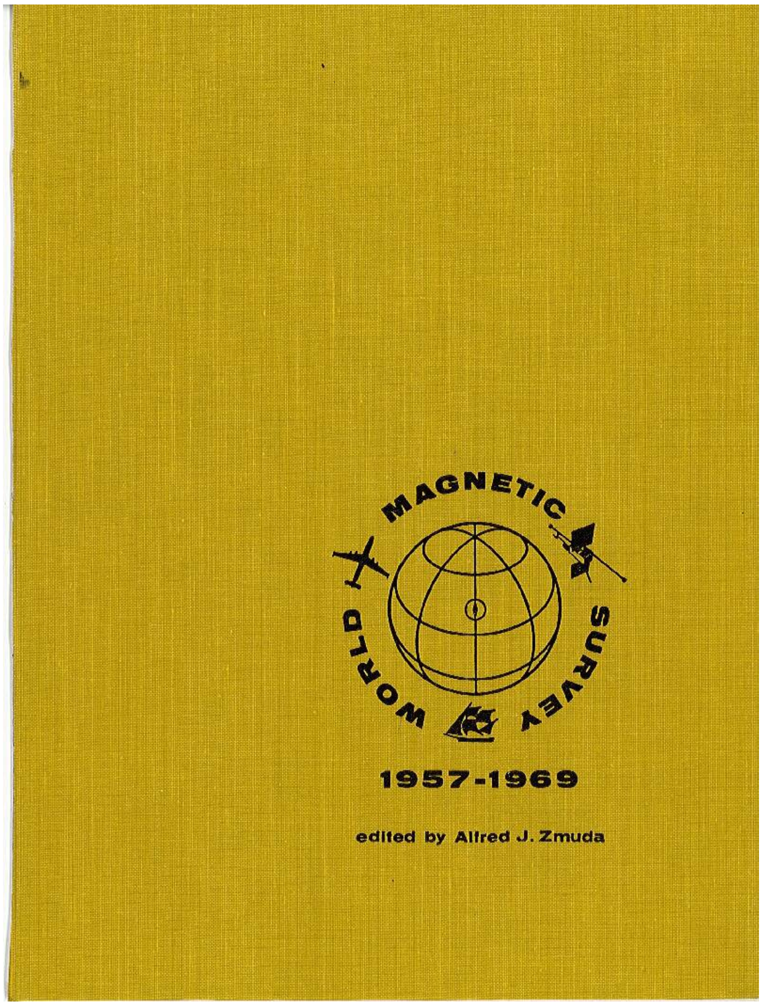

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1957-1969

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DEDICATION

Dr. Ernest Harry Vestine
May 9, 1906 - July 18, 1968

This summary volume of the World Magnetic Survey is respectfully dedicated to the memory of Dr. Ernest Harry Vestine. Dr. Vestine served as Secretary General of the World Magnetic Survey Board and formed the center for the planning and guidance of the great international enterprise, the World Magnetic Survey.

Dr. Vestine was born in Minneapolis, Minnesota, U.S.A., the son of Frida Christine (Lund) and Olaf Algot Vestine. He received a B.Sc. from the University of Alberta in 1931, Ph.D. from the University of London in 1937, and a Diploma of Imperial College from the Imperial College of Science and Technology, University of London, in 1937. His Ph.D. thesis, under Professor Sydney Chapman, dealt with electric current systems of magnetic storms.

Dr. Vestine's scientific contributions were numerous. During the Second International Polar Year (1932-33), he led the Canadian expedition to Meanook in northern Alberta, Canada, where he established a new magnetic observatory that has continued to provide important high-latitude data. While at Meanook, he made one of the first observations of night-luminous clouds and later described them in an authoritative paper. Following the receipt of his degree in Applied Mathematics from the University of London, Dr. Vestine began an association with the Department of Terrestrial Magnetism, Carnegie Institution of Washington, D. C. (1938 - 1957) where he became one of the world's leaders in geomagnetism and auroral science. In addition to writing many important papers on ionospheric physics, terrestrial magnetism, and related phenomena of the earth's interior, he directed a number of major research projects. In 1947, the Institution published two collections of modern geomagnetic data prepared under his guidance.

From 1957 until his death, Dr. Vestine was a Senior Staff member of the RAND Corporation, Santa Monica, California, U.S.A., where he continued his work in geomagnetism and auroral physics and where he also undertook mathematical and interpretive studies of the lunar atmosphere, the magnetic detection of missiles, and the electromagnetic drag on satellites. He also held the position of Professor of Meteorology at the University of California at Los Angeles from 1966 - 1968.

Dr. Vestine served as consultant for numerous U.S. organizations: the Office of the Secretary of Defense, 1947 - 1954; the Applied Physics Laboratory of The Johns Hopkins University, 1946 - 1956; Battelle Memorial Institute, 1956 - 1959; the Department of Commerce, 1959; the National Aeronautics and Space Administration, 1959 - 1966; and the National Science Foundation, 1960 - 1966.

His memberships included the following: The U.S. National Academy of Sciences, American Geophysical Union, American Physical Society, American Seismological Society, American Meteorological Society, Institute of Electrical and Electronics Engineers, Society of Terrestrial Magnetism and Electricity (Japan), the Washington Academy of Sciences, and the International Scientific Radio Union (URSI).

While a member of the U.S. National Academy of Sciences (elected 1954), Dr. Vestine served as Chairman of the Panel on the World Magnetic Survey from 1961 until his death. This panel was part of the Geophysics Research Board. From 1962 - 1967 he was a member of the Committee for the International Years of the Quiet Sun 1964 - 1965. From 1959 until his death, he was a member of the Committee on Polar Research and from 1959 - 1965 served on the Panel on the Upper Atmosphere. As a member of the Space Science Board, Dr. Vestine was a member of the Committee on International Relations from 1961 - 1965. From 1962 - 1967 he was also a member of the Committee on Consolidated Upper Atmosphere and the Space Data Center Committees.

While a member of the U.S. National Committee for the International Geophysical Year (IGY), he served on the Technical Panel on Aurora and Airglow and on the Technical Panel on Geomagnetism from 1955 - 1959. Also during the same period, Dr. Vestine held the position of Chairman of the World Data Center Committee and was an alternate on the Executive Committee for the IGY. From 1956 - 1957 he was Director of the World Data Center A Coordination Office.

Dr. Vestine held the following positions while a member of the American Geophysical Union: President of the Section on Geogmagnetism and Aeronomy, 1965 - 1968; member of the Council, 1965 - 1968; Chairman of the Committee on Cosmic and Terrestrial Relationships, 1957 - 1958; and Associate Editor of the *Journal of Geophysical Research,* 1968. He was elected a Fellow of the AGU in 1962.

In April 1967, Dr. Vestine received the John Adam Fleming Award presented by the American Geophysical Union of the National Academy of Sciences, National Research Council. This award is given for original research on fundamental aspects of geomagnetism, atmospheric electricity, aeronomy, and other related branches of sciences. In the citation, Dr. Sydney Chapman noted that Dr. Vestine had "established himself as one of the world's leaders in geomagnetism and auroral science."

Dr. Vestine was the author of 116 scientific publications. He is survived by his wife Lois Anne (Reid) and son Henry Charles.

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THE
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EARLY SURVEYS

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One of the earliest extensive collections of magnetic declination data extant is that of Joâo de Castro, a Portuguese naval commander and explorer. His measurements, 43 in all, were made as often as possible during voyages to and near India from 1538 to 1541 [*Harradon,* 1944]. Other such observations by navigators accumulated over the years. In 1899 *van Bemmelen* [1899] published maps of the declination for as much of the world as possible for various epochs, the earliest being for 1500; he found much unpublished material in the archives of the navy offices of the chief maritime nations of those centuries.

The first proposal known to me of a sea voyage for the express purpose of magnetic surveying was made to the Royal Society of London in 1692 by Benjamin Middleton, one of its Fellows; the application for a vessel was supported by Halley, but the plan never materialized.

In 1698, however, Halley, applying similarly on his own behalf, was successful in gaining from King William III the grant of a vessel for a magnetic survey of the north and south Atlantic. He sailed in 1698 and returned in 1700, and soon afterward he published the first extensive isogonic map. His observations were limited to the declination. I have often wondered why he did not also measure the magnetic dip. In 1702 he extended his chart, making it a world chart, and covered all regions for which he could obtain data.

In a statement issued with his chart Halley foretold that it would gradually become outdated because of the secular variation. From time to time partial surveys were made on land and sea, and new charts drawn for other elements as well as for declination. "But for two centuries Halley had no comparable successor in this field, and the magnetic survey of the globe was not renewed with his abounding zeal until in 1905 a young American, Louis A. Bauer (1865 - 1932), with the aid of a prince of industry, the one-time poor Scots lad Andrew Carnegie, resumed the Sisyphean task" [*Chapman,* 1943].

Nature, indeed, as Gellibrand in 1635 first found, has ordained that the task of surveying and charting the earth's magnetic field is a never-ending one. Under Bauer, appointed by the Carnegie Institution of Washington as the first director of its Department of Terrestrial Magnetism, the Department took the world as its parish. It reviewed the worst gaps in our knowledge of the field, whether on land or sea; and with funds that today seem very modest, the Department encouraged and in many cases subsidized, or itself made, land surveys where most needed. It also undertook ocean magnetic surveys, at first with a ship adapted for the purpose and later with a ship, *Carnegie,* specially constructed to be nonmagnetic. Bauer wisely and generously made the observations quickly available to the agencies in different countries that issued magnetic charts. In the second decade of this century the British Admiralty, which had long issued magnetic charts from its Hydrographic Office, transferred the responsibility for chart construction to the Royal Observatory of Greenwich; the Observatory had been under Admiralty administration since it was founded by King Charles II for the purpose of assisting navigation. At the time of this transfer I was a chief assistant to the Astronomer Royal, Sir Frank Dyson, and I well recall his appreciation of the help given by Bauer. Because of the *Carnegie* observations the isogonic charts of 1922 were the most accurate up to that date. After some time the ship was again commissioned for a renewed ocean survey, but in 1929 it was lost by fire at the harbor of Apia in Samoa. From then onward, because of the secular variation, inadequately followed by sea and land measurements, our knowledge of the current state of the field regressed. Bauer's successor as Director, J. A. Fleming (1877 - 1956), a great leader in geomagnetism, was unable to obtain funds for a new ship.

After several years the British Admiralty decided to build a new nonmagnetic ship of teak with fittings and equipment chosen partly with the advice willingly given by the Department of Terrestrial Magnetism. The ship, named *Research,* was launched but before its auxiliary engines were installed and its equipment was completed, World War II began. After the war the Admiralty reluctantly decided that it could not provide the funds needed to bring the ship into service. Efforts to find other ways to finish

* This renowned scientist died 16 June 1970. He is missed by his many colleagues throughout the world.

the vessel and its equipment and to make it internationally available for a world magnetic survey were fruitless. Meanwhile it was becoming expensive to maintain the ship in condition. Finally the Admiralty gave orders to sell it, and it was broken up for scrap—a most unfortunate waste.

From the foundation of the International Union of Geodesy and Geophysics (IUGG), its Association of Terrestrial Magnetism and Electricity, which has since been renamed with extended scope as the International Association of Geomagnetism and Aeronomy (IAGA), sought to encourage in every way open to it the improvement of our knowledge of the geomagnetic field and its secular variation. But for many decades after its first meeting in 1919, financial difficulties retarded the work; funds were difficult to obtain. Despite unfavorable world economic conditions, however, the Second International Polar Year of 1932-33 was successfully carried through. This, unfortunately, did not appreciably help the magnetic survey.

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WMS AND THE IGY

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About 1950 the U.S.S.R., acting on a proposal of Dr. N. V. Pushkov, built a nonmagnetic ship, *Zarya,* in Finland. Equipped with Russian instruments, the ship began its long series of ocean magnetic surveys in 1956. A new era for geophysics opened in 1953 when the International Geophysical Year (IGY) was organized. The concept caught the imagination of politicians and statesmen all over the world, and funds were made available for it on a scale never before experienced by geophysicists. In the field of geomagnetism, however, its main effort was to improve and extend the observation of the transient variations, with a view to increasing our knowledge of solar-terrestrial relationships. A few extracts from the *IGY Annals* will illustrate this.

At Brussels in 1953, at the first general assembly of the central organizing committee, Comite Special de l'Annee Geophysique Internationale (CSAGI), the principal problems to be attacked in geomagnetism were judged to be:

"(a) The changing morphology of magnetic storms and activity including bays and pulsations.

(b) The daily variation of the three magnetic elements in the zone containing the magnetic and geographic equator."

Some help was proposed towards the magnetic survey, but only when this could be done incidentally: "When expeditions are made to regions rarely visited, . . . , it is recommended that the magnetic elements shall be measured, particularly, in the case of stations where such measurements have been made previously, to determine the secular variation." And likewise: "Magnetic measurements at sea are recommended in the case of oceanographic expeditions made mainly for other purposes" [*IGY Annals, 2A*].

It was recognized that renewal of survey measurements on a world scale during the 1½ years of the IGY was not essential, and that the efforts of those engaged in geomagnetic observation would be best used in obtaining records for which simultaneity of measurements was vital.

In Rome at the second CSAGI assembly in 1954, the geomagnetic program included the following: "The CSAGI recommends that all IGY stations, permanent as well as temporary, be utilized for the reduction of such aeromagnetic surveys as can be carried out during the IGY, and that the IAGA committee on magnetic charts be charged with the selection of the oceanic areas for which an aeromagnetic survey would be of special importance" [*IGY Annals, 2A*].

At the third CSAGI assembly held at Brussels in 1955, the Working Group on Geomagnetism included the following passage in its statement of the observational program: "Although magnetic observations at sea do not appear as a special point in the IGY program, the Working Group drew attention to the fact that the great number of land stations to be in operation during the IGY will provide quite exceptional possibilities for a reliable reduction of sea observations made during the same period" [*IGY Annals, 2A*]. This applied, for example, to the *Zarya* observations, which were mentioned thus in the geomagnetic report of the fourth CSAGI assembly held at Barcelona in 1956: "The CSAGI notes with satisfaction that the U.S.S.R. is planning for the IGY a broad program of comparisons of standards of magnetic observatories by means of the ship *Zarya,* and that this program will be linked up with the comparison program of IAGA" [*IGY Annals, 2A*]. Likewise at the same meeting [*IGY Annals, 2A*]: "The CSAGI recommends that the IGY program should be completed by a World Magnetic Survey to be made after the end of 1958, and desires that the time and organization of that survey should be considered by IAGA."

In 1957 at the Toronto General Assembly of IUGG, the IAGA included in its program the project of the World Magnetic Survey and appointed a Committee on World Magnetic Survey and Magnetic Charts under the chairmanship of Dr. E. H. Vestine, whose untimely death is a source of grief to us all and is a great loss to our science, to which he gave such distinguished service. Later the World Magnetic Survey Board was appointed, with V. Laursen as Chairman and E. H. Vestine as Secretary General.

At the fifth and final assembly of CSAGI held at Moscow in 1958, Dr. Vestine held a meeting on the subject, for which he consented to act as IGY Reporter [*IGY Annals, 10*]. In connection therewith, the CSAGI Working Group on Geomagnetism resolved as follows: "Considering the plans for the undertaking of a World Magnetic Survey, the CSAGI Working Group on Geomagnetism suggests that the IAGA Committee on the World Magnetic Survey make suggestions as to the epoch of reduction of such a survey and prepare necessary guides for the planning of the work, including a statement of desired accuracies, and a method of compiling the data" [*IGY Annals, 10*]. This resolution was adopted as a resolution of the CSAGI Assembly at its final meeting on August 9, 1958. At the same meeting it was resolved that the World Magnetic Survey be adopted "as a deferred item into the IGY program" [*IGY Annals, 10*]. This recommendation was made by the CSAGI Bureau, the small central body of the international planning organization, which consisted of L. V. Berkner (Vice-President and absent from the Moscow meeting), M. Nicolet (General Secretary), V. V. Beloussov, J. Coulomb, and myself (President).

This adoption of the World Magnetic Survey into the IGY program as a deferred item was made in the hope that the association of the World Magnetic Survey with the IGY might lend to the Survey some of the great prestige attained by the IGY, and thereby help towards its obtaining the necessary financial support from the various national governments. Others who have been closely concerned with the Survey can judge better than I to what extent this hope has been fulfilled.

REFERENCE

IGY Annals, 1958, Vol. 2A, pp. 9, 159, 245, 354, 355; also Vol. 10 (no date), pp. 93, 211, 244.

THE WMS AND IAGA

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The responsibility of the International Association of Geomagnetism and Aeronomy (IAGA) began at the Toronto, Canada, meeting of the International Union of Geodesy and Geophysics (IUGG). The minutes of the IAGA plenary session held September 4, 1957 [Transactions of the Toronto meeting, September 4–14, 1957, *IAGA Bulletin No. 16*, pp. 17–20] record the initial steps taken and report that "Professor S. K. Runcorn presented his communication on Recent Cosmic Ray Studies and Their Relationship to the Geomagnetic Field." This communication was to illustrate a proposal by the British National Committee that asked the Association to note the discrepancy between geomagnetic data resulting from recent cosmic ray studies and those based on surface measurements and to organize a new magnetic survey to investigate this discrepancy.

Professor Runcorn continued by saying that cosmic ray evidence seems to indicate that the external part of the magnetic field is considerably greater than should be expected from available surface observations. A new magnetic survey would be needed to investigate this problem.

The paper was first discussed by Captain E. B. Roberts, Professor S. Chapman, and the President, Dr. Julius Bartels, who drew attention to the decision that had been made the day before and by which the IAGA Committee on Magnetic Charts had been transformed into a Committee on World Magnetic Survey and Magnetic Charts. Extended discussions by A. McNish, P. N. Mayaud, T. R. Kaiser, K. Whitham, D. G. Knapp, and S. K. Runcorn followed.

Following a suggestion by President Bartels it was decided to appoint at once the members or some of the members of the IAGA Committee No. 5 (World Magnetic Survey and Magnetic Charts). The delegations from the countries most directly interested were requested to suggest candidates for membership, and the following were finally appointed:

B. C. Byrnes, U.S.A.
H. F. Finch, U.K.
M. M. Ivanov, U.S.S.R.
L. Koenigsfeld, Belgium
M. Maeda, Japan
E. Maple, U.S.A.
R. O. Meyer, Federal Republic of Germany
J. H. Nelson, U.S.A.
N. V. Pushkov, U.S.S.R.
J. M. Rayner, Australia
D. C. Rose, Canada
S. K. Runcorn, U.K.
E. Selzer, France
P. H. Serson, Canada

As a result of the above discussion IAGA proposed a formal resolution to IUGG that was finally adopted by that body as follows (Resolution No. 16, Comptes Rendus de la XI Assemblee Generale de l'UGGI, Toronto, 3–14 September 1957):

"*Considering* that the need for World Magnetic Surveys stems from two principal sources as follows:

1. "The requirement for data for theoretical studies of the source and origin of the earth's magnetic field and of the secular changes occurring therein.
2. "The preparation of more accurate world magnetic charts as a primary source of information for nautical and aeronautical navigation."

Recommends That

"The principal maritime and aeronautical nations should share the task of a world magnetic survey by sea and air;

"all countries which can do so, plan and execute individual magnetic surveys of a type which will contribute to a unified world survey as prepared by the Association of Geomagnetism and Aeronomy;

"all countries give consideration to the establishment of airborne magnetic surveys to provide data on all elements of the geomagnetic field, and that such surveys be extended to all feasible areas whether adjacent to or remote from the operating countries, in order to establish worldwide continuity;

"the USSR, now operating a nonmagnetic survey ship, should give primary attention to areas of (a) Indian Ocean, (b) South Atlantic Ocean, and (c) South Pacific Ocean, which will be difficult to cover by airborne survey equipment;

"all other countries which can do so, give consideration to arrangements for making magnetic measurements at sea;

"the USA and Canada, now possessing instrumental equipment suitable for airborne all-component magnetic surveys give immediate consideration to assigning equipment for world surveys;

"the United Kingdom and the USA, who have published magnetic charts of the world, to designate areas having the greatest need of prompt coverage for the guidance of all who may be in a position to conduct survey operations;

"all countries participating in the world magnetic survey exchange and publish promptly all the data derived from their operations."

The ICSU Special Committee for the International Geophysical Year (CSAGI) at a meeting in Moscow in 1958 adopted the following resolution:

"*Considering* the plans for the undertaking of a World Magnetic Survey the CSAGI suggests that the IAGA Committee on World Magnetic Survey and Magnetic Charts make suggestions as to the epoch of reduction on such a survey and prepare necessary guides for planning of the work, including a statement of desired accuracies, and a method of compiling the data."

IAGA Committee No. 5 on World Magnetic Survey and Magnetic Charts, under the chairmanship of E. H. Vestine, prepared the following draft report of technical recommendations for the survey:

1. "(a) That the epoch of the world magnetic survey (1960-65) be reduced to epoch 1965.0 with cognizance of later need for reduction to epoch 1975.0 for inclusion of later results.

   "(b) That charts be compiled on a scale of 1:10,000,000 for publication at some suitable scale.

2. "(a) That the USSR be urged to undertake surveys over the oceans with the *Zarya* for secular magnetic change.
   "(b) That as a general aim survey stations on the ground be located about 200 km apart where feasible.
   "(c) That aeromagnetic surveys over the oceans provide profiles spaced about 300-400 km apart.
3. "That the general aim intends that the intervals of the isolines be 1° in declination (D) with a coarser interval of 6° near the poles, and at 500 gamma intervals in horizontal intensity (H), vertical intensity (Z), total intensity (F), north intensity (X), and east intensity (Y). For inclination (I) a contour interval of 2° is suggested for equatorial regions, 1° in middle and higher latitudes. The contour interval for anomalies where indicated should be about 500 gammas; this contour interval can be reduced in the case of detailed anomaly surveys, if the scale of charting permits this reduction.
4. "That a potential analysis be made providing spherical harmonic terms up to and including a degree and order useful for adequate representation of the data.
5. "That the height of aeromagnetic surveys should be noted by observers.
6. "That earth satellite measurements of the geomagnetic field or other suitable data of useful accuracy be used where feasible to supplement the values at and near the ground.
7. "That the prompt provision of observatory and other estimates of secular change be stressed and facilitated."

This draft was circulated to IAGA National Committees asking for comments.

A letter from Dr. V. Laursen, President of IAGA, to Mr. G. Laclavère, Secretary General of IUGG, written in the early spring of 1963, indicates that at an informal meeting in Rome on 20 March 1963 the Executive Committee of the IAGA decided to establish within IAGA a World Magnetic Survey Board. This Board should take appropriate steps to stimulate the worldwide cooperation so essential for the successful accomplishment of the project, coordinate national plans, and give all possible advice and assistance with regard to the carrying out of the survey and the collecting and processing of the data obtained.

At the XIII General Assembly of IUGG in Berkeley, California, U.S.A., the IAGA Executive Committee approved the formation of the World Magnetic Survey Board (WMSB) and its membership. At this assembly ten resolutions passed by IUGG pertained to the World Magnetic Survey (see *IAGA News* No. 1, December 1963).

