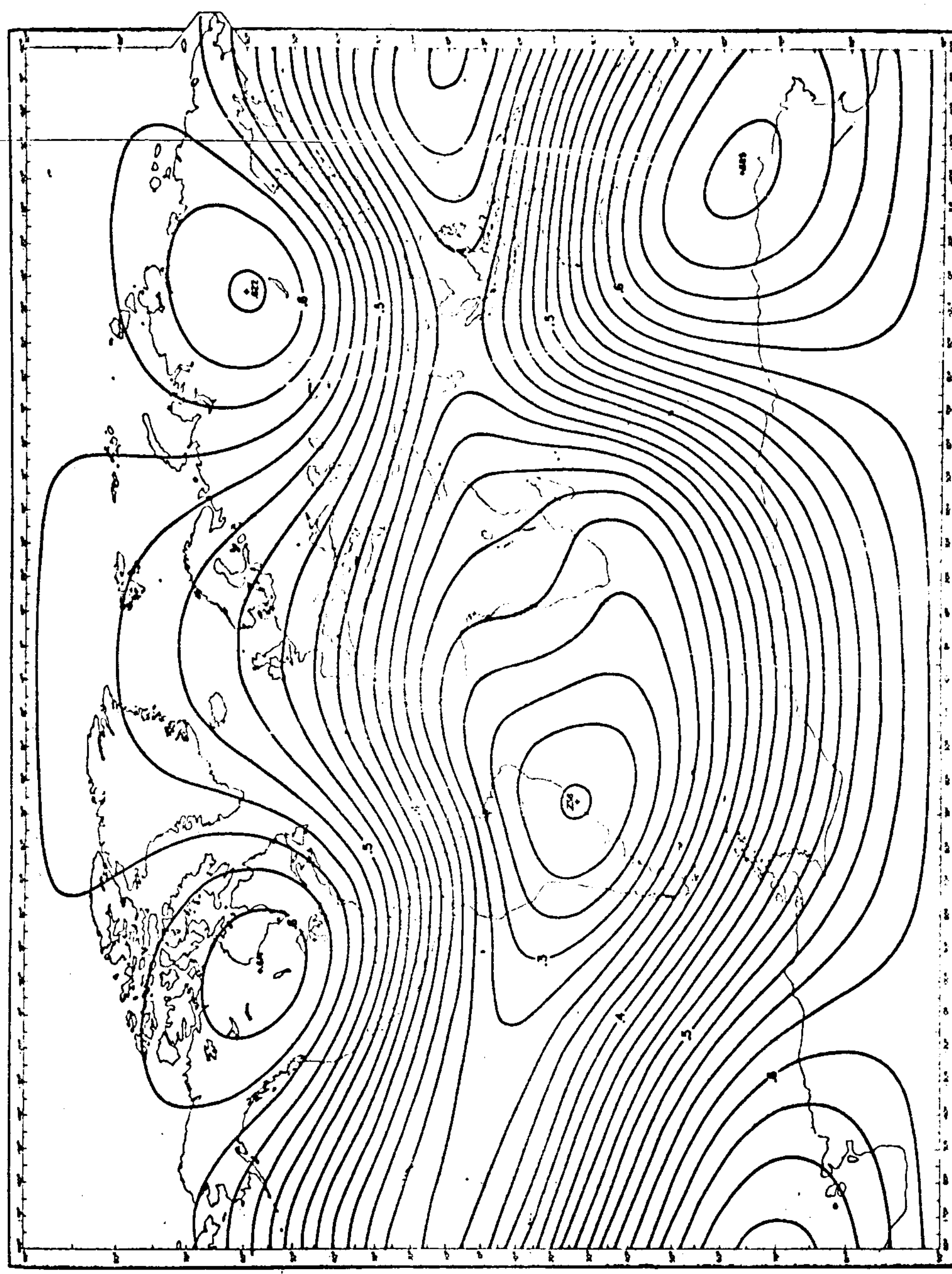


Fig. 3. Contours of the geomagnetic field in gauss (F, H, Z) or degrees (I), synthesized from the coefficients in Table 4 for epoch 1965.0.
Fig. 3a. F (total intensity). All centers are 'highs' except the South American 'low' of 0.238 Γ