The Board held meetings in August 1963 at Berkeley, California, U.S.A.; in May 1964 at Florence, Italy; in November 1964 at Pittsburgh, Pennsylvania, U.S.A.; in April 1965 at Madrid, Spain; in October 1966 at the Royal Greenwich Observatory, Herstmonceux Castle, England; and in October 1968 at Washington, D.C., U.S.A. Several of these Board meetings were held in conjunction with IAGA symposia:

"Magnetism of the Earth's Interior" in Pittsburgh
"The World Magnetic Survey" at Herstmonceux Castle
"Description of the Earth's Magnetic Field" in Washington

A series of publications, the *WMS Notes*, was issued by the IUGG/IAGA World Magnetic Survey Board. *WMS Notes* No. 1 was published in January 1964, No. 2 in October 1964, No. 3 in January 1966 and No. 4 in December 1970. The *Notes* contain information pertinent to the WMS, including minutes of the Board Meetings. The minutes can also be found in IAGA *News*. In August 1961 an *Instruction Manual on World Magnetic Survey* was prepared by E. H. Vestine and was published as IUGG Monograph No. 11; Part II, dealing with analyses and publication of results, was issued in July 1967.

INTRODUCTION TO WMS RESULTS

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Though the science of geomagnetism is old, many fundamental questions still remain unanswered on fluid motions in the earth's core and the dynamo producing and sustaining the field, interpretation of results of surveys, drawing of charts, a reference field, the secular change, and magnetic anomalies and their geologic meaning. The World Magnetic Survey (WMS) was designed to overcome the principal deficiencies in surveys and to stimulate the use of the data in studies of the fundamental problems in geomagnetism.

The WMS included the following types of magnetic surveys:

1. By land using portable instruments often at marked stations that can be reoccupied every 5 to 10 years to obtain estimates of the secular changes.
2. By sea with the Soviet nonmagnetic ship *Zarya* and with ships of other nations.
3. By airplane over a great number of countries and over the oceans. In Project MAGNET of the U. S. Naval Oceanographic Office, an airplane survey was made along 3,800,000 km of flight track spread throughout the world.
4. By satellites in the near-earth environment—the Soviet Union's COSMOS-49; the United States' OGO 2 (1965-81A), OGO 4 (1967-73A), and 1964-83C.

The magnetic field at and near the earth's surface resembles that from a strong magnet located at the earth's center and with an axis tilted by 11.5° with respect to the earth's axis of rotation. It is presently believed that this field is due to electric currents flowing in the molten material forming the earth's core and that the interactions among the field, currents, and material form a dynamo that sustains the geomagnetic field.

For many applications scientists need an analytic representation of the geomagnetic field and its secular variations in order to calculate the field values at specific points of interest. In the past, different workers used different models, and intercomparisons were difficult to make. To remedy this situation, an International Geomagnetic Reference Field (IGRF) was chosen on October 24, 1968, for calculations of the main geomagnetic field of origin internal to the earth.

The geomagnetic field interacts with materials found in the earth's crust, materials often of interest in mineral exploration by the mining and petroleum industries. The magnetic properties of some kinds of rocks have also yielded a vast amount of information about the past magnetic fields of the earth to a rapidly growing number of scientists—paleomagneticians. This is because the magnetism of these rocks (e.g., a lava flow) was acquired at the time they formed under the influence of the magnetic field. By properly studying this "fossil" magnetism, paleomagneticians are learning much about the ancient field; moreover, the ancient field and its changes have an important bearing on hypotheses about the ocean floor spreading, continental drift, and polar wandering.

The magnetic field of the earth controls the motion of solar electrons and protons that enter the earth's environment. Some of these particles become trapped in the Van Allen radiation belt; others move down the field lines into the lower ionosphere where they collide with the atmospheric constituents, which become ionized and excited. The ionization disrupts communication systems, and the excitation results in light emissions, the most prominent of which are those of the aurora. The geomagnetic field also controls the motion of electrons and ions found in the normal ionosphere, formed through ionization of the atmosphere by solar X-rays and ultraviolet emissions. Winds at an altitude of about 100 km move these charged particles to form a global current system whose daily cycle of magnetic effects is readily detectable at the earth's surface.

The following symbols and definitions are used often, according to the customary practice in geomagnetic studies.

$X =$ a magnetic field component directed horizontally in the geographical meridian (true north). It is positive if northward and negative if southward.

$Y =$ a magnetic field component directed horizontally and perpendicular to the geographic meridian. It is positive if eastward and negative if westward.

$Z =$ the vertical component of the magnetic field. It is positive if downward and negative if upward.

$H = (X^2 + Y^2)^{1/2}$, the magnitude of the horizontal field component.

$F = T = (X^2 + Y^2 + Z^2)^{1/2}$, the magnitude of the total magnetic intensity.

$D =$ arc tan Y/X, the magnetic declination or magnetic variation. It is the azimuth of the horizontal component reckoned positively from the geographical north toward the east and negatively toward the west.

$I =$ arc tan Z/H, the magnetic dip or inclination. It is positive if the field is inclined downward and negative if upward.

$1\gamma = 10^{-5}$ gauss

A magnetic chart shows the distribution of the magnetic field, usually portraying only one component of the field. An *isomagnetic* line is a line on the chart along which the magnetic element has a constant value. An *isogonic* chart or line refers to magnetic declination, D; an *isoclinic* chart or line refers to magnetic inclination, I. Charts or lines referring to intensity components (X, Y, Z, H, or F) are *isodynamic*. An *isoporic* chart (or line) shows the annual rate of change of a magnetic element, the rate being positive if it reflects an algebraically increasing value of the element.

Magnetic field values derived from the spherical harmonic coefficients that represent the International Geomagnetic Reference Field (IGRF) are referred to a geocentric system of coordinates.

UNESCO ASSISTED MISSIONS AND WORLD DATA CENTRES

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MISSIONS

The idea of promoting World Magnetic Survey (WMS) activities by sending out WMS pilot missions to various parts of the world was put forward at an early stage of the planning work. It was considered that in many countries there was a rapidly increasing interest in geomagnetism, an interest that had manifested itself in the establishment of a great number of new magnetic observatories and also in the implementation of several magnetic surveys in regions from which geomagnetic information had so far been sparse. It would be of the greatest benefit to the WMS project if these efforts could be coordinated to fit into the program of the WMS, thereby extending still further the idea of international cooperation on which the International Geophysical Year had been based.

It was considered important that an attempt be made to standardize the instrumental equipment used for magnetic survey work in the various countries. Such a standardization could, in most cases, be obtained by checking the local observatory standard against some basic standard by means of traveling comparison instruments. With a view to this possibility all the experts going on WMS missions took with them a set of standardized magnetometers for the purpose of comparing these magnetometers with the local standards in the countries visited.

Since the WMS Board has never had a budget of its own, the carrying out of the proposed missions was made possible only through the generous support of UNESCO, an organization that has, from the beginning, shown an active interest in the WMS project and that has supported not only the pilot missions but also other important activities within the frame of the general project.

During the years 1964 - 1968 four WMS pilot missions were carried out: Africa, November-December 1964; South America, October-December 1965; Mediterranean area and the Middle East, December 1966 - February 1967; and Southeast Asia, March-April 1968.

The first of these missions was formally a UNESCO mission arranged in cooperation with the WMS Board, whereas the remaining missions were arranged by the Board in consultation with UNESCO and with the financial and practical support of that organization.

One expert went on each mission, and UNESCO and the WMS Board were fortunate to be able to secure for these jobs the cooperation of highly qualified specialists who carried out the program of the missions in the most successful way, taking full advantage of the gratifying goodwill with which the missions were everywhere met.

According to the program established by the WMS Board the task of the expert was defined in the following way. The expert will:

1. Take with him a set of calibrated instruments for comparison with local observatory standards or magnetic survey instruments,
2. Collect information on national or regional geomagnetic surveys already completed or in progress, and
3. Give, if requested by the institutions visited, advice and practical training in geomagnetic methods and techniques.

The instruments carried by the experts were in all cases a set of three QHM magnetometers for the determination of H and, with the exception of the 1964 mission, a BMZ magnetometer for the determination of Z. The QHM magnetometers were made available by the IAGA Service on International Comparisons and, for the 1968 mission, by the Australian Bureau of Mineral Resources. The BMZ magnetometer was lent to the Board by UNESCO for the purpose of these missions. In all cases the magnetometers were calibrated at the Danish magnetic observatory at Rude Skov, which has for many years been serving as a sort of reference station for the IAGA Service on Comparisons. The equipment of the 1968 mission also included an Elsec proton magnetometer made available by the Bureau of Mineral Resources, Canberra.

A few details of the four missions are given in the following summary reports.

Mission to Africa, November-December 1964

This first WMS mission, formally arranged by UNESCO, was carried out by Dr. K. A. Wienert of the Fürstenfeldbruck Geophysical Observatory. The mission included the following African countries:

Sierra Leone—The following institutions and organizations were visited: the Fourah Bay College, the Department of Surveys, and the Geophysical Survey Department. Comparisons were carried out at the Freetown Geomagnetic Observatory, operated by the Fourah Bay College.

Ghana—Visits to the University of Ghana, the Geodetic Survey of Ghana, and the Geological Survey Department. The magnetometers of the University of Ghana were compared with the traveling standards.

Ethiopia—Visit to the Geophysical Observatory of the Haile Selassie I University, Addis Ababa, with comparison observations at the magnetic station of that Observatory.

Kenya—Visits to the Physics Department and the Department of Land Surveying of the University College, Nairobi, and to the Mines and Geological Department. Comparison observations were made at the geomagnetic observatory of the Physics Department.

Uganda—Visits to the Physics Department of the Makerere University, Kampala, and to the Geological Survey and Mines Department, Entebbe.

A detailed report of the mission, prepared by Dr. Wienert, has been published in the *WMS Notes* No. 3, pp. 13-25.

Mission to South America, October-December 1965

This second WMS mission was carried out by Dr. J. M. Stagg, previously Secretary General of the International Union of Geodesy and Geophysics (IUGG) and now retired from his post as Principal Deputy Director of the British Meterological Office. The itinerary of Dr. Stagg's tour included the following countries:

Brazil—The institution visited was the National Observatory, Rio de Janeiro, which is responsible for the two permanent observatories, Vassouras and Tatuoca, and for magnetic survey work in Brazil. Comparison observations were made at Vassouras.

Argentina—Visits to the Astronomical Observatory of La Plata, responsible for the observatories at Las Acacias and Trelew, and to the National Meteorological Service, Buenos Aires, responsible for the observatories at Pilar, La Quiaca, and Orcadas del Sur. Comparison observations were made at Las Acacias and Pilar.

Chile—The following institutions were visited: the Cartographic Institute, the Meteorological Office (responsible for the magnetic observatory on Easter Island), and the Geophysical Institute of the University of Chile. There is no permanent observatory on the Chilean mainland, but a site has been selected at Peldehue for the establishment of such an observatory, and here the traveling standards were compared with a magnetometer used by the Meteorological Office for survey work.

Peru—Visit to the Geophysical Institute in Lima, which is responsible for all geomagnetic work in Peru, including the operation of the Huancayo Observatory. Comparison observations were made at Huancayo.

Bolivia—Visits to the Geophysical Institute, La Paz, and to the Military Cartographic Institute. The Geophysical Institute has established two recording stations, one near La Paz and one near Santa Cruz. Comparisons were made at the first of these stations.

Colombia—The institution visited was the Geographic Institute Agustin Codazzi, Bogota, which is responsible for all geomagnetic work in Colombia, including the operation of the Fuquene Observatory. Comparison observations were made at Fuquene.

A complete report of the mission, prepared by Dr. Stagg, has been published in *IUGG Chronicle* No. 66, pp. 198-207 and *WMS Notes* No. 4.

Mission to the Mediterranean Area and the Middle East, December 1966-February 1967

This third WMS mission was carried out by Dr. Wienert, as a continuation of his 1964 mission to Africa. The following countries were visited:

Greece—Visit to the Geophysics Branch of the Institute for Geology and Subsurface Research, which is responsible for recent survey work in Greece and for the operation of the Pendeli Observatory. Comparison observations were made at Pendeli.

Turkey—Visits to the Istanbul-Kandilli Observatory, Istanbul, and to the Turkish Geodetic Survey Department, Ankara. Comparison observations were made at the Kandilli Magnetic Observatory.

Lebanon—The geomagnetic observatory at Ksara was visited, and comparison observations were carried out.

Iran—Visit to the Geophysical Institute of the University of Teheran. Comparison observations were made at the magnetic observatory, which forms part of that Institute.

Pakistan—The institutions visited were the Pakistan Meteorological Service, responsible for the operation of the magnetic observatories at Quetta, Chittagong, and Gilgit, and the Survey of Pakistan, which is responsible for ground survey work in Pakistan. Comparison observations were made at Quetta.

United Arab Republic—Visit to the Helwan Observatory, which is responsible for geomagnetic survey work in the UAR and for the operation of the Misallat Observatory. Comparison observations were made at Misallat.

A detailed report of the mission has been prepared by Dr. Wienert. The report was published in the *WMS Notes* No. 4.

Mission to Southeast Asia, March-April 1968

This WMS mission was carried out by Dr. P. M. McGregor, who has for many years been in charge of the Gnangara Observatory, Australia, and who is now holding a post in the Canberra Headquarters of the Bureau of Mineral Resources. The arrangement was made possible through the courtesy of the Bureau of Mineral Resources, which also provided a set of calibrated QHM magnetometers and an Elsec proton magnetometer to be used for comparison observations during the mission. After the completion of the mission the QHM's were sent to Denmark for a supplementary comparison at Rude Skov. The mission visited the following countries and territories:

Philippines—Visits to the Bureau of Coast and Geodetic Survey and to the Manila Observatory. The Bureau of Coast and Geodetic Survey is responsible for geomagnetic survey work and is operating the Muntinlupa Observatory, whereas the Manila Observatory is operating magnetic recording stations at Manila, Baguio, and Davao. Comparison observations were carried out at Muntinlupa and Baguio.

Indonesia—Visit to the Meteorological and Geophysical Service, which is responsible for geomagnetic work in Indonesia, including magnetic surveys and the operation of the Tangerang Observatory. Comparison observations were made at Tangerang.

Hong Kong—The two institutions visited, the University of Hong Kong and the Royal Observatory, have for some time been engaged in a joint effort for the reestablishment of a magnetic observatory in Hong Kong. The WMS expert was able to give useful technical advice in the matter and to examine by means of the instrumental equipment of the mission the magnetic homogeneity of three areas that were at that time being considered as possible sites for the new observatory.

Timor—The institution visited, the Meteorological Service of Timor, is engaged in magnetic survey work on the Island, but does not operate a magnetic observatory. Local survey instruments were compared with the traveling standards at the repeat station of Tibar near Dili.

Dr. McGregor's detailed report of the mission was published in the *WMS Notes* No. 4.

Outcome of the WMS Missions

From the point of view of the WMS, the four missions have been extremely useful. The mission reports contain much information concerning survey work actually going on in the countries visited and also concerning many earlier surveys that may still be of interest to the WMS project. The experts have done well in emphasizing everywhere the importance of putting all available information at the disposal of the WMS Board or the geomagnetic World Data

Centres, and they have drawn attention to the advantages to be obtained from a close cooperation not only on an international but also on a regional scale for the purpose of arriving at a uniform and consistent presentation of magnetic survey results. One crucial factor in this connection is, of course, the agreement between national standards, and here the missions have been effective not only in stressing the importance of this point, but also in providing the necessary means of checking the agreement.

The need for an active regional cooperation within the domain of geomagnetism was perhaps most clearly recognized in South America, where there was a general acceptance of Dr. Stagg's suggestion that it would be extremely useful to arrange a meeting of South American specialists to discuss problems in connection with the carrying out of magnetic surveys and the presentation of survey results. As a consequence of the suggestion made, and thanks to the active interest which Dr. Lelio I. Gama, Principal Investigator in Geomagnetism of the National Observatory, Rio de Janeiro, took in the matter, such a meeting was in fact arranged in Rio de Janeiro in January 1969 with Dr. Gama as convener and reported in *IAGA News* No. 8, pp. 31-35.

As previously mentioned, the experts going on the missions were prepared to give such practical advice in geomagnetic methods and techniques as might be requested by the institutions visited, and it would seem that a good many observers took advantage of this opportunity to discuss technical difficulties or observational problems with the visiting expert. As stated in the reports of the first missions, it became clear from these discussions that in many places there was a pronounced need for an elementary manual in observatory and survey work, a manual that would give practical advice with regard to the use of some of the more common types of instruments and would treat such day-to-day problems with which an observer involved in geomagnetic work would inevitably be confronted. The WMS Board considered that such a manual would be of incontestable benefit not only to the WMS project, but also to future survey activities, and that it might lead to an improvement of the actual operational standard at many magnetic observatories. With the support of UNESCO, such a manual was prepared by Dr. Wienert in consultation with Dr. Stagg and others, and published in 1970 as No. 5 of the UNESCO series "Earth Sciences" under the title "Notes on Geomagnetic Observatory and Survey Practice."

In conclusion, the author of this summary report wishes to express on behalf of the WMS Board his sincere thanks to all those organizations and individuals who made it possible for the Board to carry out the pilot missions and who contributed to their success. The WMS Board owes a debt of gratitude to UNESCO for its generous financial support and for its invaluable assistance with regard to the practical arrangement of the missions; the three experts who so willingly placed their time and their expert knowledge at the disposal of the Board deserve a special thanks, as do the many authorities, institutions, and individuals in the countries visited, who without exception received the missions in the most cordial way and who, through their active and interested cooperation, contributed so largely to their success.

CENTRES

The system of World Data Centres (WDC) for the various geophysical disciplines was originally established for the purpose of the International Geophysical Year 1957 - 1958. However, the main part of the centres continued to function also after the end of the IGY, partly in order to serve subsequent international geophysical projects, as the Year of International Geophysical Cooperation 1959 and the International Years of the Quiet Sun 1964 - 1965, and partly because experience had shown in a general way that the WDC's are useful instruments for the collection and distribution of geophysical data.

Among the IGY Centres still in operation are the four WDC's for geomagnetism:

WDC A
U.S. Coast and Geodetic Survey, ESSA
Rockville, Maryland, 20852, U.S.A.

WDC B
IZMIRAN, Molodezhnaya 3
Moscow, B-296, U.S.S.R.

WDC C_1
Meteorological Institute
2920 Charlottenlund, Denmark

WDC C_2
Kyoto University Library
Kyoto University, Kyoto, Japan.

The principal types of geomagnetic data collected are:

a(i): monthly tabulations of mean hourly scalings of magnetograms

a(ii): microfilm copies of normal magnetograms
b: microfilm copies of rapid-run magnetograms with, in addition, copies of
e: tabulations of K- and C-indices
g: tabulations of Q-indices
h: tables of special events.

The data mentioned under e, g, and h are supplied primarily to the Permanent Services of IAGA at

The Royal Netherlands Meteorological Institute
De Bilt, Netherlands (e)

Institut für Geophysik
Postfach 876, 34 Göttingen, Germany (e, g)

Observatorio del Ebro
Roquetas (Tarragona), Spain (h)

which Services act as supplementary WDC's.

When the World Magnetic Survey project was first suggested as a deferred item in the programme of the International Geophysical Year, the Special Committee for the IGY, the CSAGI, in accepting the formal responsibility for this new project, also accepted the suggestion that the WMS data should be supplied to the newly established WDC's for geomagnetism along with the observatory data specified above. When the CSAGI went out of existence, the Executive Board of the International Council of Scientific Unions (ICSU) decided in 1962 that the WMS should be the responsibility of the IUGG, whereas the WDC's became the responsibility of the International Geophysical Committee of the ICSU. The IGC accepted a suggestion by IAGA that WMS data should continue to be collected in the WDC's, and in the *Guide to International Data Exchange* published by IGC in 1963 there was included, among the instructions pertaining to the WDC's for geomagnetism, a separate specification, prepared by Dr. Vestine, of WMS data to be supplied to these Centres.

During the years an extensive and valuable stock of WMS data has been collected in the WDC's. These data are of three different types representing the results of land observations in a network of observational points, ocean observations made on board ships, and airborne magnetic surveys.

Most of the data are in the form of lists of observations and/or geomagnetic maps. There are the results of magnetic surveys of tiny oceanic islands, often of particular interest in view of their isolated geographical position, and there are the latest magnetic maps of the whole earth. In addition a number of publications treat questions relating to the World Magnetic Survey, as examples, secular variation and general problems in connection with the description of the earth's magnetic field.

In WDC C_1, with which the author of this paper is intimately connected, WMS results have so far been received from more than 20 countries throughout the world. These many contributions illustrate the worldwide interest taken in the WMS project, and they also illustrate the useful part played by the WDC's as connecting links between the national agencies carrying out the survey work and the international agency, the WMS Board, entrusted with the coordination of the work and the publication of a final summary report of the result obtained.

WMS Notes No. 4 contains a list of publications in WDC C_1.

SURVEYS

GENERAL INFORMATION ON SURFACE SURVEYS*

BOLIVIA

Magnetic measurements were started in 1914 by the Department of Terrestrial Magnetism, Carnegie Institution of Washington. The U.S. Coast and Geodetic Survey began measurements later.

A systematic survey of magnetic components D, H, and I throughout the territory was started in 1951. The magnetic coverage of the entire country consists of 120 magnetic field stations and 14 magnetic repeat stations.

The field work has been carried out using a Ruska field magnetometer standardized with the absolute instruments in Fredericksburg Magnetic Observatory.

The collected data have permitted preparation of isomagnetic charts of three components for the 1955.0, 1958.0, 1963.0, and 1965.0 epochs.

The persons responsible for the work are Ing. Reynaldo Salgueiro Pabon (Instituto Geofisico Boliviano); Ing. Salvador Del Pozo Guzmán (Instituto Geografico Militar), Tec. Carlos Avila Soria (Instituto Geografico Militar), and Sr. Carlos Sanjinez (Instituto Geografico Militar).

Askania variographs and Ruska variometer stations have been operated intermittently; the collected data have been used for diurnal corrections and earth conductivity studies. The following stations were established: La Paz, Sica-Sica, Desaguadero, Cochabamba, Tarija, Riberalta, Santa Cruz, Caranavi, San Borja, Trinidad, Comarapa, Sucre, and Viru-Viru.

Investigations on the conductivity of the earth's mantle are being made in close cooperation with Carnegie Institution of Washington, D. C. and the Instituto Geofisico del Perú.

QHM and BMZ variographs will be used for absolute measurements in La Paz Observatory (La Cour variometer).

The Santa Cruz La Cour variometer was destroyed by persons unknown. Another observatory must be established.

The following papers and publications were produced:

1. Salgueiro, R., Cartas isomagneticas de Bolivia, *Boletin del Instituto Boliviano del Petroles, Tomo 2,* Vol. 1, 1961. This paper was presented at the First National Convention of Geophysicists, Geologists, and Petroleum Engineers held at La Paz, 1960.
2. Salgueiro, R., Isogonic chart of Bolivia and its applications to geology, paper presented at the Second National Convention of Geophysicists, Geologists, and Petroleum Engineers held at La Paz, 1962.
3. Schmucker, U., S. E. Forbush, O. Hartmann, R. Salgueiro, S. Del Pozo, A. A. Giesecke, Jr., M. Casaverde, and J. Castillo, Electrical conductivity anomaly under the Andes, *Carnegie Institution of Washington, Year Book No. 65,* pp. 11-28, 1965-1966.

CANADA

From 1940 - 1967, 911 three-component magnetic stations were occupied in Canada. Of these, 397 were exact reoccupations and are listed as repeat stations in the following table; the 514 new stations include approximate reoccupations.

Interval	*Repeat*	*New*
1940–44	39	4
1945–49	63	93
1950–54	114	281
1955–59	78	48
1960–64	74	59
1965–67	29	29

Before 1947, D, I, and H were measured with deflection magnetometers, earth inductors, dip circles, and compass theodolites. Fluxgate magnetometers measuring D, I, and F were developed for high latitudes in 1947 and were soon adopted for all parts of Canada. After 1962, portable proton magnetometers were used to measure F, while D and I were still obtained with the fluxgate magnetometer. With present equipment, the probable error of a single set of observations, requiring 10 minutes, is $\pm 0.2'$ in D, $\pm 0.1'$ in I, and $\pm 3\gamma$ in F. Since 1964, three-component recording fluxgate magnetometers have been used at each repeat station for a period of at least 30 hours.

The chief difficulty in determining secular change from repeat station data has been the correction of

* This section was prepared by Edward R. Dyer, Jr. and J. Hugh Nelson from the various national reports submitted.

TABLE 1

DIFFERENCE BETWEEN ANNUAL AND DAILY MEANS

Observatories	*Geomag. Lat. (degrees)*	*1960* ΔD	ΔH	ΔZ	*1965* ΔD	ΔH	ΔZ
Resolute	83.1	6.2°	75γ	120γ	4.5°	51γ	81γ
Baker Lake	72.9	54′	112	120	39′	54	81
Meanook	61.9	7.5′	129	60	4.3′	98	64
Agincourt	55.2	3.3′	96	52	3.4′	23	19

field observations for S_q and magnetic disturbances. Until 1951, there were only two permanent magnetic observatories in Canada, and, although the number has since increased to ten, most repeat stations are too distant from the nearest observatory for adequate control. The problem is, of course, accentuated by local ionospheric currents in the auroral zone. Our approach to this problem has been to make a complete set of observations at hourly intervals over a period of at least two days. From them, a smooth daily variation curve is derived, and time gaps and disturbed intervals are interpolated with the help of observatory magnetograms where possible. The mean of this curve is the reported station value. The portable recording magnetometers help greatly in the determination of the mean of the day.

For the study of secular change, an annual mean would be preferred to the daily mean. An estimate of the difference of these means was derived by analysis of observatory records for the survey months May to September in a disturbed year, 1960, and a quiet year, 1965. The average differences are shown in Table 1. It is clear that a method of correcting the mean of the day to the mean of the year must be found, especially for stations north of geomagnetic latitude 60°N.

A second difficulty has been the infrequent reoccupation of stations. In 1962, the number of repeat stations in Canada was sharply reduced from 544 to 102; the stations were carefully selected for accessibility and uniformity of distribution.

It is now possible to reoccupy all stations within five years in a regular program. Auxiliary stations are established near the repeat sites to guard against loss of stations by building construction.

Total intensity measurements have been made with proton magnetometers towed by oceanographic research ships of the Bedford Institute of Oceanography and the Institute of Oceanography of Dalhousie University. Detailed magnetic surveys have been made over the Mid-Atlantic Ridge at 45°N, Hudson Bay, Baffin Bay, and the Labrador Sea.

Magnetic charts are available covering Canada, Greenland, Iceland, and part of Alaska, at a scale of 1:6,336,000, for the following elements at the epochs indicated:

D and its annual change, 1955.0; 1960.0; 1965.0 (contour interval 1°)

I and its annual change, 1955.0; 1965.0 (contour interval 1°)

H and its annual change, 1955.0; 1965.0 (contour interval 1000γ)

Z and its annual change, 1955.0; 1965.0 (contour interval 1000γ)

F and its annual change, 1955.0; 1965.0 (contour interval 1000γ)

Declination charts with annual change, epoch 1955.0, are available for Manitoba, Saskatchewan, and Alberta at a scale of 1:1,267,000, contour interval 1°.

FEDERAL REPUBLIC OF GERMANY

Geomagnetic field stations were occupied during 1964 and 1965 as a contribution to the World Magnetic Survey and were financed by the Deutsche Forschungsgemeinschaft.

The field stations were selected from the Magnetische Reichsvermessung 1935.0 [*Bock, Burmeister, and Errulat,* 1958] in such a manner that, first, they were evenly distributed over the surveyed area; second, the deviations of the observed values from the normal field values of 1935 were small in all components. For the southern part of the surveyed area some suitable stations were added from the Second Order Geomagnetic Survey of Bavaria [*Burmeister,* 1960]. Some new stations were occupied as substitutes for old stations that are no longer suitable for occupation. In some cases stations were occupied as spares for important secular variation stations that might be lost in the near future. The spacing of the stations ranges from 50 to 70 km.

The northern part of the Federal Republic of Germany was surveyed by D. Voppel, Wingst Observatory, who used three QHM's (D, H) and a proton spin magnetometer (F). In the southern part K. Wienert observed by means of two HTM's (D, H) and a proton spin magnetometer (F). This combination of instruments enabled not only a rapid progress of the survey but also afforded a favorable possibility for the computation of Z and I.

Before occupation, the homogeneity of the magnetic field on the station site was investigated by means of proton spin magnetometer observations around the station. An occupation consisted of the observation of three to eight QHM sets and five to fifteen readings of the proton spin magnetometer. The observations were evenly distributed over two to four hours.

The field survey was carried out in traverses or loops comprising 5 to 20 stations and lasting from four to nine days. Before and after each traverse the field instruments were compared with the observatory standards of Wingst and Fürstenfeldbruck, respectively.

The agreement of results obtained by the two field parties was checked at four stations that were occupied by both field parties. The stability of the observatory standards of Wingst and Fürstenfeldbruck was ascertained by comparing 02^h GMT values of the two observatories on the ten quiet days of every month. The standards of the two observatories were compared directly in November 1965, and all checks indicated that the standards had remained constant throughout the period of the survey.

The errors of observation and reduction to epoch were estimated from the disagreement of results at stations that were repeatedly occupied (up to four times). The following errors of a single occupation were found:

Element	RMS *Error*	*Maximum Error*
D	$\pm 0'.6$	$\pm 1'.2$
H	$\pm 3\gamma$	$\pm 5\gamma$
F	$\pm 2\gamma$	$\pm 4\gamma$

One-hundred sixty occupations were carried out at 129 stations. The raw results were reported to World Data Center A as prescribed by Dr. E. H. Vestine in his WMS manual.

After reduction of the observed values to epoch 1965.0 and correction to the International Magnetic Standard, the normal field equations and the equations for the secular change from 1935.0 to 1965.0 and from 1955.0 to 1965.0 were computed by E. Weingärtner. Charts based on the measurements made in 1964 - 1965 and on values updated from previous surveys were drawn for epoch 1965.0 in D, H, Z, I, and F. A declination chart for 1970.0 is being prepared. At the time of this writing, preparations are being made for the publication of the survey results.

This report was taken from one submitted by Professor Dr. O. Meyer, Deutsches Hydrographisches Institut, 2 Hamburg 4, Bernhard-Nocht-Strasse 78; Dipl. Geophys. D. Voppel, Observatorium Wingst, 2171 Höftgrube/N.E.; and Dr. K. Wienert, Geophysikalisches Observatorium, 808 Fürstenfeldbruck. Additional references are the following:

Bock, R., F. Burmeister, and F. Errulat, Magnetische Reichsvermessung 1935.0, *Geophysikalisches Institut Potsdam,* Abh. No. 6, Berlin, 1958.

Burmeister, F., Magnetische vermessung II, Ordnung von Bayern 1955.0, *Veröffentl. Geophys. Obs. Fürstenfeldbruck,* Serie B, No. 1, München, 1960.

FINLAND

During the period 1945 - 1967 magnetic observations were made at 63 stations in Finland. The locations were well distributed over the entire country. Most of the stations were repeat stations, many of them having been occupied more than a dozen times during the interval. Two magnetic observatories were in operation, Sodankylä in the north and Nurmijärvi in the south.

Beginning in 1945 the use of QHM and BMZ magnetometers supplanted the earlier instruments that used the classical Gauss method. Through careful comparison of the instruments with magnetic observatory standards, accuracies of 2γ in H, 3γ in Z, and 1.5 minutes of arc in D were attained.

In 1957 the Finnish Meteorological Institute purchased an Askania portable three-component geomagnetic recorder, and in 1959 a declinometer. A portable proton-precession magnetometer (Elsec) was purchased in 1963, and the field observing procedures were modified to take full advantage of the increased accuracy potential.

A series of Studies in Earth Magnetism has been published by the Finnish Meteorological Institute. Number 20 of this series, entitled *Measurements at Geomagnetic Secular Stations in Finland, 1945-1967,* by Christian Sucksdorff, published in 1968, presents a very satisfactory account of the Finnish contribution to the World Magnetic Survey. It describes the equipment used, gives information regarding diurnal and yearly variations of magnetic activity, systematic variations in magnetic recordings, and methods of reducing the data, and gives a tabulation of all results obtained during the 23-year interval.

FRANCE

The French participation in the WMS deals mainly with magnetic measurements at sea. The work in this field was started in 1964, although not having the WMS as the principal objective; however, it was considered later to be a suitable contribution to the WMS. These observations were carried out as a study of the Atlantic Continental Shelf, as a study of certain geologic structures in the western Mediterranean, as a study of the dorsal middle Indian Ocean, and finally, since 1968, as a study of the Atlantic Continental Margin in the Gulf of Guinea.

In 1964, approximately 400 km of magnetic profiles were taken along the Atlantic Continental Shelf between the 45th and 46th north parallels up to the meridian 4°30′W. In 1965, 7500 km of profiles, covering a sector delimited by the parallels 47° and 48°20′N and the meridians 5° and 7°W, were surveyed. In 1966, 13,000 km of profiles were taken in a narrow band, confined to the north of the parallel 48°30′N between the Ushant Island and the meridian 7°W: In 1967, 20,000 km of profiles were surveyed between Penmarc'h Point and Belle-Isle. The work undertaken was actually continued, in this case, to cover the entire zone of the open sea of Brittany. The data reduction steps are in progress, and an interesting map of all the surveys will be offered soon.

In the Mediterranean, more than 5,000 km of magnetic profiles were taken in the Western Mediterranean in this project to study some specific geologic structures. In the Antarctic in 1965 two north-south magnetic profiles, connecting Australia to Adelie Land and totaling 5,000 km, were taken providing an opportunity to make a reconnaissance of the dorsal middle ocean and to determine the intensity in an area where the observations are very rare.

Two cruises for marine geophysics (magnetometry and bathymetry) were undertaken in the Indian Ocean between the islands of Reunion, Mauritius, Amsterdam, Kerguelen, and Crozet during 1966-1967 and 1968. A total of 31,000 km of profiles was taken. These observations, providing new data on the dorsal middle ocean, allowed us, specifically, to state precisely the "uniqueness" of the formation mechanism of the dorsals; furthermore, for the hypothesis of sea-floor spreading, the simultaneous formation of these structures up to distances of as much as 10,000 km could be determined. Finally it was possible to fix a rough sketch of the structure of these dorsals in the southern part of the Indian Ocean. All these observations permit a better definition of the intensity values of the earth's magnetic field in a region where there exist only a very few observatories.

Slightly less than 10,000 km of regularly spaced profiles, oriented north-south, were surveyed in the Gulf of Guinea from the coast to the parallel 2°S between the meridians 10°W and 3°E. The object of this survey was to study the continental margin of the Ivory Coast and, in particular, the extensions of the large fractures of the equatorial Atlantic.

All magnetic measurements made at sea were made with the proton magnetometer constructed by the Varian Company and equipped with a numerical recording device (punched tape).

FRENCH CONTRIBUTION IN AFRICA

This summary was abstracted from a report submitted by Hans G. Barsczus of the Overseas Scientific and Technical Research Office (ORSTOM), 24, Rue Bayard, Paris 8, France.

Magnetic surveys of vast regions comprising about one-fourth of continental Africa have been in progress since early in 1950 when ORSTOM began operating the observatory at M'Bour and the observatory at Bangui, Central African Republic (formerly

French Equatorial Africa). The following is the status of the surveys in the various countries.

WEST AFRICA

Country	*No. of Observations*					
	New			*Repeat*		
	D	*H*	*Z*	*D*	*H*	*Z*
Ivory Coast	34	42	43	34	26	25
Dahomey	11	12	12	8	8	8
Guinea	17	22	22	11	6	6
Upper Volta	20	35	40	35	7	9
Mali	74	85	91	68	40	43
Mauritania	86	100	104	31	19	16
Niger	310	315	316	54	33	43
Senegal	8	14	14	9	10	10
Togo	6	7	7	3	3	3

EQUATORIAL AFRICA

Country	*No. of Observations*		
	D	*H*	*Z*
Cameroon	43	44	44
Chad	105	105	105
Gabon	22	25	25
Central African Republic	89	94	95

The repeat observations are "repeat" only in a broad sense, since, in general, reoccupations are made with a positional accuracy of several score or hundreds of meters.

Magnetic measurements were carried out at the same time as the large-mesh (grid) gravimetric survey of the regions of interest except for the following countries: Guinea, Ivory Coast (major part), Dahomey, Togo, and Senegal. In this manner a density of 1 to 4 stations per square degree is achieved. In addition, at each point where gravimetric measurements were made (on the average, every 4 to 5 km on profiles spaced 20-30 km apart), Z was measured at a total of about 50,000 points.

Magnetic charts of West Africa and Equatorial Africa were made although, in some cases, the supply is exhausted. Information on charts, instruments, and surveys may be obtained from Hans Barsczus.

INDIA

The Survey of India since 1901 has carried out field magnetic surveys in the country to cover the entire area with a mesh of field magnetic stations primarily for preparation of magnetic charts for the country. The surveys consist of observations and computations of horizontal force, vertical force, and declination at repeat stations and field stations using QHM, BMZ, and T2 theodolite. Observations for horizontal force and vertical force anomalies are carried out using variometers. The station spread for repeat stations is of the order of 200-300 km. The field stations are 20-30 km apart in some areas and 60-80 km in other regions. The whole of the country had been covered by such repeat and field surveys by February 1967.

There are presently six geomagnetic observatories: one maintained by the National Geophysical Research Institute (N.G.R.I.) at Hyderabad; four at Alibag, Kodaikanal, Trivandrum, and Chidambaram maintained by the India Meteorological Department; and one by Survey of India at Dehra Dun. A continuous record of geomagnetic elements (H, V, and D) is being made at each place. In addition to their use for worldwide studies in geomagnetism and allied upper-air phenomena, the data from these stations are also being used for evaluation of electrical conductivity distributions in the deep crust and mantle employing geomagnetic variations of different periods as observed at the surface.

There are several other magnetic studies being undertaken in India in connection with geological investigations. The Geological Survey of India undertakes regional and detailed magnetic surveys in addition to gravity and electrical surveys for mineral exploration of Singhbhum, Aravalli, and other regions of the country. The Oil and Natural Gas Commission takes up routine gravity and magnetic surveys in the sedimentary basins of the Indo-Gangetic plains, Narmada, Tapati, Kaveri, Godavari river basins, etc., and the eastern and western coastal tracts of India. The data from these surveys are being processed presently, and it is hoped that the data will yield useful information for crustal studies, which can be supplemented by the reflection seismic studies. Andhra University during 1960 - 1962 conducted regional magnetic surveys in the lower Godavari basin for studying the basement configuration of the upper Gondwanas (coal-bearing strata) and Deccan traps of the Rajahmundry area, supplemented by paleomagnetic and rock magnetic studies of the rocks. The N.G.R.I. conducted detailed gravity and magnetic surveys in the Sittampundi Anorthosite basic rock complex of south India for delineation of the complex and interpretation of the genetic history of the basic rocks supposed to have come from the upper mantle.

IRAN

The Institute of Geophysics, Tehran University, carried on a magnetic survey during the period 1961 - 1963, constituting the first survey operations in the area since the Carnegie Institution of Washington did similar work in 1908 and 1909. The WMS measurements were made at 37 stations fairly well distributed throughout the country. The results are published in Publication No. 35, *Report on the Secular Variations of Geomagnetic Field in Iran.*

A magnetic observatory began operating at Tehran during the International Geophysical Year 1957-58. The quality of the records and accuracy of the data have been improved substantially within the past few years.

IRELAND

Measurements of the magnetic elements had been made at various places throughout Ireland in the first half of the nineteenth century and were collected by *Sabine* in 1870 and published in the papers of the Royal Society. More complete surveys were carried out by *Rucker* and *Thorpe* in 1886 and 1891 and by *Walker* in 1915. A survey of the vertical component of the earth's magnetic field was made by the Geological Survey of Ireland in 1949. In 1950 Professor *Murphy* of the School of Cosmic Physics measured the magnetic elements at 44 stations, 33 of which were identical with or very close to those measured by Walker in the earlier survey. In 1959 the Meteorological Service carried out a magnetic survey of 12 sites that were set up close to the meteorological stations. During the years 1960 to 1963, repeat observations were made at these stations, and observations at these 12, together with other more suitably sited stations, will be repeated regularly to determine the secular variation of the various magnetic elements.

Since the majority of the countries of the world intended to participate in the World Magnetic Survey during the period 1964 - 1965, the Irish National Committee for Geodesy and Geophysics recommended in January 1961 that the Meteorological Service and the Ordnance Survey should cooperate in a comprehensive magnetic resurvey of the country during 1964 - 1965. It was felt that this period, with its low level of geomagnetic activity, would be regarded as Ireland's contribution to the great enterprise of the World Magnetic Survey. Details of the organization of the survey were worked out between officers of the Ordnance Survey and the Meteorological Service during 1963 and early 1964.

All the necessary reconnaissance work, the marking and description of stations and the determination of azimuth of any new stations, was done by Mr. J. P. Cassidy and Mr. M. McPadden of the Ordnance Survey. For those stations in Northern Ireland, similar work was carried out by officers of the Ordnance Survey there. The actual magnetic measurements at all stations were made by Messrs. J. Byrne, F. Donaldson, and J. Hardy, all of the Meteorological Service.

The stations used in the present survey are mainly those used by Murphy in his 1950 survey, together with the 12 secular variation stations that were set up in 1959 adjacent to the meteorological stations. The instruments used in the latest survey were: for declination, a Gurley Transit Magnetometer (loaned by the U. S. Coast and Geodetic Survey) and two QHM instruments; for horizontal force, two QHM instruments; for vertical force, a BMZ instrument; for total force, a proton precession magnetometer (borrowed from the School of Cosmic Physics). All instruments were compared at intervals with the standards at the Valentia Observatory. The observatory records were used as controls for the removal of instantaneous deviations from the mean values at the times of field observations.

Isomagnetic charts of Ireland were compiled for the magnetic elements, declination, inclination, horizontal intensity, vertical intensity, and total intensity, for epoch 1965.5. Each chart shows both the "true" (detailed) isomagnetic lines as well as the "terrestrial" (highly smoothed) lines. The terrestrial lines are based on simple analyses of the field distribution, having the form

$$E = A(\varphi - 50) + B(\lambda - 5) + C$$

where φ and λ are the north latitude and west longitude, respectively, in degrees, and A, B, and C are derived constants.

The above information was abstracted from *A Magnetic Survey of Ireland for Epoch 1965.5,* a report of the Meteorological Service, Department of Transport and Power, Dublin, 1966.

ITALY

The Italian Commission of the International Geophysical Committee appointed a special working group to establish a national magnetic network within the WMS project. The "ad hoc" working group consisted of experts from many Italian scientific institutes who have cooperated in carrying out absolute measurements at the stations of the Italian network.

The Institutes which participated in the magnetic survey are the following: Istituto Geografico Militare (Firenze), Osservatorio Vesuviano (Napoli), Istituto di Geodesia e Geofisica (University of Bari), and Istituto Nazionale di Geofisica (for the two magnetic observatories). Measurements were made by GSI Sokkisha magnetometers, one of first order and two of second order. Instruments were calibrated at the National Geomagnetic Observatory at L'Aquila of the Istituto Nazionale di Geofisica at the beginning as well as at the end of each survey. The reduction of data for H and Z to an international standard (with 1-2γ accuracy) was accomplished by direct comparison measurements made at the above Observatory in cooperation with the Fürstenfeldbruck Observatory (Germany). These measurements were carried out by a nuclear precession magnetometer and three HTM's. On the average 15 measurements were made at each station of the national network. The mean error is 2γ for H and Z and 0′.2 for D, for each measurement made with the first-order magnetometer. The mean error is 6γ for H and Z and 0′.4 for D, for each measurement made with a second-order magnetometer.

The reduction of all measurements to 1965.0 epoch was computed on the basis of data from L'Aquila Observatory, which is situated approximately in a central position with respect to all the stations. The values of magnetic field elements were calculated as averages for a period of six months before and after 1965.0 epoch. The differences at L'Aquila Observatory between the magnetic values at the moment of each measurement and the values for 1965.0 epoch were determined, these differences representing the corrections made to the measurements. Where daily variation (particularly for H) presented a sensible difference in comparison with the magnetic variations recorded at L'Aquila Observatory (e.g., in south Italy and Sicily), measurements were reduced to 00 hour of the observation day using recordings of a portable magnetometer.

The list of the stations and their geographic coordinates, as well as the data of the earth magnetic field absolute measurements for the elements D, I, H, Z, and F, are given in the full report of the Commission, published in Rome on March 25, 1968.

JAPAN

The most recent land magnetic survey of Japan was started in September 1964 and completed in October 1965. For the reduction of observed values, data were used from the four magnetic observatories: Memambetsu, Kakioka, and Kanoya (of the Japanese Meteorological Agency), and Simosato (of the Hydrographic Office). The survey, made by the Hydrographic Office, used the GSI-type magnetometer described in the *Bulletin of the Geographical Survey Institute*, Vol. 2, 1951. Forty stations were occupied. At each station the complete vector determination was made each hour from 00 to 2300 U. T.; the results have been published in Publication No. 592, *Data Report of Hydrographic Observations, Series of Magnetic Survey,* No. 1, February 1968. The Japanese national program for the World Magnetic Survey included airborne surveys that are discussed elsewhere in this book (see article by T. Nagata).

Through the use of both the land and airborne data, magnetic charts were compiled for epoch 1965.0 and depicted the seven magnetic elements: declination, inclination, horizontal intensity, vertical intensity, northward component, eastward component, and total intensity. Each chart also contained isoporic lines delineating the annual rate of change of the element.

The charts, a complete tabulation of the data, descriptions of equipment and procedures, and details of data reduction methods are contained in Publication No. 592 of the Maritime Safety Agency, mentioned in the first paragraph of this section.

LUXEMBOURG

Within the framework of the International Geophysical Cooperation and along with the World Magnetic Survey project, the magnetic survey of the Grand Duchy of Luxembourg was carried out during June 1968 by the Internal Geophysical Department of the Belgian Meteorological Institute, in collaboration and participation with the Ministry of Cultural Affairs of the Grand Duchy of Luxembourg. The network of observing points chosen for the total (F) and horizontal (H) intensity covers 51 stations in an area 2600 km^2. For seven stations in this network the magnetic declination was also measured.

The determinations of F and H were made at each station, using a proton magnetometer (Elsec model) and two QHM's; the magnetic declination measurements were made with a geodetic theodolite (Wild T2) and a magnetic theodite (Askania). The stations were always chosen in areas relatively free of all artificial disturbance. With these elementary precautions, it was assured by a preliminary survey that the chosen points were not affected by a purely local anomaly. For this work, determinations of F were made in at least three places within a distance of 50-100 m of the site chosen for the measurements.

The difference method was used for reducing the measurements, taking the magnetic station of Dourbes as the reference station.

The differences

$$H_{Db} - H_{st}, F_{Db} - F_{st}, D_{Db} - D_{st}$$

were reduced to January 1, 1965 (epoch 1965.0), the date chosen for the WMS epoch, by taking the mean of the monthly means of the last six months of 1964 and the first six months of 1965.