Fig 4

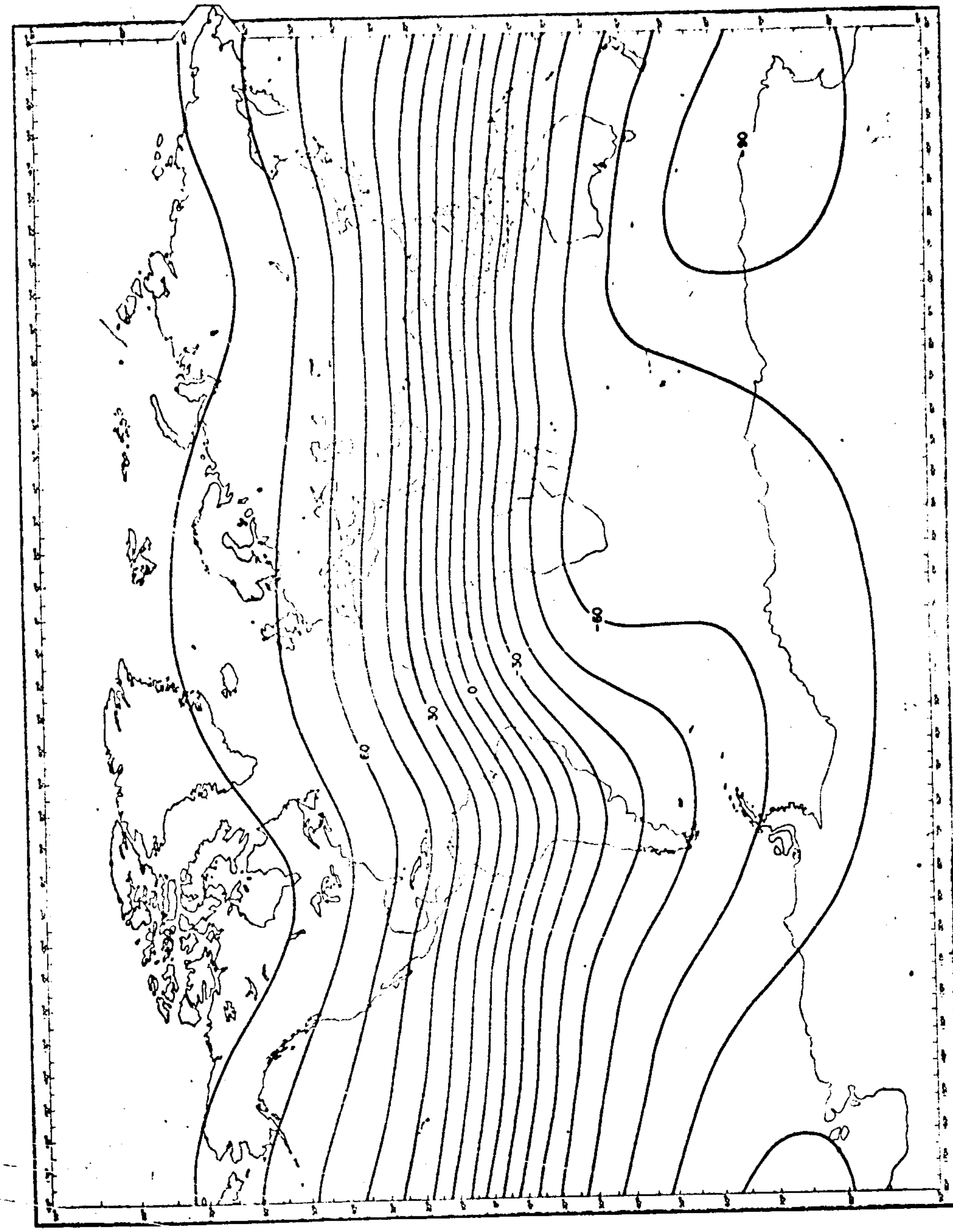


Fig. 3c. *I* (inclination).