The data derived from the magnetic survey work are presented in a pamphlet published in 1968 by the Ministere des Affaires Culturelles du Grand Duché de Luxembourg entitled, *La Distribution du Champ Magnetique Terrestre au Grand Duché de Luxembourg au ler Janvier 1965,* by A. De Vuyst and J. Pohl. The publication also contains magnetic charts of Luxembourg depicting the isogonic and isoclinic lines and isodynamic lines of the horizontal, vertical, and total-field components of intensity. The locations of the observing points and the measured values are shown on the charts.

MOROCCO

The coordinates of the new observatory at Averroes are 33°17′53″N, 7°24′48″W, 230 m altitude. Three La Cour variometers with slow recording rate (15 mm/h) have been in service since November 1, 1966. They are located in a cellar 12 m deep, where the temperature is constant. Scale values are 3.28γ/mm for H, 0.6 arc-sec/mm for D, and 3.40γ/mm for Z.

Baseline values were obtained with the help of the following instruments for making absolute measurements: (1) for H, three QHM's calibrated in 1966 by P. Mayaud and F. Soubrane, through comparisons with standards brought from Chambon-le-Forêt; (2) for D, a Chasselon theodolite and the QHM's calibrated against the theodolite; and (3) for Z, an Elsec proton magnetometer, which replaced a BMZ used earlier.

A critical study of the new observatory has been undertaken, including its installation, discussion of the results, comparison with neighboring magnetic observatories, study of induced currents, etc.

During the months of March, April, and July 1967, a total of 17 stations was established with uniform coverage for the entire region. The values for H, D, and F for each point were reduced to the epoch 1967.5. The stations, listed in approximate order of geographic latitude are: Goulimine, Tata, Zagora, Tiouine, Taouz, Tinerhir, Rich, Safi, Fkih ben Salah, Bou Arfa, Averroes, Outat Oulad, Ifrane, Rabat, Guen Fouda, Al Hoceima, and Tangiers.

A publication on the results is *Le Nouveau Reseau Magnétique de Maroc, Etabli en 1967*, by F. Soubrane and J. C. Sibuet. Scheduled for publication are the following: (1) a critical study of the new Averroes Observatory; (2) hourly values for H, D, and Z, scale values, and baseline values for the period November 1, 1966 to December 31, 1967.

Nearly 500 measurements of the total magnetic field were carried out during 1967 at stations along the highways of Morocco. Some of the measurements were made by the Service de Physique du Globe in cooperation with the Topographic Service. The entire work was carried out with an Elsec proton magnetometer belonging to the Direction des Mines et de la Géologie and was completed in 1968. An isomagnetic chart with scale 1:1,000,000 was drafted by the Départment de Géophysique of the Direction in early 1968; a preliminary draft version was then available showing the position of the stations (geographic and Lambert coordinates for Morocco), together with a list of the measured values.

Systematic coverage of Morocco by an aeromagnetic survey is foreseen, although it will be several years before a chart of the whole can be published.

This summary is based on reports by J. C. Sibuet, Laboratoire de Géomagnétisme, Service du Physique du Globe, Institut Scientific Chérifien, Rabat, and by A. H. Demnati, Départment de Géophysique, Division de la Géologie, Direction des Mines et de la Géologie, Rabat.

NIGERIA

Magnetic surveys in Nigeria started as early as 1916. Observations consisted mainly of the determination of magnetic declination (D) at stations situated throughout the country with the view to preparing an accurate and complete isogonic chart for Nigeria.

The first isogonic chart was drawn and reproduced by Federal Surveys in 1949 on a scale of 1:3,000,000. Magnetic declinations were shown on this chart at intervals of 30 minutes. The surveys from 1916 to 1948 were executed by Federal Surveyors and surveyors from the Regional Survey Offices. For this exercise, magnetic declinations were observed at 1093 different places in the country. The instrument used was the Conolly compass. Most of the stations occupied were old triangulation and traverse pillars of known bearings to other control pillars used as reference objects in the magnetic measurements. When new stations were used, azimuth observations were carried out. The results of all observations over the 32-year period showed that the declination in any part of the country was decreasing at a mean annual rate of 5.5 minutes of arc. As of January 1, 1949, the declination in Nigeria ranged from 4° 30′ to 10° 00′ west of true north.

The Conolly compass was used until 1953. In 1958, new observations were made at 183 repeat stations using the Winkfield standard compass. These were carried on until 1962. The Winkfield compass had the advantage of speed over the old Conolly compass. The mean annual variation deduced for the 10-year period from 1952 - 1962 was 6.2 minutes of arc eastward, slightly bigger than the 5.5 minutes obtained from the pre-1949 observations.

In 1963 - 1964, repeat observations were again performed using the Hilger and Watts master compasses. Results from the different Regional Survey Offices are received by Federal Surveys, who compiles the records. Since results over periods of only one or two years will not be sufficient to show poor observations, the 1963 - 1964 values had not been analyzed and no conclusions have been drawn as yet. However, in an attempt to explain the causes of some discrepancies between old observations and some repeat observations done years later, it was concluded that the differences are due to (a) observations having been taken by different observers in each locality, and (b) use over the years of at least two or three instruments of different makes.

The Federal Surveys of Nigeria is at present engaged in another magnetic survey of the entire country. The instruments being used are the BMZ and QHM magnetometers. This time, all three components (horizontal force H, vertical force Z, and declination D) of the earth's magnetic fields are being measured. Observations of 39 stations in the Western State had already been completed in December 1967.

Over the past four years the Director of Federal Surveys, Mr. R. Oluwale Coker, in association with the Surveyor General, Western State, Mr. W. Gascoyne, has been responsible for directing and planning the observations.

Among the difficulties encountered is the lack of local facilities for maintenance, servicing, repairing, and recalibrating the instruments. These difficulties are overcome by shipping the instruments overseas by air for repairs. In fact the instrument used for the recently completed observations at the 39 stations in the Western State was damaged, and it had to be sent to the Danish Meteorological Institute in Denmark for repairs and recalibration. Several months elapse before the instruments are returned.

It is proposed to carry out observations at about 400 field stations in the country or approximately at one station per 2000 km^2 of land area.

It is hoped that after this new magnetic survey using BMZ and QHM magnetometers is completed some light could be thrown on some of the still unresolved discrepancies of previous observations. This would give a more accurate and up-to-date isogonic chart for Nigeria.

This report was submitted by C. T. Horsfall for the Director of Federal Surveys, Federal Survey Department, Lagos, Nigeria.

PAKISTAN

The first general surface geomagnetic field survey of West Pakistan was carried out during the period 1959 - 1961 and that of East Pakistan was done in 1962 - 1963. Isogonic charts of the two wings of the country at epochs 1960.0 and 1963, respectively, were published by 1964. The consolidated book of results originally scheduled for 1964 has, however, not yet been published although the data are available in manuscript form.

The repeat survey for updating the isomagnetic charts of West Pakistan to the epoch 1965.0 was completed on time between December 1964 and August 1965. The isogonic chart of West Pakistan, epoch 1965.0, has since been published. The repeat survey in East Pakistan was done in 1966 - 1967, and the isogonic chart of East Pakistan at epoch 1967 has also been published. The books of detailed results are still under preparation.

A total of 60 magnetic stations was reoccupied during the repeat survey of West Pakistan, 1964 - 1965. Recovery of the permanently marked stations, for exact reoccupation, was 90%, and it is expected that continuity of this order of exact reoccupation will be maintained in future magnetic surveys. Since West Pakistan territories comprise a huge area of over 300,000 square miles, two magnetic survey parties were put in the field: one operating in the northern half of West Pakistan used the GSI magnetometer No. 39 (Japanese) for declination (plus inclination), HTM's for horizontal force, and BMZ's for vertical force; and the other party working in the southern and southwestern portions of West Pakistan used QHM's for D and H, and BMZ's for Z. Motor vehicles were mainly used for transportation but the railway and air services were also used whenever required. Quetta Magnetic Observatory is the base for West Pakistan where all field instruments were calibrated against the National Standards at the commencement as well as at the end of all field work.

The field work in East Pakistan 1966 - 1967 was accomplished by a single field party in view of the much smaller area (a little over 55,000 square miles) to be covered, for which observations at only 20 stations sufficed. The rate of recovery of the permanently marked stations of the 1963 survey was about 70% because of the very heavy population and very soft soil of East Pakistan. QHM's and BMZ's were the magnetic instruments used. The national railways were the principal means of transport but steamers, motor boats, and even country craft were also used extensively.

Except for a few broken suspension fibers, no exceptional incident marred the smooth functioning of the field parties throughout the period of the repeat surveys.

The compilation of the consolidated volumes of results is currently in abeyance because of the preoccupation of the staff with other high-priority jobs. It is hoped, however, that an all-inclusive volume embodying the results of the two previous surveys (1960 - 1965 epochs) and the forthcoming survey, at epoch 1970, may be brought out by 1972.

The original information for this summary was supplied by M. S. Rajput, Secretary, Sub-Committee on Geomagnetism of N.C.G.G. Survey of Pakistan, Rawalpindi.

PORTUGAL

The field work of the geomagnetic survey of Angola was extended in 1966 and 1967. The magnetic elements, D, H, and Z, were measured at 93 field stations. The instruments used on the survey were Askania theodolites and La Cour QHM's and BMZ's.

The geomagnetic survey of Mozambique has been completed. Data derived from observations of D, H, and Z at 240 field stations are being used for the compilation of magnetic charts of the three elements.

In addition to the operation of the magnetic observatory at San Miguel, special observations were made during the International Year of the Quiet Sun for determination of mean component field values at Horta (Azores) and in Angra do Heroísmo. Field observations were made on Ìlha do Porto Santo, and magnetic charts of D, H, and Z were compiled for the epoch 1963.2.

SOUTH AFRICA

The Hermanus Magnetic Observatory has continued and extended the long-term secular program instituted in 1938 under the direction of Dr. A. Ogg. The permanently marked stations were reoccupied in 1947 - 1948, 1952 - 1953, 1961, and 1966. In 1948 the network was extended to Rhodesia.

In order to improve the coverage the secular variation network has been considerably modified and extended in recent years, and more stations are being added. In 1966, 55 geomagnetic repeat stations were occupied in the Republic of South Africa, South-West Africa, and Botswana. Of these, 46 were reoccupations of the stations occupied during 1961. The remaining nine stations had been established during the interim period 1961 - 1966.

Since 1961, the Department of the Surveyor-General of Rhodesia has undertaken the reoccupation of the repeat stations in that territory. Through the courtesy of the Rhodesian authorities, the results have been incorporated in the field publications of the Hermanus Observatory.

The program of observations at a field station consists of taking measurements of each of the elements D, H, and Z at 20-minute intervals over a period of ten hours. This is achieved by taking alternate readings with two instruments only, viz., a vertical field balance (BMZ) and a horizontal force magnetometer (QHM). Provided the azimuth circle of the H magnetometer remains undisturbed throughout the series of observations, the "zero torsion" readings provide relative values of the magnetic declination. These readings are converted into absolute values by observing D immediately before and after the series of H observations. The declination is measured with a conventional fiber declinometer. To reduce the effect of differential heating in the magnetometers, all observations are made in special nonmagnetic tents.

The method used for evaluating the field observations was described elsewhere. All field observations are referred to the Hermanus Magnetic Observatory (previously the Cape Town Magnetic Observatory). In 1966 the magnetic observatories of Lourenco Marques and Tsumeb provided additional control.

The results of the secular variation surveys were published in Reports Nos. C_1 - C_4 of the Hermanus Observatory. Each report includes a set of smoothed magnetic charts of D, H, and Z for the area covered by the field network. The isopors shown on these charts refer in each case to the immediately preceding interval.

In the case of the 1966 survey report No. C_4, the isogonic and isodynamic charts refer to the epoch 1965.0 and the isoporic charts to the interval 1961 - 1966. The D chart is based on a least-squares fit of the declination data to a cubic equation of the form

$$D = Do + aX^3 + bX^2Y + cXY^2 + dY^3 + eX^2 + fXY + gY^2 + hX + iY$$

where X and Y here are the geographical coordinates of the stations. The declination data used in this analysis include the results of compass observations taken at about 130 intermediate points in the network.

A detailed analysis recently carried out on the geomagnetic secular variation patterns in southern Africa from 1938 - 1966 will be published in the near future.

During the period 1964 - 1966 the Hermanus Magnetic Observatory carried out measurements of the total magnetic intensity on voyages of the Antarctic supply ship *RSA* from Cape Town to Marion Island, Tristan da Cunha, and Antarctica. The observations were made at approximately half-hour intervals using a proton precession magnetometer with towed detector.

During recent years, the Agulhas Bank Geophysical Survey has conducted intensive magnetic surveys in the oceanic areas adjacent to southern Africa. The program is sponsored by the Geological Survey of the Republic of South Africa and conducted from the Department of Geology, University of Cape Town.

During the past two decades, the Geological Survey carried out an extensive magnetometric survey of the vertical intensity, covering the greater part of the Republic of South Africa and parts of South-West Africa.

Prospecting firms have carried out airborne magnetic surveys over selected areas of South Africa and South-West Africa.

SPAIN

Seven magnetic observatories were operated during the period of the World Magnetic Survey, providing hourly mean values of the magnetic vector and accurate data for determination of the secular change rates. The observatories were those at Toledo, Logroño, Almeria, Tenerife, Moca, Del Ebro, and San Fernando. The annual mean values and much of the hourly data have been filed with the World Data Centers for Geomagnetism.

SWEDEN

The Swedish contribution to the WMS consisted of magnetic field measurements made, for the most part, at locations where similar measurements had been made prior to 1939, thus constituting repeat measurements suitable for determination of secular change. Numbers of stations occupied and years of observation are shown below:

Year	*Number of Stations* *Repeat*	*New*	*Elements Observed*
1953	9	0	D, H, Z
1955	8	0	D, H, Z
1959	46	6	D, H, Z
1960	37	5	D, H, Z
1963	3	0	D, H, Z
1964	6	0	D, H, Z
1967	0	54	F

Data from an aeromagnetic survey of Scandinavia, performed in 1965 by Dominion Observatory, Ottawa, Canada, have been made available to the World Data Centers for Geomagnetism. These data are discussed in an article by Paul H. Serson in this volume and in the report, "The Aeromagnetic Survey of Denmark, Finland, Norway, Sweden, 1965," prepared and published at the Geomagnetism Section of the Swedish Board of Shipping and Navigation under the supervision of Folke Eleman, Kjell Borg, and Ulf Oquist in consultation with Christian Sucksdorff, Helsinki, 1969.

UNITED STATES

Prior to 1940 the U.S. Coast and Geodetic Survey (USC&GS) obtained measurements of the strength and direction of the earth's magnetic field at about 10,000 magnetic stations scattered throughout the United States and its dependencies. These data, correlated with secular change data from strategically located repeat stations, constitute the main source of distribution information for preparation of the U.S. magnetic charts.

A wide variety of magnetic data from many sources is obtained and used by USC&GS in the compilation of world and special area (regional) magnetic charts. Two major contributors to these worldwide data files are the U.S. Naval Oceanographic Office (through Project MAGNET) (which is discussed elsewhere in this volume) and the Inter-American Geodetic Survey (IAGS). The data are of both repeat and nonrepeat nature.

Repeat station data from USC&GS and IAGS sources, beginning with the fiscal year 1943, are reflected below:

Fiscal Year	*Number of U.S. Repeat Stations*	*Number of Other Non-U.S. Repeat Stations*
1943	52	45
1944	96	45
1945	104	18
1946	1	28
1947	13	20
1948	36	—
1949	36	—
1950	46	—
1951	5	—
1952	19	—
1953	52	101
1954	5	—
1955	6	66
1956	13	88
1957	4	90
1958	81	169
1959	61	128
1960	7	150
1961	18	109
1962	59	44
1963	56	122
1964	42	114
1965	32	80
1966	3	80
1967	13	56
1968	27	69

USC&GS is currently using a network of approximately 125 repeat magnetic stations, strategically interspersed among the observatories throughout the U.S. and its dependencies, to support and strengthen its secular change program. A continuing field operation, timed and coordinated with the chart publication program, ensures that essentially all the repeat stations are reoccupied between chart publication epochs, now spaced at five-year and ten-year intervals. Certain stations in areas of suspected rapid change or impulse are reoccupied at closer intervals, preferably twice or more between chart epochs; thus, an annual average of about 30 U.S. repeat stations is the current goal for field work. Because of frequent destruction of repeat stations resulting from encroachment by expanding civilization, "twin stations" (separated by no more than a mile or so) are much preferred.

Because of the relatively great distances between observatories, the repeat program was revised in 1958 to include the use of a portable magnetic observatory. The portable recording equipment is moved from point to point as repeat work progresses. Though not adopted as a rigid procedure, at present most repeat stations are occupied while a portable observatory is in operation in the general vicinity, for example, no more than a mile or so away. Usually about three days of continuous recording produce adequate control for reducing the repeat station data to a mean datum.

At the present time, USC&GS is operating in strategically located areas 14 permanent magnetic observatories, distributed geographically from Point Barrow, Alaska, to the South Pole and from Puerto Rico to Guam, Mariana Islands.

The general locations of USC&GS magnetic observatories are:

Fredericksburg, Virginia	Sitka, Alaska
San Juan, Puerto Rico	College, Alaska
Dallas, Texas	Barrow, Alaska
Boulder, Colorado	Honolulu, Hawaii
Tucson, Arizona	Guam, Mariana Islands
Castle Rock, California	Byrd, Antarctica
Newport, Washington	South Pole, Antarctica

Seven of the above observatories were in operation in 1950. Ten were in operation in 1960.

Magnetic observations at four island stations in the Pacific Ocean area were obtained during the International Year of the Quiet Sun. The four recording stations were located on Majuro, Midway, Koror, and Adak.

In 1960 USC&GS became actively engaged in the collection of magnetic data over ocean areas by towed magnetometer. To date many single track lines between widely separated points, as well as systematic surveys (fixed line spacings, with tielines) of significant ocean areas, have been done. Recognizing the merits of systematic ocean surveys, USC&GS in 1961 formalized a marine program as part of a national plan for ocean surveys and incorporated the technique to develop the geophysical characteristics of the area between Hawaii and the Aleutian Islands. Magnetometers have since been installed aboard most of the USC&GS ships, and measurement of the field intensity has become an integral part of all systematic, as well as single track, ocean surveys. Large areas of the region between Hawaii and Alaska have now been covered.

The marine magnetic survey data are recorded in scalar intensity only. The proton precession magnetometer, with the sensing head towed about 500 ft or more aft, is now employed exclusively. To date, about 300,000 lineal miles of towed magnetometer data have been gathered, but a large percentage of it is insufficiently processed for immediate scientific use.

USC&GS compiles and publishes the U.S. Magnetic Charts at five-year and ten-year intervals, the isogonic chart being the only one published at the shorter interval. The entire series was last published in 1965. Through cooperation and collaboration with the U.S. Naval Oceanographic Office, USC&GS also compiles the World Magnetic Charts on the same time schedule as the U.S. Charts. The World Charts are then published and distributed by the Naval Oceanographic Office.

Hand-cartographic methods have been essentially eliminated in favor of computer-driven automatic plotters in chart production. The last issue of the World Magnetic Charts was compiled for the first time by use of spherical harmonic analysis and computer-driven automatic plotters, thus essentially eliminating human bias from the process. The next issue of both the U.S. and the World Charts will employ some additional improvements through increased application of mathematical analysis and further automation.

ZARYA AND AIRBORNE SURVEYS

RESULTS WITH THE NONMAGNETIC SHIP ZARYA, 1956-1968

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Magnetic surveys in the oceans with the nonmagnetic ship *Zarya* have been conducted since 1956. During the past 12 years the *Zarya* covered about 500,000 km in the Atlantic, Indian, and Pacific Oceans and adjacent seas (Fig. 1) with the continuous registration of D, H, Z, and F. The methods of measurement were unchanged during the entire survey period. The errors of the results are the following: F, $\pm 50\gamma$; H and Z, $\pm 100\gamma$, with the component errors arising mainly from the errors in the gyroscopic stabilization system. It is believed that the stabilization accuracy would not be significantly increased in the near future, and consequently the accuracy of the component measurements would not be increased. As shown in the figure the *Zarya* tracks, though widely spaced, formed a rather even network within the latitudes 40°N - 40°S. The survey yielded data of great importance for studies on improving the analytical representation of the geomagnetic field.

What are the main problems facing the *Zarya,* and what are their solutions?

There is the problem of collecting data for the compilation of the smoothed world charts. Since U.S.S.R. representatives treat elsewhere in this volume the cartography and analytical presentation of the magnetic field using the *Zarya* data, these aspects are not further considered here.

Another problem is the study of the secular variation distribution in the world's oceans. With the *Zarya* data for the period 1956 - 1960 and the *Carnegie* surveys, the resultant schematic secular variation charts of D, H, Z, and F were compiled for the Atlantic, Indian, and Pacific Oceans [*Ivanov,* 1958; *Matveyev,* 1965]. These summary charts showed that the main errors of the world charts were evidently caused by insufficient information on the secular variation. To estimate the reliability of the *Zarya* data for the secular variation determination, a special experimental study was carried out [*Kas'yanenko and Rose,* 1968]. A pattern of that chart, updated approximately to 1956 - 1966, is given in Fig. 2 and should be considered as preliminary and not recommended for practical usage. Examination of this chart shows that if one accepts the details of this secular variation and takes into account the measurement accuracy estimated above, then for such a secular variation pattern it would be necessary to repeat observations alongside the routes spaced nearly 10° by 10° in latitude and longitude, and within an interval of about ten years. In this case the accuracy of the secular variation chart would be of an order of some 10 - 20γ/year. If the mean values over a certain interval of the route were used as initial data for the charts, the errors due to the local anomalies and uncertainties of the route position would be minimized.

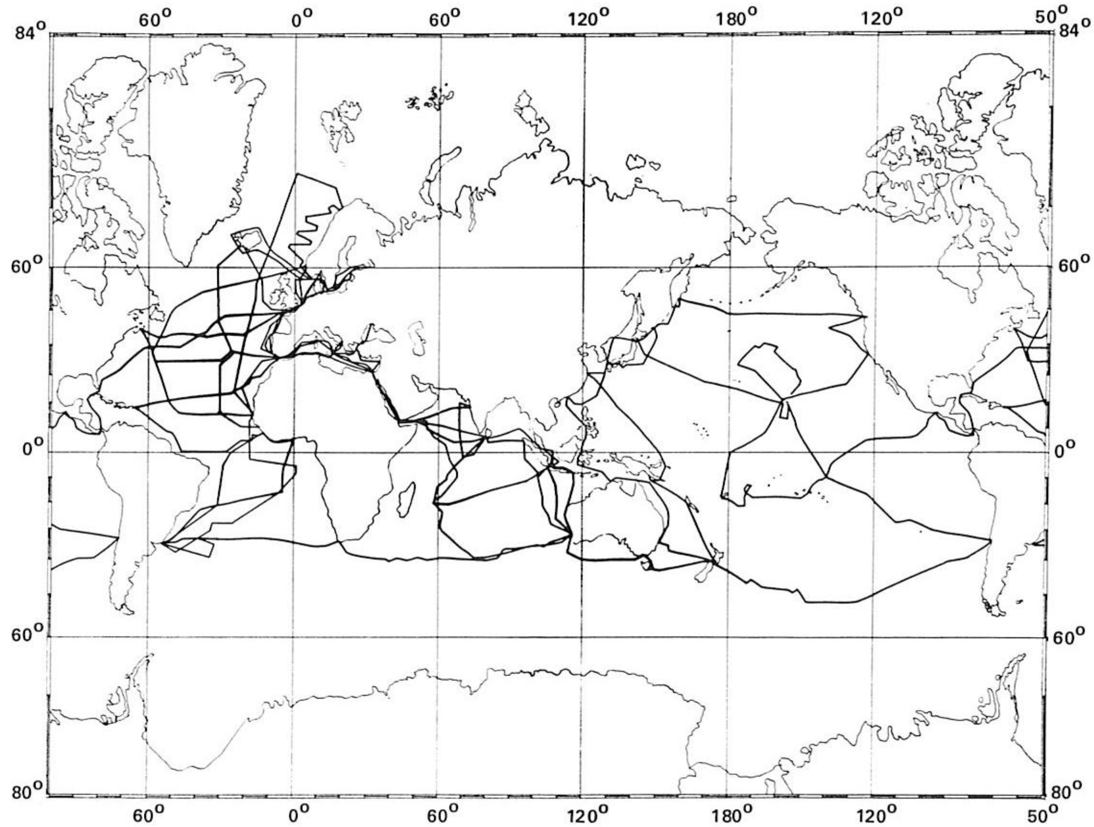

Fig. 1. Tracks of the Zarya, 1956–1967.

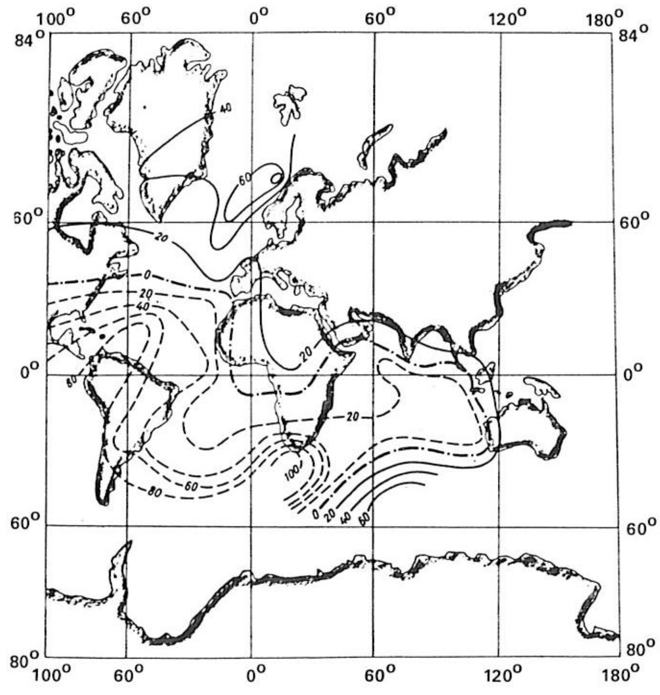

Fig. 2. Sample of Chart for Secular Change of Scalar Intensity, γ/Year.

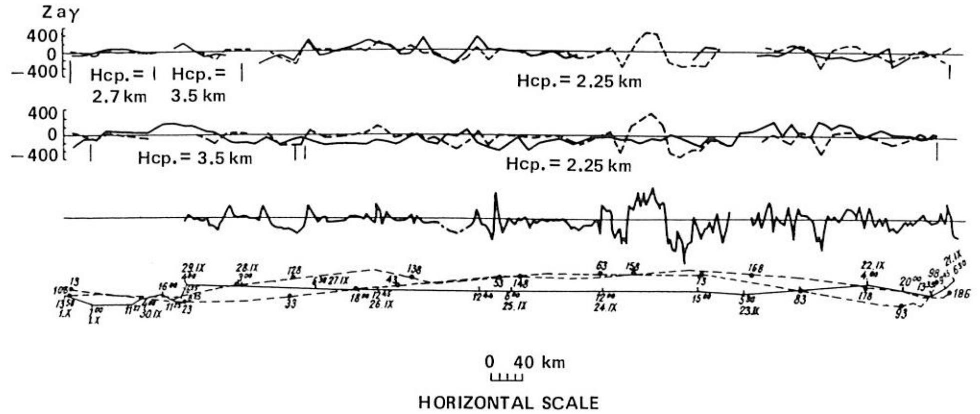

Fig. 3. Results of Comparison between Data from Project Magnet and from the Zarya.

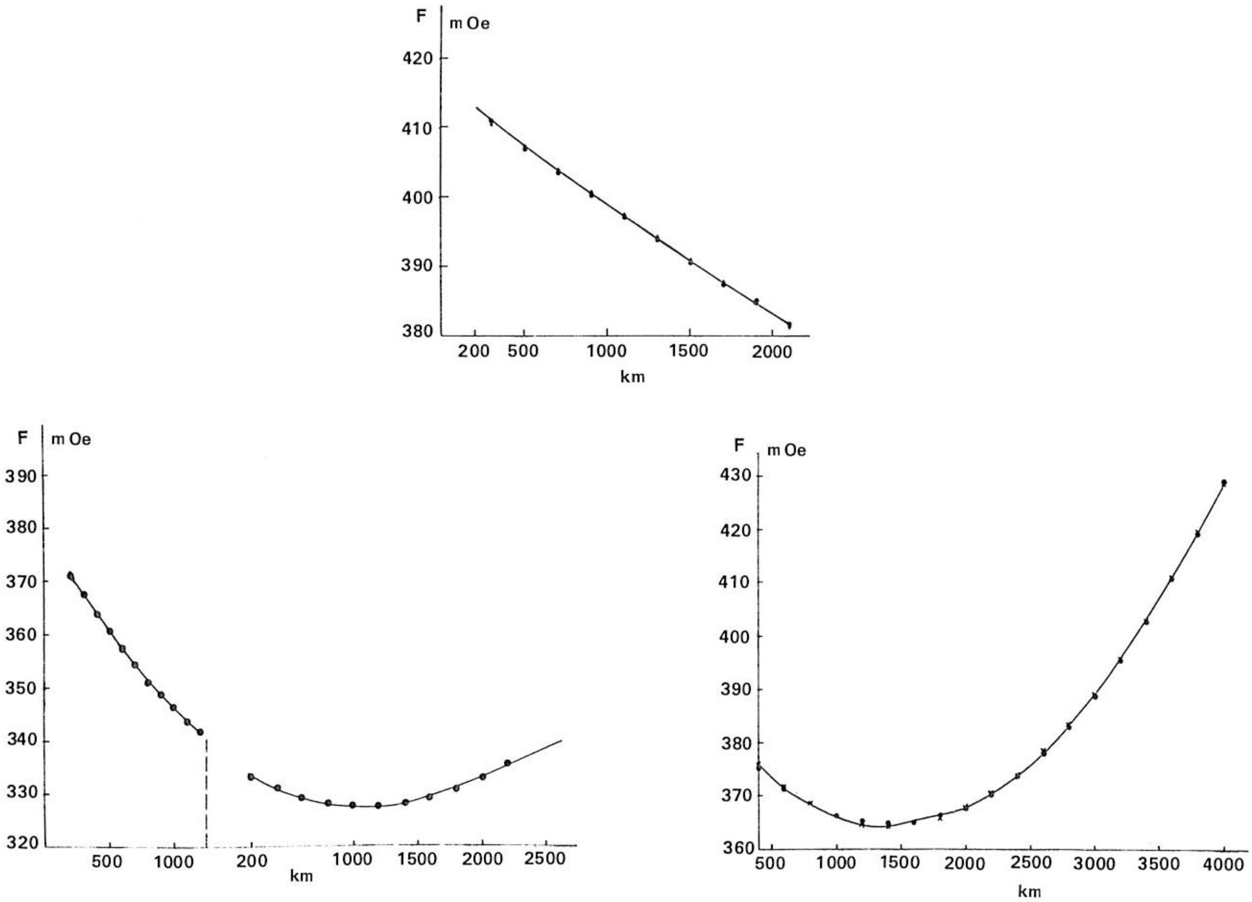

Fig. 4. The Variation of the Normal Field along some Zarya Tracks.

A very important geomagnetic problem is the study of anomalies over the oceans. The comparison of the data from Project MAGNET and from the *Zarya* [*Ivanov*, 1963] showed that the aeromagnetic surveys are hardly applicable to study the fields generated by the sources located in the oceanic crust. The results of this comparison are given in Fig. 3. A difficulty in applying the *Zarya* data stems from the fact that while much data exist along the tracks, the tracks themselves are widely spaced. Hence an

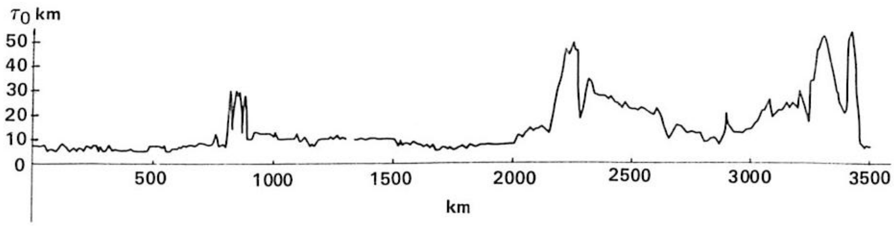

Fig. 5. Examples of Divisions of the Ocean Floor Provinces by τ_0.

uncertainty arises when removing the normal field in order to study the anomalies. In one of our previous papers we obtained the main field from the *Zarya* data by means of a certain graphical smoothing of the observed field [*Ivanov,* 1961]. Later [*Rose,* 1968; *Efendieva,* 1968] another approach to the normal field problem was tried. The investigation of the geomagnetic field statistical properties such as dispersion of the anomalous field and its spectral density permitted defining more correctly the averaging interval, which in most cases equalled 300 - 400 km. Now the normal field may be derived easily by taking the running averages over the defined interval. A pattern of the normal field obtained in such a way is given in Fig. 4 [*Efendieva,* 1968]. These curves may be easily fitted by polynomials of the second or third degree.

The analytical field computed using the first nine harmonics of the spherical harmonic expansion could not be, in our opinion, recommended as a global normal field in reference to the separation of the crust anomalies, though this field may be quite suitable for certain considerably larger regions.

In the interpretation of the anomalous field obtained along an isolated profile, an additional and significant difficulty arises from the fact that the spatial distribution of the field is unknown. Nevertheless, a number of the depth definitions performed in order to fix the sources of anomalies showed that they were located within a thin oceanic crust. We suggest that the mega-relief of the depths of the sources reflects the mega-relief of the oceanic bottom in general. At the same time neither a direct correlation nor an anti-correlation is found between the relief of the anomalous field and the relief of the ocean floor, though in some cases isolated anomalies are indisputably connected with the relief features [*Ivanov,* 1963; *Efendieva,* 1968].

The statistical analysis of a number of long magnetic profiles shows that the anomalous field may be regarded as "block-stationary", and dimensions of such blocks may be determined by the dimensions of geological provinces of the ocean floor. Dimensions or extensions of geological provinces may vary greatly [*Rose,* 1968]. The division of these provinces may be successfully performed using the statistical treatment of the anomalous field characteristics. Figure 5 illustrates such a division. The investigation by statistical methods of the anomalous field and its properties is in progress now.

The measurements of the electric fields in the oceans together with the geomagnetic measurements allow us to reveal the connection between the transient variations of the electric and geomagnetic fields [*Pushkov and Fonarev,* 1970]. This is of great importance when the problem of excluding the transient magnetic variations is considered.

The *Zarya* active sailing is nearly terminated now. The Academy of Science of the U.S.S.R. is making arrangements to design a new nonmagnetic ship which would not only replace the *Zarya* but would also extend the number of geophysical investigations in the world's oceans. We look forward to the realization of this plan, and we hope that the Soviet Union will be able to continue magnetic measurements in the oceans in the near future.

Listings of three-component magnetic data for the years through 1967 have been sent to the World Data Centers.

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NATIONAL MAGNETIC SURVEY OVER JAPAN AND ADJACENT AREAS

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Description of the Geomagnetic Field and the Compilation of Magnetic Charts Based on Aeromagnetic Survey Data

Under the Japanese national program of WMS, three-component aeromagnetic surveys over Japan and the adjacent sea areas were conducted by the Geographical Survey Institute (GSI) and the Hydrographic Office from 1961 to 1964. The total area of the surveys amounts to about $3 \times 10^6 \text{km}^2$. The aircraft altitude was always kept at about 3 km; the total number of flight tracks equals 289, with the tracks over sea extending about 250 nmi from the coast. The descriptions of the airborne magnetometers used, the observed data, and magnetic charts of D, H, I, F, X, Y, and Z at epoch 1965.0 are reported in *Report on Aeromagnetic Survey in Japan* [1966] and are only summarized here.

The data obtained in the Japanese national program are combined with data from Project MAGNET of the *U.S. Naval Oceanographic Office* [1963, 1965]. The distribution of the magnetic field in Japan and adjacent sea areas of all components is illustrated on charts based on the freehand interpolation method. In addition the distribution of the field with latitude and longitude is computed by each of two analytic methods using polynomial expressions, the results being illustrated in the same charts.

First, for D, H, I, F, and Z, the distribution is represented by quadratic formulas in terms of latitude φ and longitude λ, the coefficients of which are obtained by the method of least squares. The numerical results are the following:

$$\text{D (west)} = 7°08' + 0'.384\,\Delta\varphi - 0'.063\,\Delta\lambda - 0'.00001\,\Delta\varphi^2 - 0'.00011\,\Delta\lambda^2 - 0'.00002\,\Delta\varphi\Delta\lambda \quad P = \pm 3' \tag{1}$$

$$H = 30{,}260 - 6.79\,\Delta\varphi - 1.44\,\Delta\lambda - 0.0013\,\Delta\varphi^2 - 0.0003\,\Delta\lambda^2 + 0.0017\,\Delta\varphi\Delta\lambda \text{ gammas} \quad P = \pm 53\gamma \tag{2}$$

$$I = 50°58' + 1'.206\,\Delta\varphi - 0'.142\,\Delta\lambda - 0'.00026\,\Delta\varphi^2 + 0'.000003\,\Delta\lambda^2 - 0'.00003\,\Delta\varphi\Delta\lambda \quad P = \pm 7' \tag{3}$$

$$F = 47{,}980 + 9.07\,\Delta\varphi - 4.24\,\Delta\lambda - 0.0003\,\Delta\varphi^2 - 0.0002\,\Delta\lambda^2 + 0.0002\,\Delta\varphi\Delta\lambda \text{ gammas} \quad P = \pm 143\gamma \tag{4}$$

$$Z = 37{,}300 + 16.99\,\Delta\varphi - 3.91\,\Delta\lambda - 0.0043\,\Delta\varphi^2 - 0.0006\,\Delta\lambda^2 + 0.0011\,\Delta\varphi\Delta\lambda \text{ gammas} \quad P = \pm 136\gamma \tag{5}$$

In the above and succeeding equations, P is the probable error, $\Delta\varphi = (\varphi - 37°00'\text{N})$, and $\Delta\lambda = (\lambda - 135°00'\text{E})$.

Second, for D, H, X, and Y, the distribution is calculated by the method of least squares using the same polynomial expression but with the added condition that curl $\mathbf{B} = 0$. In this case,

$$X = X_o + a_x\Delta\varphi + b_x\Delta\lambda + c_x\Delta\varphi^2 + d_x\Delta\varphi\Delta\lambda + e_x\Delta\lambda^2 \tag{6}$$

$$Y \cos\varphi = Y_o \cos\varphi_o - b_x\Delta\varphi + b_y\Delta\lambda - \tfrac{1}{2}d_x\Delta\varphi^2 - 2e_x\Delta\varphi\Delta\lambda + e_y\Delta\lambda^2 \tag{7}$$

$$\frac{\partial(Y\cos\varphi)}{\partial\varphi} + \frac{\partial X}{\partial\lambda} = 0 \tag{8}$$

$$H = \sqrt{X^2 + Y^2} \tag{9}$$

$$D = \tan^{-1}\frac{Y}{X} \tag{10}$$

where $\varphi = \varphi_o + \Delta\varphi$, $\lambda = \lambda_o + \Delta\lambda$, and X_o and Y_o are the values of X and Y, respectively, at the point (φ_o, λ_o).

The numerical results are as follows:

$$\text{D (west)} = 7°11' + 0'.386\,\Delta\varphi - 0'.064\,\Delta\lambda + 0'.00004\,\Delta\varphi^2 - 0'.00013\,\Delta\lambda^2 - 0'.00005\,\Delta\varphi\Delta\lambda \tag{11}$$

$$H = 30{,}270 - 6.81\,\Delta\varphi - 1.44\,\Delta\lambda - 0.0014\,\Delta\varphi^2 - 0.0001\,\Delta\lambda^2 + 0.0019\,\Delta\varphi\Delta\lambda \text{ gammas} \quad (12)$$

$$X = 30{,}030 - 7.18\,\Delta\varphi - 1.36\,\Delta\lambda - 0.0015\,\Delta\varphi^2 - 0.00003\,\Delta\lambda^2 + 0.0020\,\Delta\varphi\Delta\lambda \text{ gammas} \quad P = \pm 61\gamma \quad (13)$$

$$Y \cos\varphi = -3{,}020 - 1.36\,\Delta\varphi + 0.53\,\Delta\lambda + 0.0010\,\Delta\varphi^2 + 0.0009\,\Delta\lambda^2 - 0.0001\,\Delta\varphi\Delta\lambda \text{ gammas} \quad P = \pm 33\gamma \quad (14)$$

$$Y = -3{,}780 - 2.51\,\Delta\varphi + 0.69\,\Delta\lambda + 0.0006\,\Delta\varphi^2 + 0.0012\,\Delta\lambda^2 + 0.0002\,\Delta\varphi\Delta\lambda \text{ gammas.} \quad (15)$$

Comparing the coefficients of the polynomial series for D and H in the second class (where curl **B** = 0) with those of the first class, one notices that differences in the corresponding coefficients are not significantly large and are within the limits of probable error.

In comparison with the above mentioned small discrepancy between isomagnetic lines derived from the two kinds of polynomial expressions, the difference between the isomagnetic lines obtained by simple interpolation of observed values from those of either one of the polynomial expressions is significantly large (see Fig. 1). The magnitude of root mean square (rms) differences between observed and chart values is the smallest in the case of the freehand simple interpolation chart. It may thus be concluded that the freehand simple interpolation magnetic charts are the most reliable provided that a sufficiently large amount of observational data can be used for compiling such magnetic charts.

Isoporic Charts for 1965

Isoporic charts for 1965 for the area previously discussed have been compiled by the Hydrographic Office by combining annual mean values at ten magnetic observatories in Japan and its neighboring area with secular variation data obtained at 40 repeat stations [*Maritime Safety Agency,* 1968]. The magnetic observatories are Memanbetsu, Kakioka, Kanoya, and Shimosato in Japan; Sakhalinsk, Vladivostok, Srednikan, Yakutsk, and Irkutsk in U.S.S.R.; and Guam.

A magnetic element M(t) at a station and at a time t can be approximately expressed by

$$M(t) = A + B(t - 1965.0) + C(t - 1965.0)^2$$

where A is its value at epoch 1965.0 and B and C are coefficients related to the secular change of the element. In most cases, the magnitude of C is negligibly small.

The surface variation of B may be represented by a polynomial with respect to latitude φ and longitude λ, such as

$$m = m_o + a\Delta\varphi + b\Delta\lambda + c\Delta\varphi^2 + d\Delta\varphi\Delta\lambda \quad (16)$$

where $\Delta\varphi = (\varphi - 37°)$ and $\Delta\lambda = (\lambda - 135°)$.

The distributions of the secular variation at 1965.0 for D, H, and I, respectively, are given by the following polynomial expressions:

$$\frac{dD}{dt}\text{(west)} = 0'.4 + 0'.0002\,\Delta\varphi - 0'.002\,\Delta\lambda + 0'.0000003\,\Delta\varphi^2 - 0'.0000003\,\Delta\lambda^2 - 0'.0000002\,\Delta\varphi\Delta\lambda \text{ minutes of arc/year} \quad P = \pm 0'.1/\text{year} \quad (17)$$

$$\frac{dH}{dt} = 11 + 0.004\,\Delta\varphi - 0.004\,\Delta\lambda + 0.000005\,\Delta\varphi^2 - 0.000002\,\Delta\lambda^2 + 0.000002\,\Delta\varphi\Delta\lambda \text{ gammas/year} \quad P = \pm 2\gamma/\text{year} \quad (18)$$

$$\frac{dI}{dt} = 1'.6 - 0'.0006\,\Delta\varphi + 0'.0006\,\Delta\lambda + 0'.0000004\,\Delta\varphi^2 + 0'.00000002\,\Delta\lambda^2 - 0'.0000004\,\Delta\varphi\Delta\lambda \text{ minutes of arc/year} \quad P = \pm 0'.1/\text{year.} \quad (19)$$

The secular variations in F, X, Y, and Z obtained from dD/dt, dH/dt, and dI/dt are described by the following expressions:

$$\frac{dF}{dt} = -10 - 0.001\,\Delta\varphi - 0.012\,\Delta\lambda + 0.000007\,\Delta\varphi^2 - 0.000003\,\Delta\lambda^2 + 0.000004\,\Delta\varphi\Delta\lambda \text{ gammas/year} \quad (20)$$

$$\frac{dX}{dt} = 10 + 0.003\,\Delta\varphi - 0.002\,\Delta\lambda + 0.000004\,\Delta\varphi^2 - 0.000002\,\Delta\lambda^2 + 0.000004\,\Delta\varphi\Delta\lambda \text{ gammas/year} \quad (21)$$

$$\frac{dY}{dt} = -5 - 0.003\,\Delta\varphi + 0.015\,\Delta\lambda - 0.000002\,\Delta\varphi^2 + 0.000002\,\Delta\lambda^2 - 0.000006\,\Delta\varphi\Delta\lambda \text{ gammas/year} \quad (22)$$

$$\frac{dZ}{dt} = -22 + 0.006\,\Delta\varphi - 0.013\,\Delta\lambda + 0.000003\,\Delta\varphi^2 - 0.000001\,\Delta\lambda^2 + 0.000004\,\Delta\varphi\Delta\lambda \text{ gammas/year} \quad (23)$$

where $\Delta\varphi = (\varphi - 37°)$ and $\Delta\lambda = (\lambda - 135°)$ are expressed in minutes.

Land Magnetic Survey by the GSI

The magnetic surveys by the GSI are of three classes: the First Order, the Second Order, and the Aeromagnetic. (For the sea gravity survey, a shipborne survey is also conducted during the cruises with the GSI-type surface ship gravity meter.)

The First Order Survey aims to clarify the general features of the geomagnetic field and its secular variation on Japan. At each First Order Station, marked by a permanent granitic monument, about

20 sets of magnetic observations and a few sets of Polaris observations are made throughout the day. There are 92 First Order Stations, 20 of which are selected as the Standard Order Stations and reoccupied every two or three years. Other First Order Stations are reoccupied every five years.

The purpose of the Second Order Survey is to construct more detailed magnetic charts and to clarify regional and local aspects of magnetic anomaly by completing one survey of the entire 781 stations in Japan. Then the Second Order Revision examines the detailed geographical distribution of the geomagnetic secular variation. It may be related to the research on prediction of earthquakes by clarifying whether there exist geomagnetic disturbances before and after the occurrence of a large earthquake. At each Second Order Station a few sets of magnetic observations are made within about one hour. For improving the accuracy of the epoch reduction, observation times are restricted to those occurring after 1600 local time in order to avoid the troublesome influence of the S_q variation with geographical position.