Fig 5

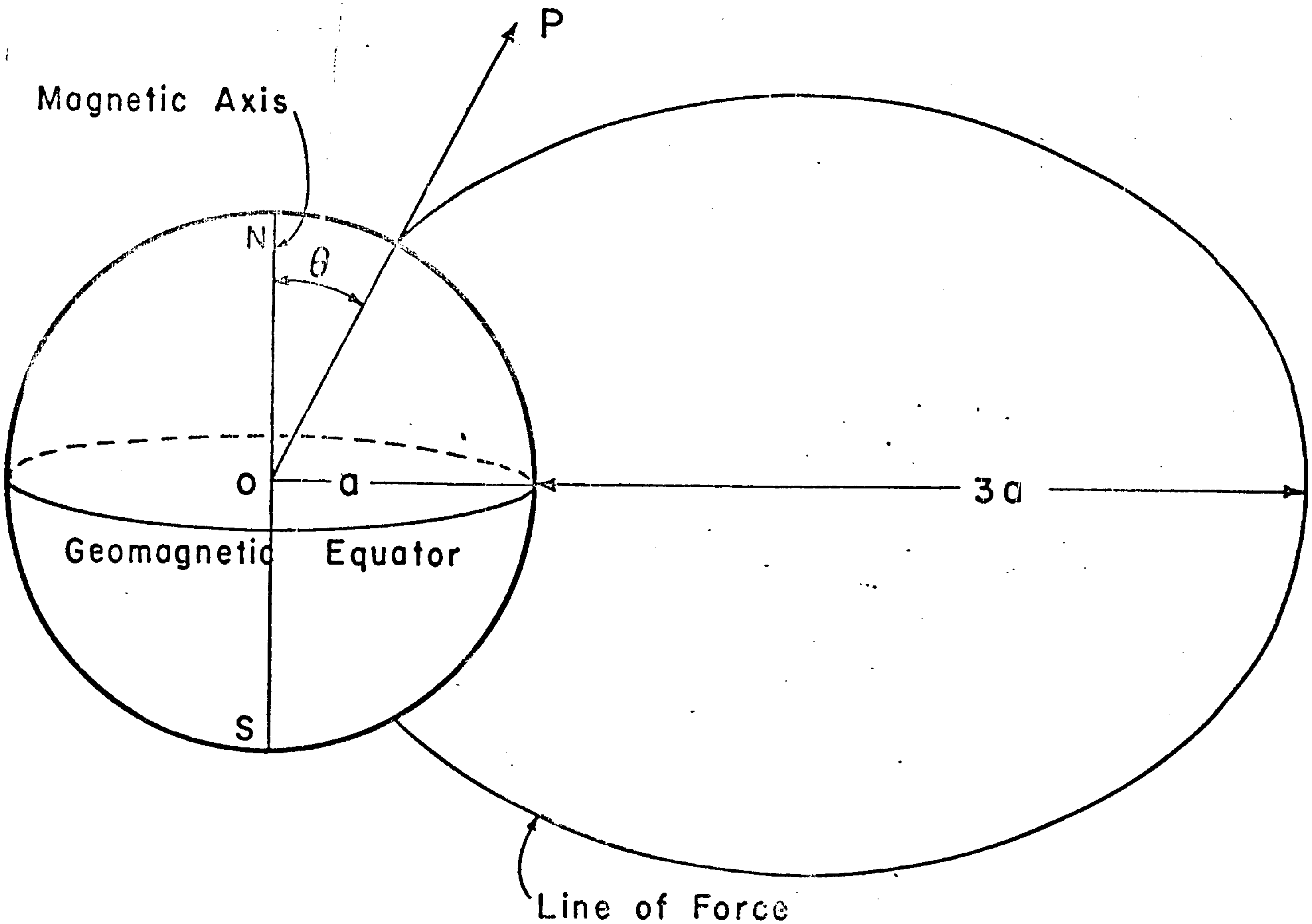

P
Magnetic Axis
N
θ
o
a
3a
Geomagnetic Equator
S
Line of Force

Fig 6