The instrument used for both the First and the Second Order Surveys is the GSI-type magnetometer, which has the accuracy of $0'.1$ in D and I, and 1γ in H [*Tsubokawa,* 1951a, b]. Recently the GSI has developed a new portable magnetometer, the principle of which is a combination of an earth-inductor for measurement of D and I with a proton-sensing head for F to obtain more stable absolute accuracy.

The isomagnetic charts of Japan are revised every five years using the results of the First and the Second Order Surveys; the charts for epoch 1965 have already been constructed. In general, magnetic anomalies are quite small in the western part of Japan except in the volcanic areas of Aso and Kirishima in the Kyushu district; anomalies are very small in the Shikoku and Chugoku districts. On the other hand, isomagnetics are much disturbed in the northeastern part of Japan where the Bouguer gravity anomalies are mostly positive. For example, an isoanomaly chart of the vertical component in Japan is shown in Fig. 2 [after *Harada,* 1964].

From the results obtained so far by the First Order Surveys, locally anomalous geomagnetic variations are found in several areas. The distribution of these anomalous annual rates of changes seems to have a close correlation with that of recent large earthquakes (Fig. 3), where circles indicate the location of epicenters of shallow earthquakes with magnitudes greater than 6.0 that occurred during 1959 - 1964 [*Tazima,* 1968].

Further discussion of some of the points discussed in this section are found in treatments by *Fujita* [1968], *Matsuda* [1962], and *Tazima and Sekiguchi* [1968].

Ocean Magnetic Survey

Results of the marine geomagnetic measurements in the western Pacific region around the Japanese Islands have been summarized by *Uyeda et al.* [1967], *Yasui et al.* [1967a, b, 1968], *Sewaga et al.* [1967], and *Tomoda and Segawa* [1967]. Tentative isodynamic and isodynamic anomaly charts of the area (28° - 56° N, 130° - 164° E) are shown in Figs. 4 and 5. In these figures, measurements by the Lamont-Doherty Geological Observatory, the Scripps Institution of Oceanography, and the U.S. Naval Oceanographic Office have also been applied. Subtraction of the regional field from these F charts was made graphically using U.S. Hydrographic Office Chart No. 1703. Digital reduction of all the data using the reference field of *Cain et al.* [1967] has been undertaken by Uyeda and Isezaki, and some changes in the anomaly patterns are expected. Since most of the data were taken during cruises that were originally planned for other purposes, ships' tracks (Fig. 6) are unevenly distributed. The investigations made to date show the following characteristic features of the geomagnetic field in the northwest corner of the Pacific:

1. Prominent ENE-WSW trending linear magnetic anomaly belts exist off northeast Japan. These lineations are similar to those found in the eastern Pacific but, on the whole, are much less persistent spatially. They become vague approaching the trenches and do not exist inside the trenches. The lineations are not correlated with the bottom relief. Although less remarkable, similar trending anomaly patterns seem to exist in the Japan Sea and the Sea of Okhotsk.

2. Shikoku Basin does not show the linear trends.

3. Fourteen seamounts located in the seas around Japan have been surveyed in detail and their magnetizations have been computed [*Uyeda and Richards*, 1966; *Vacquier and Uyeda*, 1967]. The results of these works indicate that the northwest Pacific Ocean floor might have drifted northward by a few tens of degrees since the time of formation of these seamounts, which is believed to be Mesozoic. These attempts are considered to be useful as a method of paleomagnetic study of the ocean floor as will be shown elsewhere.

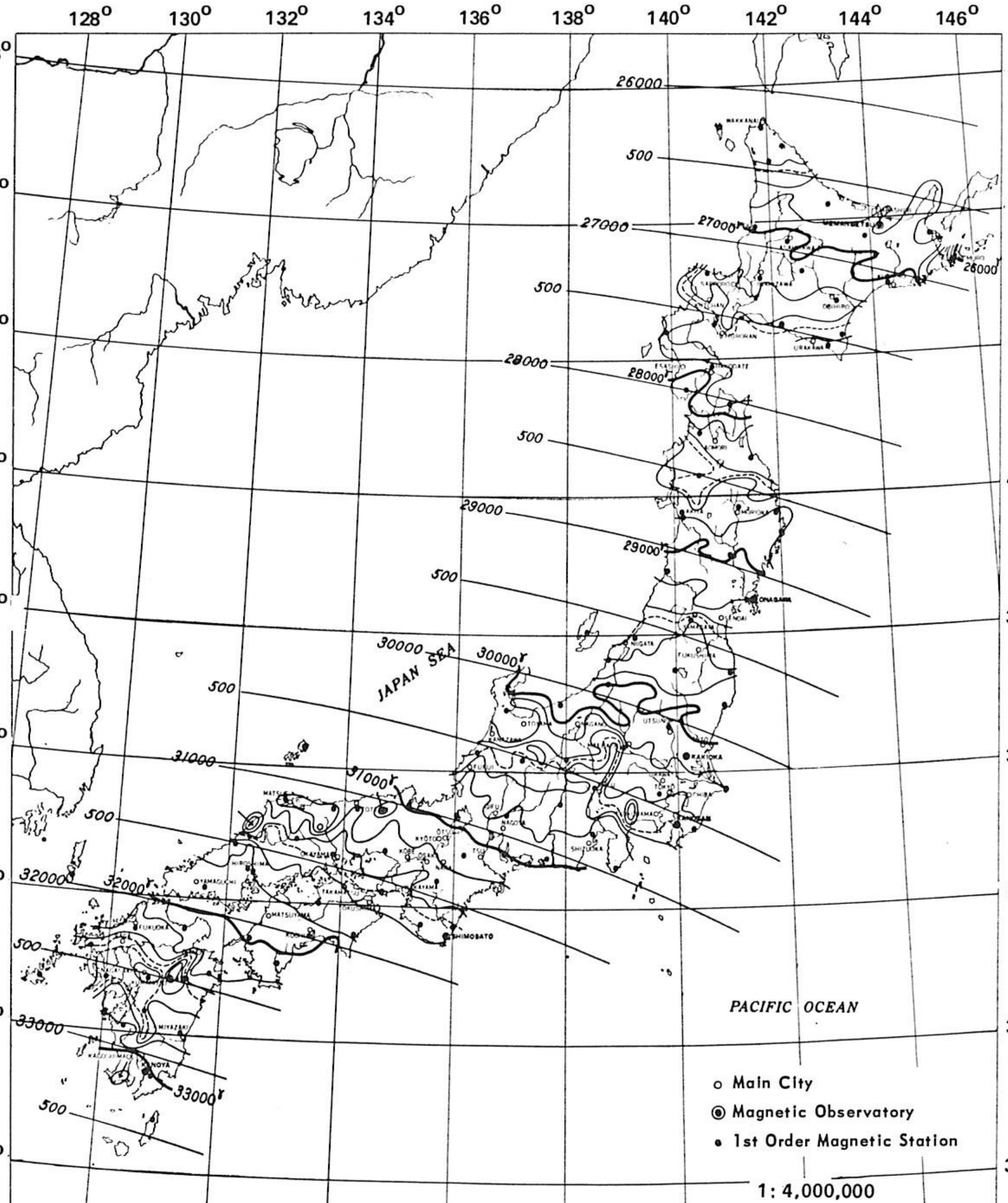

Fig. 1. Contour Lines of Equal Horizontal Intensity for 1965.0. Freehand Curves (Dark Contours) are Drawn by Direct Interpolation of Observed Values at About 800 Points and Smoothed Lines are from a Quadratic Approximation.

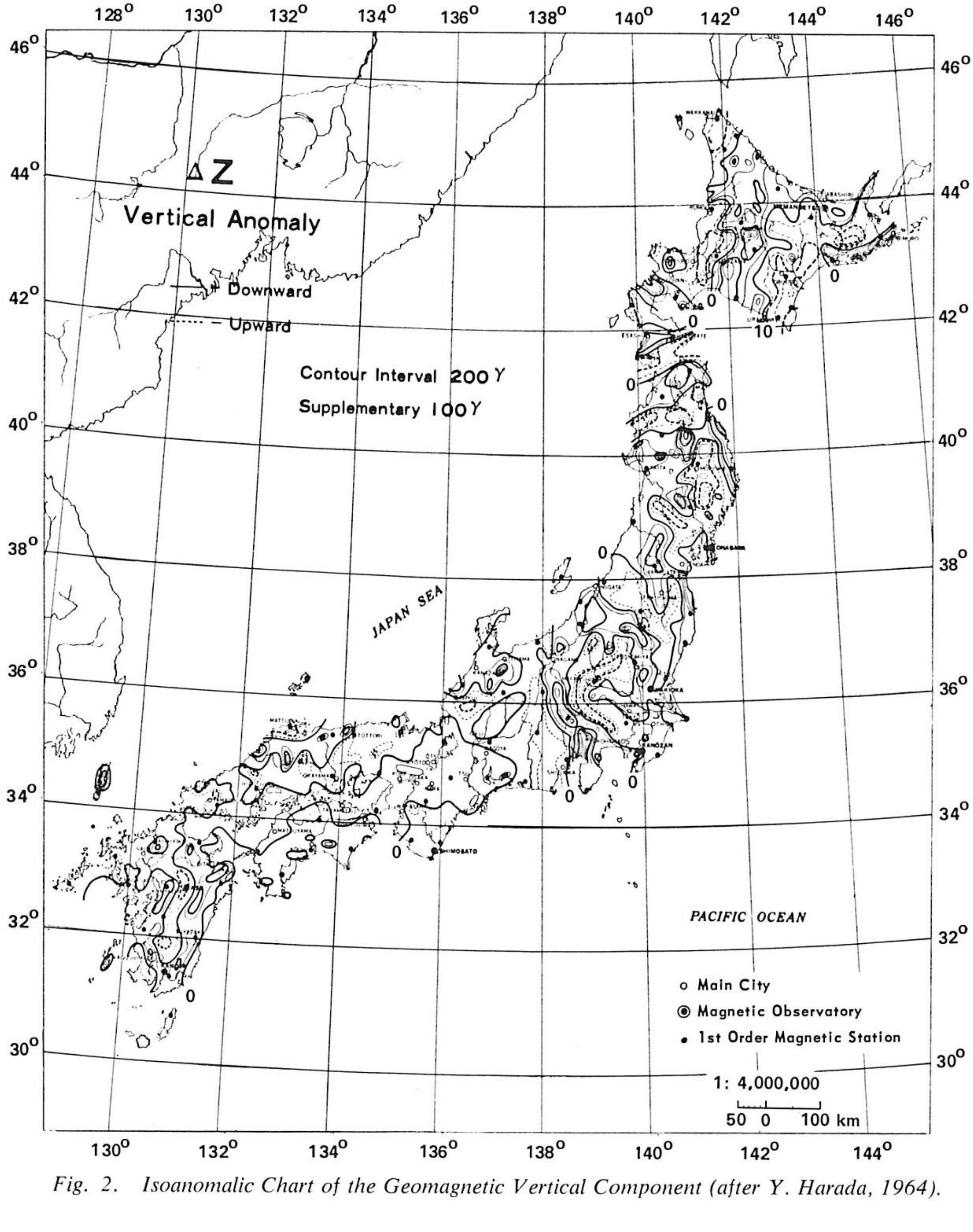

Fig. 2. Isoanomalic Chart of the Geomagnetic Vertical Component (after Y. Harada, 1964).

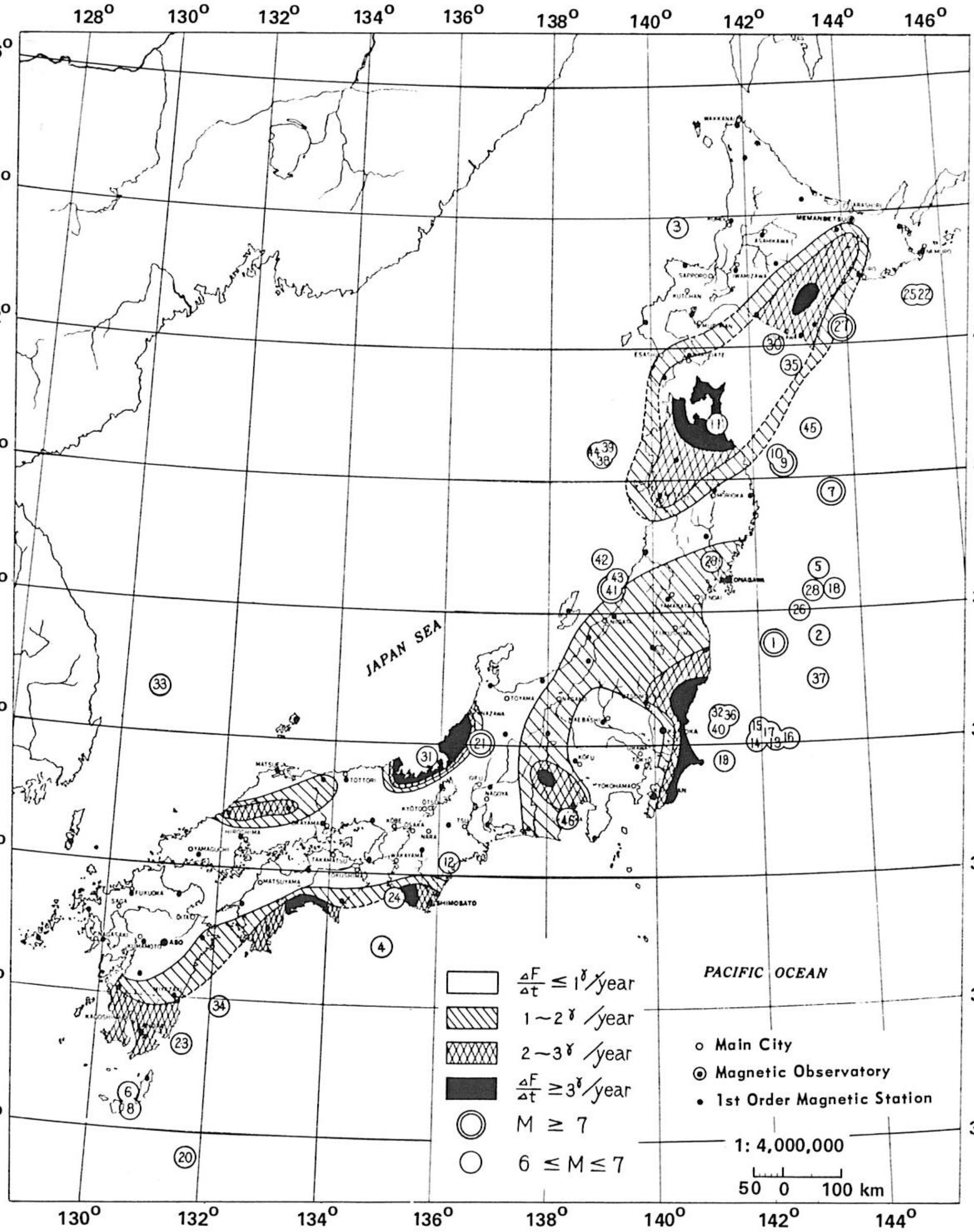

Fig. 3. Anomalous Regions of the Geomagnetic Secular Change (1955–1960) (after M. Tazima, 1968).

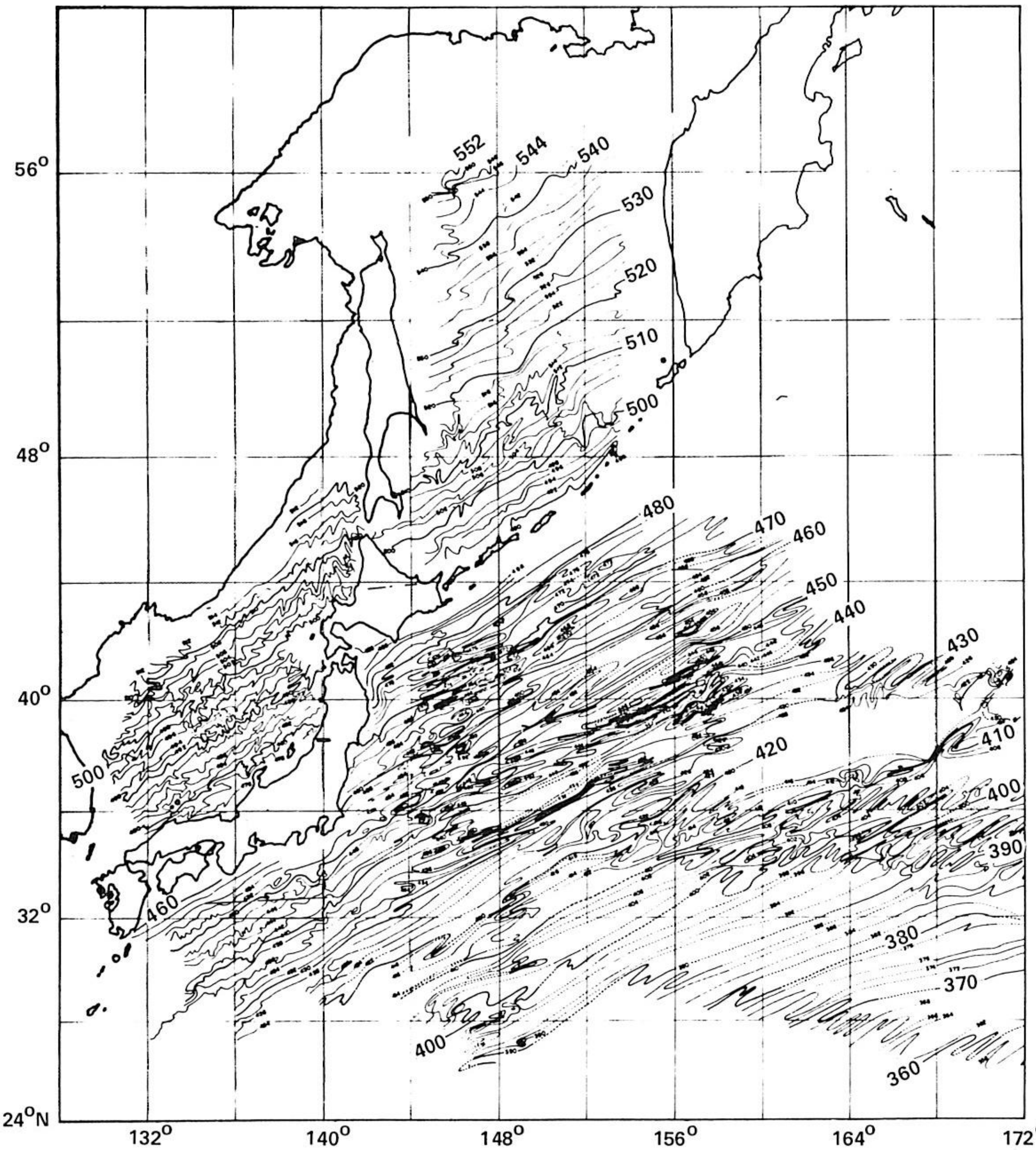

Fig. 4. Geomagnetic Total Force Distribution around Japan, Units of 100γ (after Uyeda et al., 1967; Yasui et al., 1968).

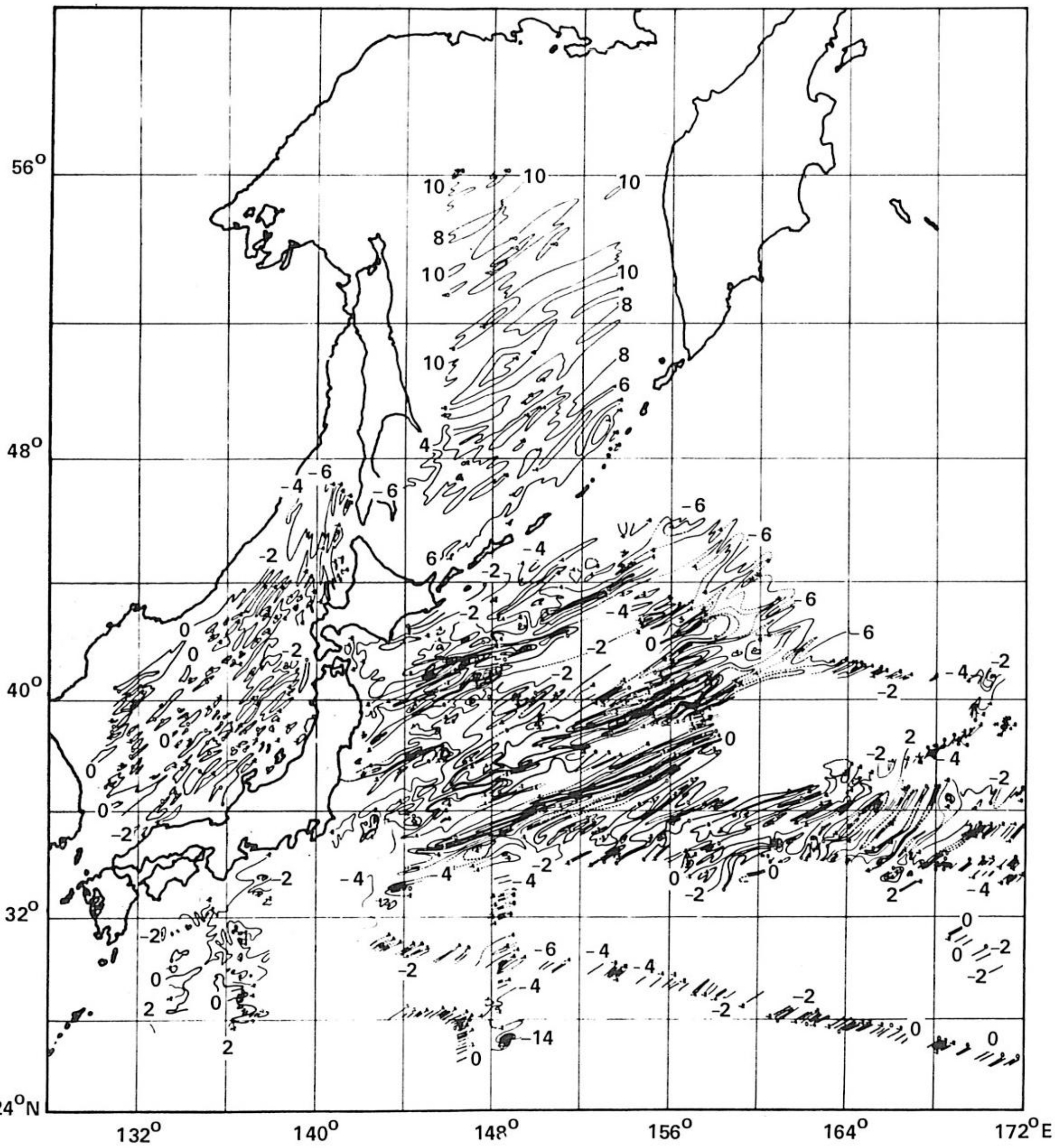

Fig. 5. Geomagnetic Total Force Anomaly Distribution around Japan in Units of 100γ (after Uyeda et al., 1967; Yasui et al., 1968).

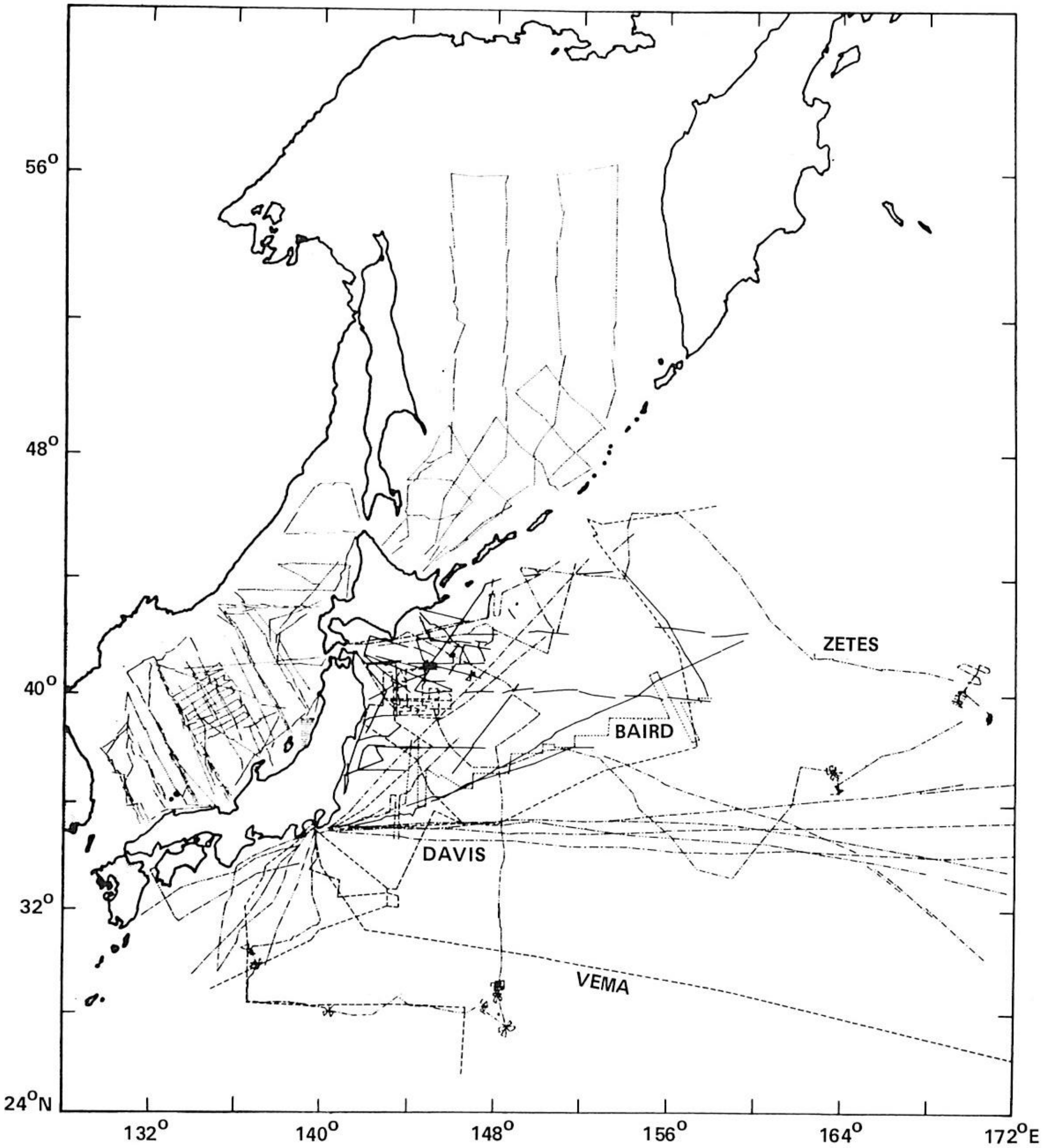

Fig. 6. Ships' Tracks along Which Magnetic Data were Available for Constructing the Magnetic Charts. Unlabeled Tracks are Those by Japanese Vessels (after Uyeda et al., 1967; Yasui et al., 1968).

Summary

The Japan Islands and their neighboring sea areas were geomagnetically surveyed using two kinds of three-component airborne magnetometers at an altitude of about 3000 m. One magnetometer set consists of elements F, D, and I, whereas the other consists of elements X, Y, and Z. The WMS magnetic charts over this area were self-consistently compiled based on the data coming from two different sources. With the assumption that curl $\mathbf{B} = 0$, smoothed magnetic charts for H, D, X, and Y are obtained and compared with those derived without this assumption. The distribution of geomagnetic secular variation of 1965.0 is also obtained for this area based on data from magnetic observatories and repeat stations. Several local areas where the secular variations behave anomalously have been found to be closely related to recent large earthquakes of shallow depth. Seaborne surveys of F have also been carried out extensively in the northwestern area of the Pacific Ocean, the result showing prominent ENE-WSW trending linear magnetic anomaly patterns.

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AIRBORNE MAGNETIC SURVEYS OF CANADA AND SCANDINAVIA

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Introduction

Most airborne magnetic surveys fit into one of two classes: surveys of total intensity, flown on closely spaced flight lines at low altitudes; and surveys of the complete magnetic vector, giving the direction as well as the intensity of the geomagnetic field and flown on widely spaced flight lines at high altitudes.

This paper is primarily concerned with surveys of the second type. However, it begins with a review of detailed total-intensity surveys in Canada and the Scandinavian countries, with emphasis on the economic importance of the surveys. The term "Scandinavia" will include Finland, Iceland, and Greenland, as well as Norway, Sweden, and Denmark.

Detailed Total Intensity Surveys

Figures 1 and 2 show the regions of Canada and the Nordic countries over which detailed aeromagnetic surveys have been made and for which contour maps have been published or are in the process of publication. Not indicated are the areas surveyed by oil and mining companies for which maps are not published, although this information is frequently available to government and university scientists on request. For example, more than half the area of Sweden has been covered by private companies with airborne surveys of varying density, but the figure shows only the regions covered by the Geological Survey of Sweden. About 50% of Norway and 80% of Finland are covered by government aeromagnetic surveys. The survey lines are less than 1 km apart, and the height of observation is from 30 to 300 m above the ground.

The purpose of these surveys is, of course, to add to the knowledge of the geology of a region in the hope that economically important discoveries of

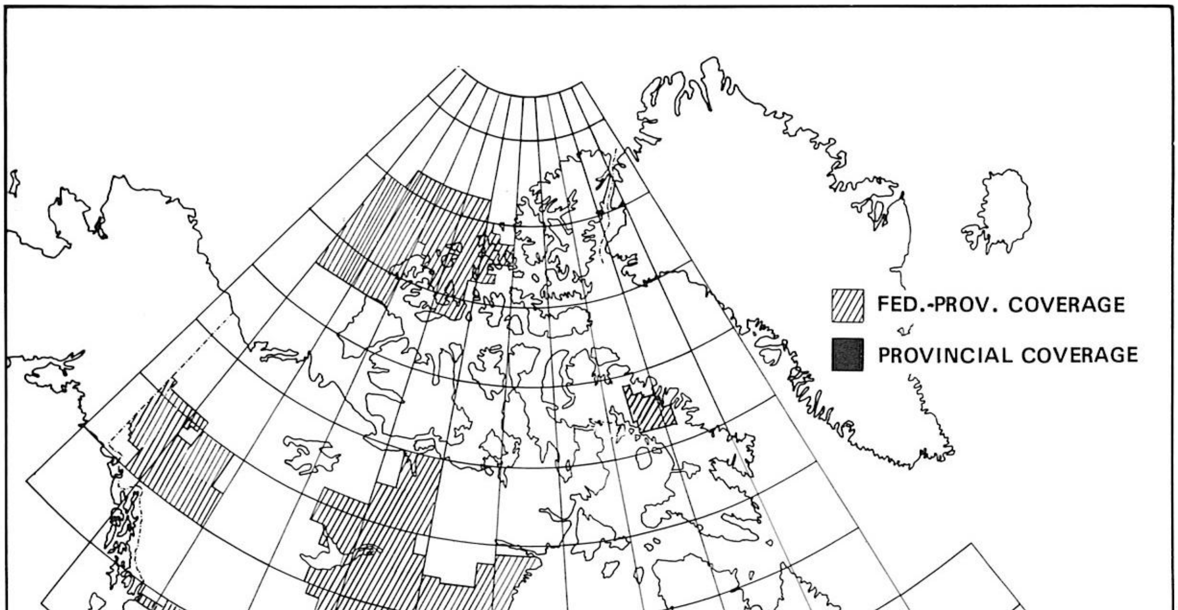

Fig. 1. Areas of Canada Covered by Detailed Total-Intensity Magnetic Surveys by Government Agencies.

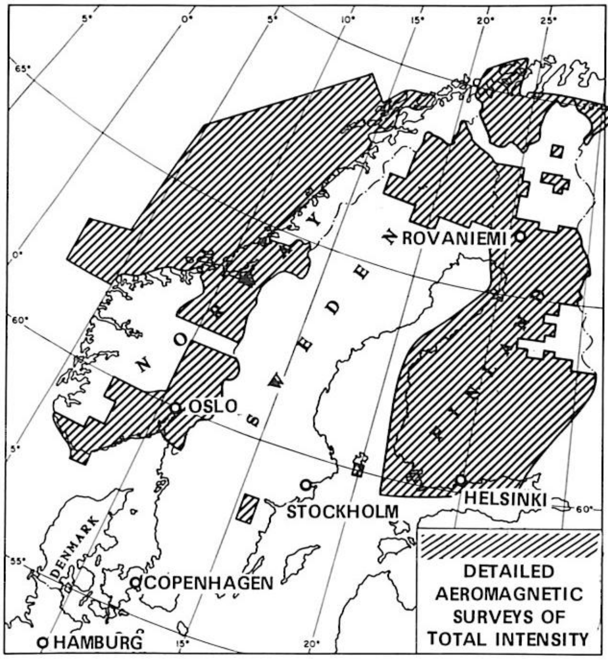

Fig. 2. Areas of Nordic Countries Covered by Detailed Total-Intensity Magnetic Surveys by Government Agencies.

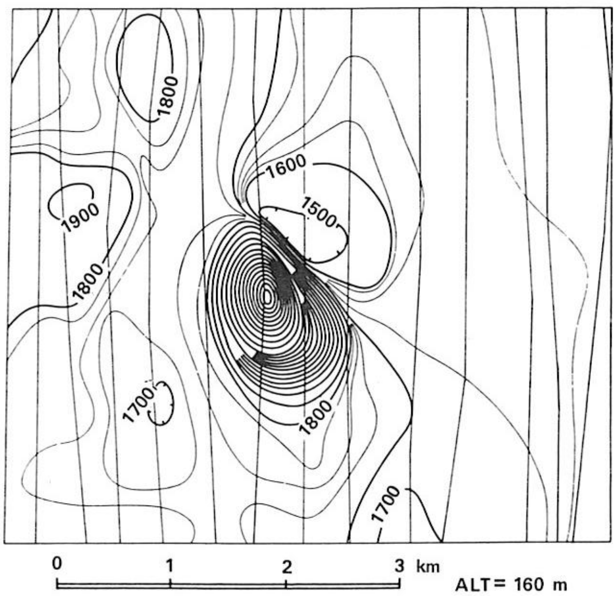

Fig. 3. Anomaly Values, in Gammas, of Total Intensity over Marmora Iron Ore Deposit, Ontario, Canada.

minerals, oil, or gas will result. Aeromagnetic surveys, when carried out on a reasonably large scale, provide the cheapest and most rapid method of preliminary exploration of mineral resources. The cost of surveying a whole country may be repaid by a single important discovery.

Paradoxically, it is not easy to find examples of important mineral discoveries that can be credited exclusively to aeromagnetic surveys. One textbook case is the Marmora iron-ore deposit, which was found beneath 40 m of limestone, about 50 km north of Lake Ontario. The area was well mapped geologically, but the first indication of an ore body was from chance aeromagnetic observations; it happened to lie directly beneath a main east-west air route. The aeromagnetic map published in 1950 by the Geological Survey of Canada revealed an isolated circular anomaly 1 km in diameter (Fig. 3) with a maximum of about 7000γ. The depth of burial, probable concentration of magnetite (50%), and mass of the body (20 million tons) were all readily estimated from the map. The estimates were confirmed by diamond drilling, and within five years 20 million tons of limestone cover had been removed and the mine was in production. This early success encouraged the use of aeromagnetic surveys in Canada.

Such clear cases of discovery by airborne magnetometer are rare, especially in countries with a long history of mineral development. In Sweden, where magnetic methods have been used in prospecting for iron ore since 1640, the simpler anomalies were investigated before the development of airborne techniques, and a more typical application is in extending and tracing ore bodies whose existence has long been known. A good example is the Fosdalen mine in Norway, where a careful analysis of airborne magnetic measurements indicated that the ore body continued to the east of its previously assumed boundary, but only after a downfault of 600 m. An underground magnetic survey provided further evidence, and, finally, drilling confirmed the extension of the ore sheet between 700 and 1200 m below the surface [*Espersen*, 1970].

The two examples given involve magnetite-type iron ores. Few other valuable ores are strongly magnetic in themselves. Oil is, of course, quite nonmagnetic, and it is in oil prospecting that the airborne magnetometer has received its most extensive application. The success of magnetic methods in the location of minerals other than iron depends on the fact that almost all rocks contain some magnetite: sedimentary rocks very little, granitic rocks considerably more, and basic rocks much more. Aeromagnetic maps can thus indicate the location of contacts between different types of rocks, and such contacts are favorable places for the occurrence of mineralization. Again, valuable ores are frequently associated with faults that can often be identified from the resulting discontinuity in the pattern of magnetic anomalies.

An interesting case is the Bourlamaque batholith in western Quebec. A successful gold mine had operated since 1920 on the edge of a granitic outcrop, but it was not until magnetic surveys showed that the batholith extended for 20 km beneath a thin cover of Precambrian sediments that the region was fully exploited. Many more mines were developed on the circumference of the hidden intrusion, and they have produced over 500 million dollars worth of gold, copper, zinc, lead, and silver. The characteristic of the batholith useful in tracing it magnetically is the absence of local anomalies over it, in contrast to the complex anomalies associated with the surrounding rocks.

One cannot discuss the economic importance of aeromagnetic surveys in isolation; they make their greatest contribution in combination with other geophysical, geochemical, and geological methods of exploration. A series of base metal discoveries in New Brunswick (eastern Canada) may be cited. Here very few outcrops of rock penetrate a layer of about 10 m of glacial drift. The discovery of valuable ores associated with massive sulfide bodies must be credited primarily to airborne electromagnetic surveys. Electromagnetic surveys revealed many anomalies of electrical conductivity, but most of them were due to useless carbonaceous or graphitic sediments. Aeromagnetic surveys were of great value in determining which of the conductivity anomalies were due to sulfides.

It can be argued that the most important role of aeromagnetic surveys in mineral exploration is in indicating where one should not dig or drill. Certainly, much useless exploration by expensive techniques has been avoided through the proper use of aeromagnetic surveys, but it is difficult to document the resulting savings in specific cases. A simple statistical argument can be convincing, however.

It has been estimated that over the Canadian Shield, geological and geophysical surveys will reveal one "indicator" for every 10 km^2: an outcrop, structural feature, or a magnetic or gravity anomaly inviting further investigation [*Brant,* 1967]. If all indicators are drilled, the probability of finding an ore deposit is about 1 in 100. The probability that this ore deposit will have a value exceeding 100 million dollars is about 1 in 5. There is thus an excellent chance that a well-conducted program of geological and geophysical surveys followed by diamond drilling will discover one or two ore deposits worth more than 100 million dollars in an area of 10,000 km^2. A detailed aeromagnetic survey of a 10,000 km^2 area might cost $120,000, or one-thousandth of the potential value of the ore. The drilling program would cost at least ten times as much as the magnetic survey, even when drilling is limited to the most favorable geophysical indicators. The economic justification for aeromagnetic surveys of the highest quality is obvious.

Espersen [1970] has described the part played by geophysical exploration in a coordinated plan for the social and economic development of Swedish Lapland. One goal of the ten-year program is a detailed inventory of the region's iron-ore reserves. Aeromagnetic and geological surveys are followed by detailed magnetic and gravity surveys on the ground in all the more interesting areas. Finally, the geophysical interpretation is followed by a comprehensive drilling program to prove the reserves. Magnetic measurements are made in the drill holes, and the magnetic properties of the drill cores are studied.

It is clear that any country interested in the exploitation of its mineral resources should ensure that detailed aeromagnetic surveys of high quality are carried out. The cost is small in relation to the potential return, and the resulting charts are of permanent value. It must be stressed that, by themselves, aeromagnetic surveys are unlikely to discover anything of economic importance except magnetic iron ore. The full advantage of this rapid and inexpensive method of mineral exploration is realized only when it is combined with other geological and geophysical techniques.

Three-component Surveys

Figure 4 shows the locations of flights made between 1953 and 1965 with the Dominion Observatory's three-component airborne magnetometer. The altitude of observation ranges from 2 to 7 km above sea level with most flights at 3 or 4 km. The average spacing of the flight lines is about 100 km over Canada, 35 km over the Nordic countries, and 200 to 300 km over Greenland and the ocean areas.

Much of the following discussion will be based on the 1965 survey, which extended from the west coast of Greenland to the eastern boundary of Finland (Figs. 5 and 6). This survey was undertaken as a contribution to the World Magnetic Survey by the governments of Norway, Sweden, Finland, Denmark, and Canada, in cooperation. It is no small accomplishment to bring five governments to the point of

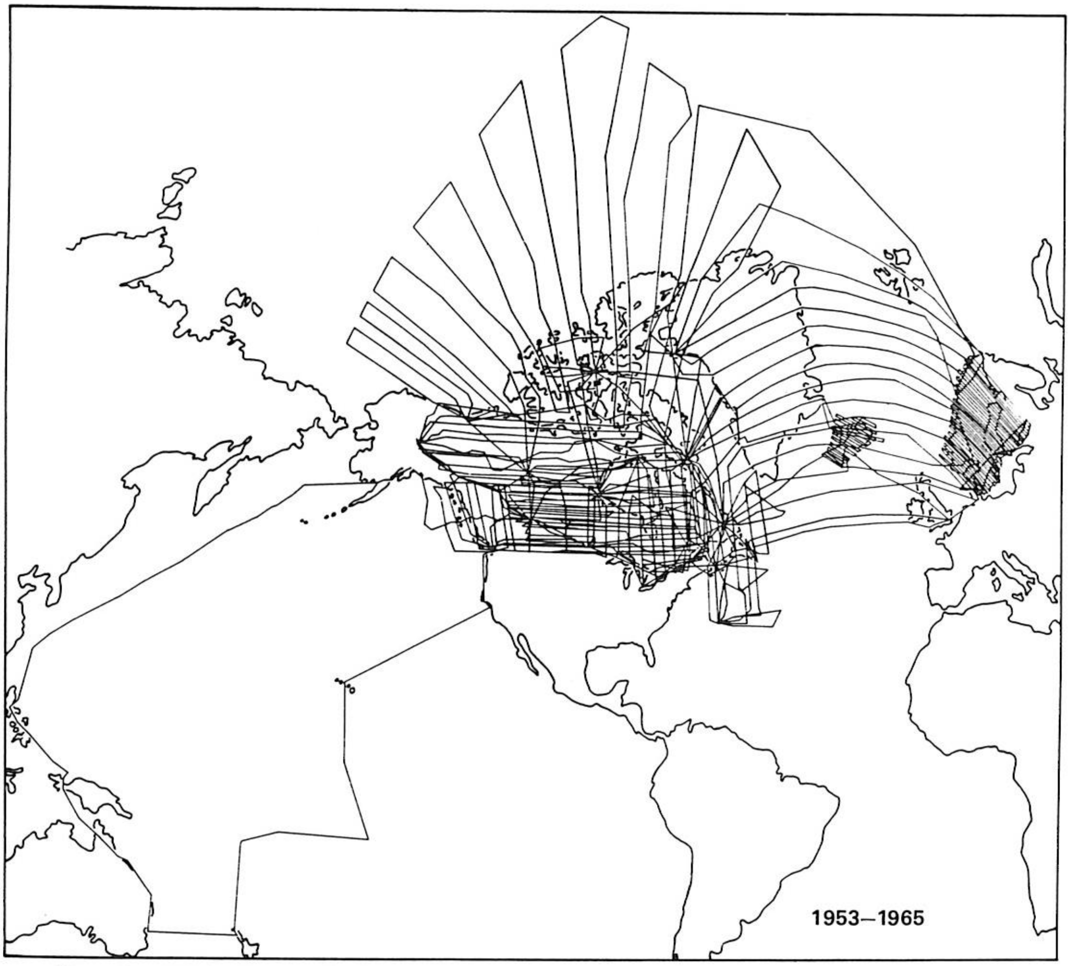

Fig. 4. Flight Lines of Three-Component Airborne Magnetic Surveys Conducted by Dominion Observatory, Canada, 1953–1965.

producing money simultaneously. The credit for this feat belongs to Dr. Nils Ambolt, recently retired from the Swedish Board of Shipping and Navigation.

The fundamental difficulty in measuring in an aircraft any element of the geomagnetic field other than total intensity is the maintenance of an accurate direction reference system. An error of 1 minute of arc in the direction of the reference axes can produce errors of 15γ in the measured geomagnetic components. An aircraft in apparently smooth and steady flight undergoes accelerations that can deflect a pendulum or a level bubble from the true vertical by an angle of the order of $1°$.

In the Dominion Observatory instrument, this basic difficulty has been overcome by using an elaborate gyro-stabilized platform which is maintained horizontal to an accuracy of 1 minute of arc under good survey conditions. The sensitive part of the magnetometer is linked mechanically to the gyro-stabilized platform. The azimuth reference necessary for measurement of declination is provided by a free gyroscope mounted on the stable platform. Its slow drift (a fraction of $1°$/hr) is monitored by periodic observations of a star, a planet, or the sun by means of a periscopic sextant, which is also stabilized in roll, pitch, and azimuth. Corrections for the drift are computed after the survey and added to the observed declination.

The Canadian three-component magnetometer measures D, H, and Z. Direct currents flowing in two sets of coils, with their axes respectively horizontal and vertical, continuously null the horizontal and vertical components of the earth's field at the center of the sensing head assembly. The currents

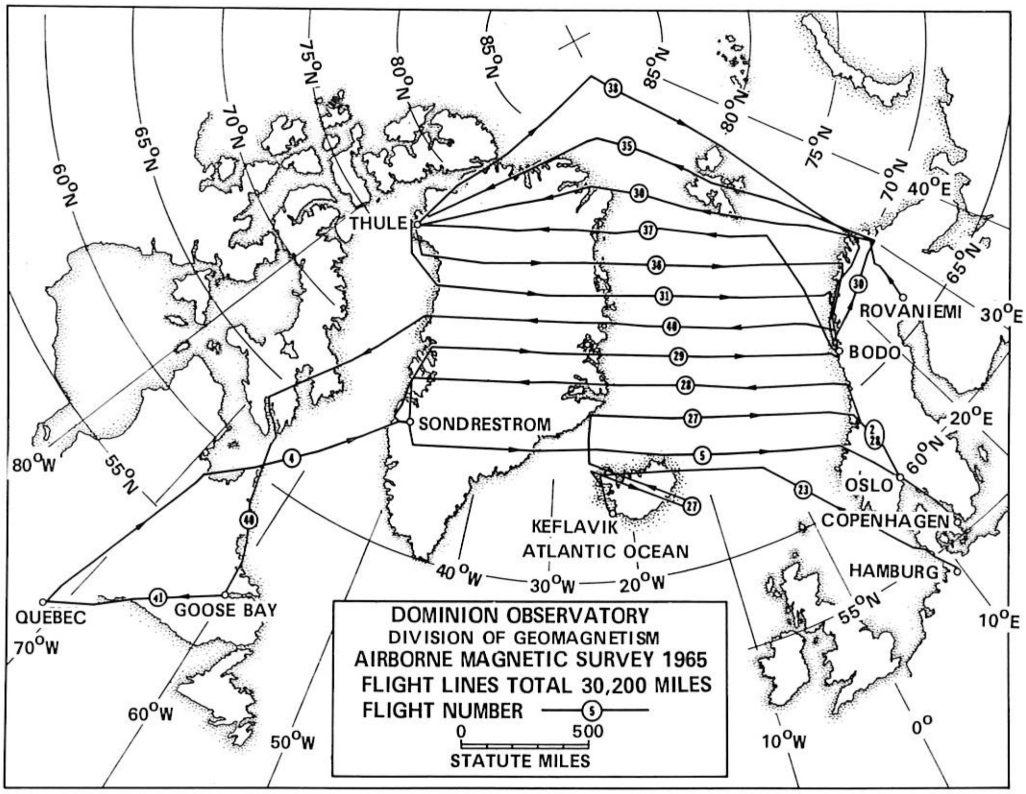

Fig. 5. Three-Component Magnetic Survey of Greenland and the Greenland Sea, 1965.

are controlled by two fluxgate sensors in the center. A third fluxgate controls a servomotor that rotates the whole head in azimuth, keeping the axis of the H coil pointing magnetic north. The angle between the H axis and the azimuth reference gyroscope is converted into a DC voltage proportional to D. Voltages proportional to H and Z are obtained by passing the nulling currents through resistors. The remainder of the equipment simply records these three voltages in the most useful form.