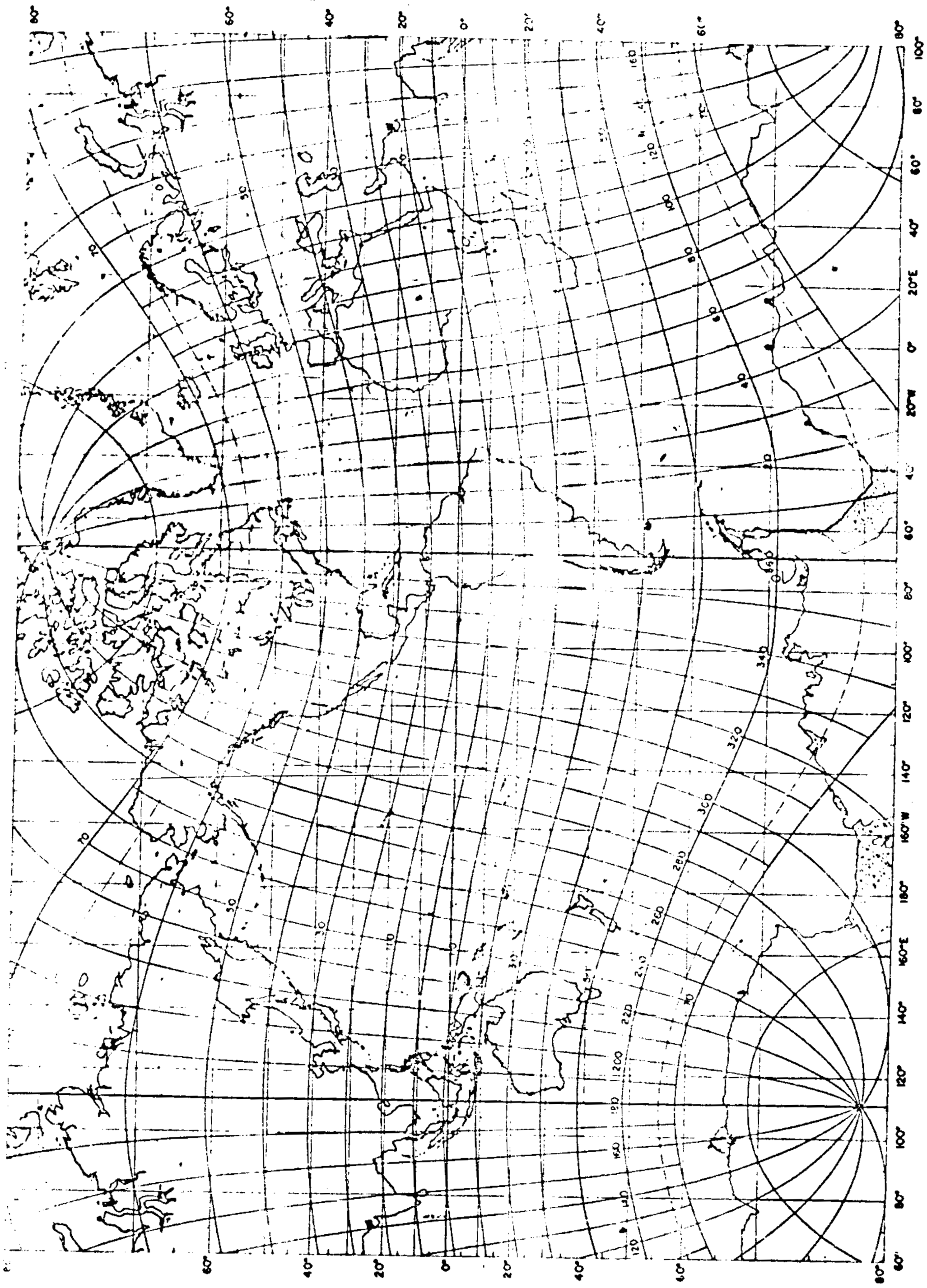


Fig. 10-6. Coordinates for Concentric Geomagnetic Dipole Field (Vestine Computations - 1945)