The data are recorded in three different ways:

1. As continuous pen-and-ink traces by roll-chart recording meters,
2. As digitized samples every 3 seconds on digital magnetic tape, and
3. As digital average values, computed over successive 5-minute time intervals.

The 5-minute averages, corresponding to 30 km segments of the flight path, are the most useful output for the construction of smoothed charts. They are the values that have been reported to the World Data Centers. The more detailed records are, of course, useful in the study of anomalies.

During the 1965 survey, total intensity was also recorded using a proton precession magnetometer (Barringer Research Ltd., Model AM-101A). The sensor was installed in the end of a hollow boom that extended 3½ m from the rear of the fuselage. Theoretically, the three-component measurements describe the geomagnetic field completely, and the total intensity measurements are redundant. However, the inherent accuracy of the proton magnetometer and the fact that its sensing head could be mounted outside the aircraft away from sources of artificial magnetic disturbance made it a valuable addition to the instrumentation.

The three-component magnetometer measures the field at a point inside the cabin of the aircraft, and its readings are affected by the magnetic field of the aircraft. These effects are removed from the survey data by applying corrections that are determined by calibration flights carried out at approximately weekly intervals throughout the survey operation. In a calibration flight, the aircraft is flown in different directions over a point where the magnetic elements are accurately known. The point is selected in a region free from local anomalies within a radius of at least 10 km. It should be close enough to a magnetic observatory to permit corrections for transient variations and must, of course, be easily identified from the air, either visually or by radio methods.

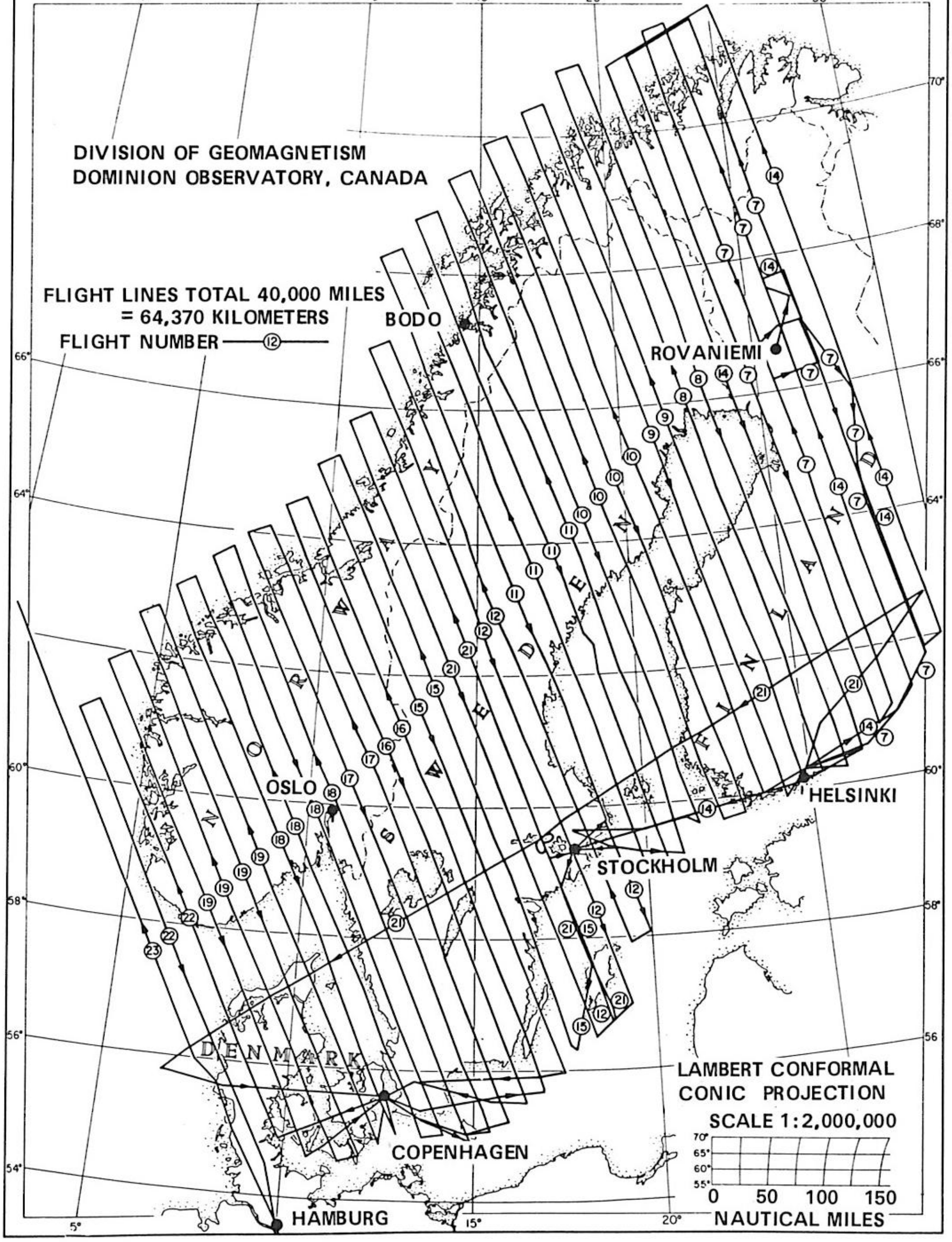

Fig. 6. Three-Component Magnetic Survey of Nordic Countries, 1965.

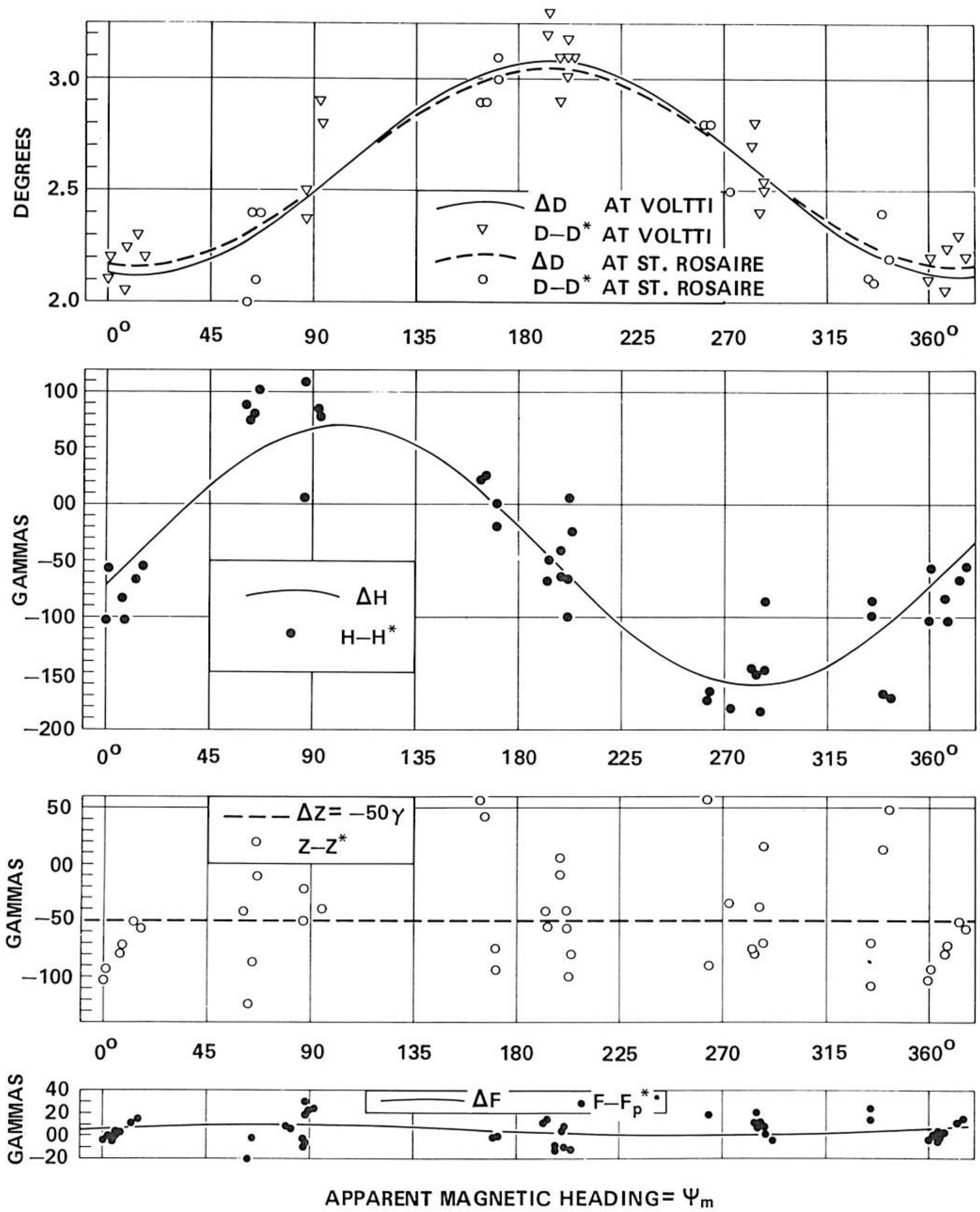

Fig. 7. Differences between Ground and Airborne Values from Calibration Flights, as a Function of Magnetic Heading of the Aircraft. D, H, Z, F are Calculated from Ground Observations. D, H*, Z*, F* are Values Observed in Aircraft. ΔD, ΔH, ΔZ, ΔF are Adopted Correction Curves.*

Figure 7 shows the differences between ground and airborne values on about 40 passes over the calibration point from six calibration flights of the 1965 survey, plotted as a function of the magnetic heading of the aircraft. From the differences in D and H, it appears that there is a horizontal field of 120γ fixed to the aircraft. The figure shows correction curves based on this assumption. The data fit these curves with standard deviations of 0.15° in D and 34γ in H. The vertical component of the aircraft field varied considerably from day to day, resulting in the scatter evident in the Z values.

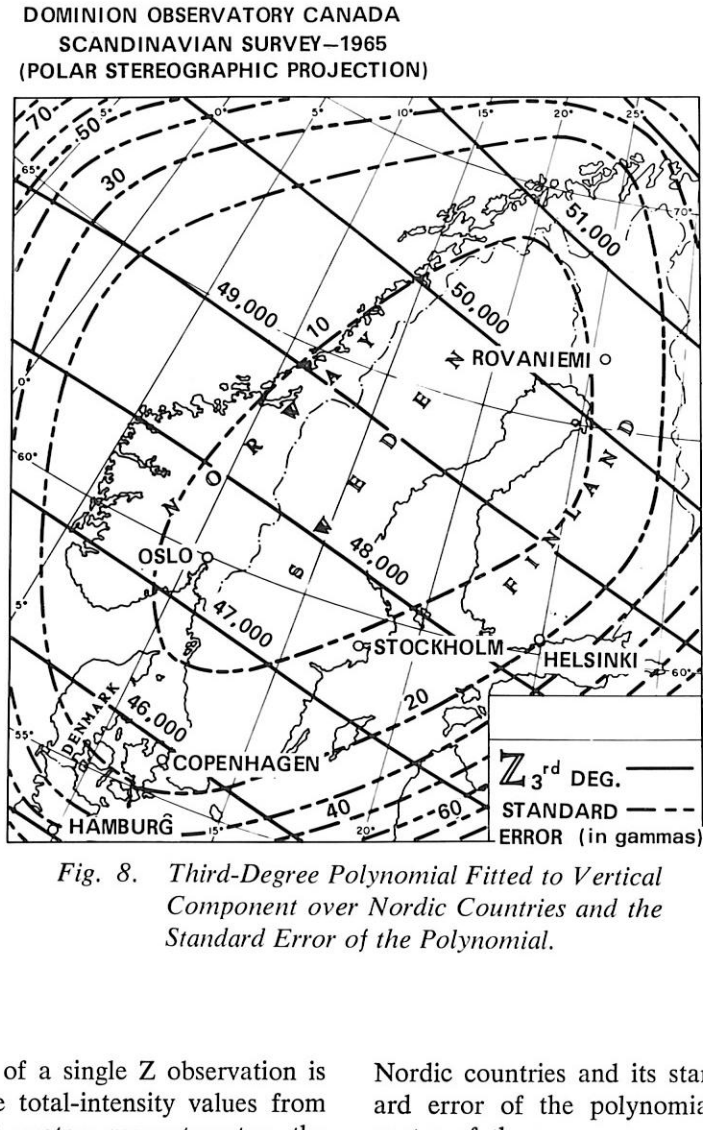

Fig. 8. Third-Degree Polynomial Fitted to Vertical Component over Nordic Countries and the Standard Error of the Polynomial.

The standard deviation of a single Z observation is 48γ. In the case of the total-intensity values from the externally mounted proton magnetometer, the effect of aircraft heading is small, amounting to $\pm 5\gamma$. The scatter is also smaller with a standard deviation of 9γ.

When Z was computed from observations of F and H by the relation $Z^2 = F^2 - H^2$, a standard deviation of 16γ was obtained, one-third as large as the standard deviation of the directly observed Z values. Accordingly, in reporting the survey data, values of Z calculated from F and H are given wherever possible, rather than the observed Z values, with their greater uncertainty due to aircraft fields.

After the survey data have been corrected for the field of the aircraft, polynomials of the third degree were fitted by least squares to three orthogonal magnetic components [*Haines,* 1968]. Figure 8 shows the polynomial fitted to Z data obtained over the Nordic countries and its standard error. The standard error of the polynomial is about 10γ in the center of the survey area, and the 20γ contour includes most of the data points used in the solution. Near the boundary of the data area, however, the standard error rises rapidly.

This standard error is analogous to the "standard error of the mean" in the measurement of a single quantity. It depends on the number and distribution of the observations and the magnitude of local anomalies, and it includes the effects of transient variations and some instrumental errors. It is perhaps not a very useful measure of the accuracy of the survey; for example, the whole polynomial surface could be in error by a constant amount due to improper calibration. But it does illustrate the unreliability of the polynomial as a predictor of the geomagnetic field outside the data area. To obtain an estimate of the accuracy of the polynomial as a predictor of the field at any point, one must, of course, combine with the standard error of the polynomial the root mean square (rms) deviation of the individual observations from the polynomial representation. In the case of the vertical component, this estimate would vary from 190γ at the center of the survey area to 200γ near the boundary of the data distribution.

The polynomial representations were useful in several ways in the reduction of the survey data. First, accidental errors in the preparation of data for the computer could be quickly identified from plots of the residuals or differences between the observed values and the polynomial. Second, the residuals were examined to check whether the corrections for the aircraft field had, in fact, removed from the data all systematic effects related to the heading of the aircraft. To our surprise, statistical tests revealed that the D and H data in many parts of the survey contained systematic differences on adjacent flight lines, flown in opposite directions. Apparently the field of the aircraft assumed several distinct modes, each mode persisting for a few days in succession, but for every calibration flight the aircraft field had returned to the same mode. Attempts to correlate the sudden changes in the aircraft field with other factors were unsuccessful, and we can only ascribe them to changes in the distribution of direct currents in the electrical circuits of the aircraft.

After a careful analysis of the residuals, additional corrections were applied to the observations of D and H to remove the remaining heading errors. Most of the corrections were of the order of 50γ, but for a few flights they exceeded 100γ. The statistical basis of the adjustment is described by *Hannaford and Haines* [1969].

As was stated above, the results from the calibration flights indicate that the standard error of a single observation is 0.15° in D, 34γ in H, and 16γ in Z. The same accuracy cannot be claimed for a typical survey observation because of the uncertainty in the adjustments applied to the survey data. An independent estimate of the accuracy of a survey observation was derived from an analysis of 70 intersections of the flight lines over the Nordic countries. It indicated that the standard error of a single observation was 0.4° in D, 70γ in H, and 40γ in Z. These figures include effects due to transient geomagnetic variations and to errors in navigation, as well as the uncertainty in the magnetic field of the aircraft, and thus provide a more realistic estimate of the accuracy of the survey data than the calibration flight results.

A third use of the polynomial representations was to estimate the vertical gradients of the various geomagnetic components for the reduction of the survey data to a common elevation. It was concluded that, for this region, the assumption that the field decreases as the inverse cube of the distance from the center of the earth gives the correct vertical gradients to within 3γ/km. The inverse cube relationship was therefore used, for reasons of simplicity, in reducing data to sea level from the 3 km altitude of observation.

A fourth use of the polynomials is a reference field against which local magnetic anomalies are plotted. Examples of the residual maps are shown in Figs. 9 through 13.

In Fig. 9, the residuals in Z over the Nordic countries are plotted at intervals of about 3 km along the flight path to form profiles, with Z increasing to the right. The sharp anomalies due to near-surface deposits of magnetite in the Kiruna district of northern Sweden are apparent as narrow positive peaks as large as 2500γ. Some large-scale patterns occur over well-known geological features, such as the series of anomalies following the Oslo rift valley and the anomalies over the high mountains of southwestern Norway.

The most remarkable feature of Fig. 9 is the large area of positive Z anomaly centered at 62°N, 14°E. The vertical component is 500γ above the normal value over a region 400 km by 200 km. An anomaly of this breadth and magnitude is not easily explained. If one assumes it to be caused by a uniformly magnetized body in the form of an elliptical plate extending from the surface to the depth of the Curie point isotherm (25 km), the intensity of magnetization can be calculated as 0.004 emu/cm^3. This intensity of magnetization, which is high even for volcanic rocks, is the minimum value that would cause such an anomaly.

The northern half of the anomaly is in a region shown on geological maps as Caledonian; the southern half is in the Precambrian. In the Precambrian part, diabase flows and intrusions are visible at the surface [*Geijer*, 1963]. Apparently, there is a great mass of volcanic rock, similar in composition to the oceanic basalts, underlying the magnetic anomaly and extending far into the region classed as Caledonian. If the body is thermoremanently magnetized, as seems probable from the high intensity of magnetiza-

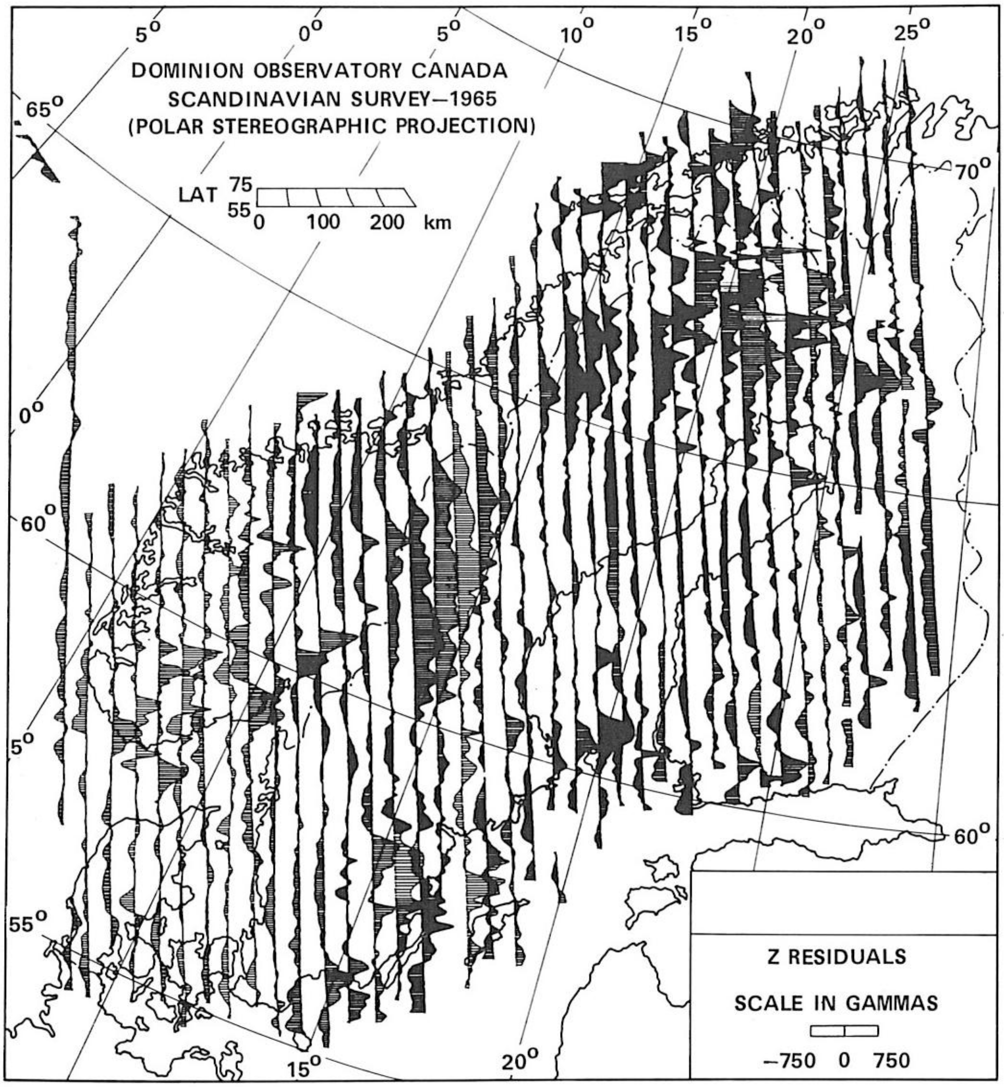

Fig. 9. Observed Vertical Component Minus Third-Degree Polynomial. Positive Anomalies to the Right.

tion, it must have been formed in a relatively short time during an interval of constant geomagnetic polarity. One would expect a positive gravity anomaly to be associated with such a large volcanic body, but available gravity maps show no unusual feature.

Figure 10 shows profiles of the anomalies in D. Over the center of the great anomaly in Z, the value of D is close to normal. Along the eastern and western boundaries of the hypothetical magnetic body, anomalies of 2.5° occur with the deflection of the compass always toward the center of the body.

Because the long axis of the supposed body lies in a north-south direction, the anomaly is less apparent in the map of H (Fig. 11). However, positive anomalies in H occur at the southern end of the body and negative anomalies at the northern end, as would be expected if the body were magnetized in the present direction of the geomagnetic field.

Some long magnetic lineations show more clearly in the profiles of H than in other elements. The feature extending across northern Sweden and Finland at latitude 67°N is especially striking.

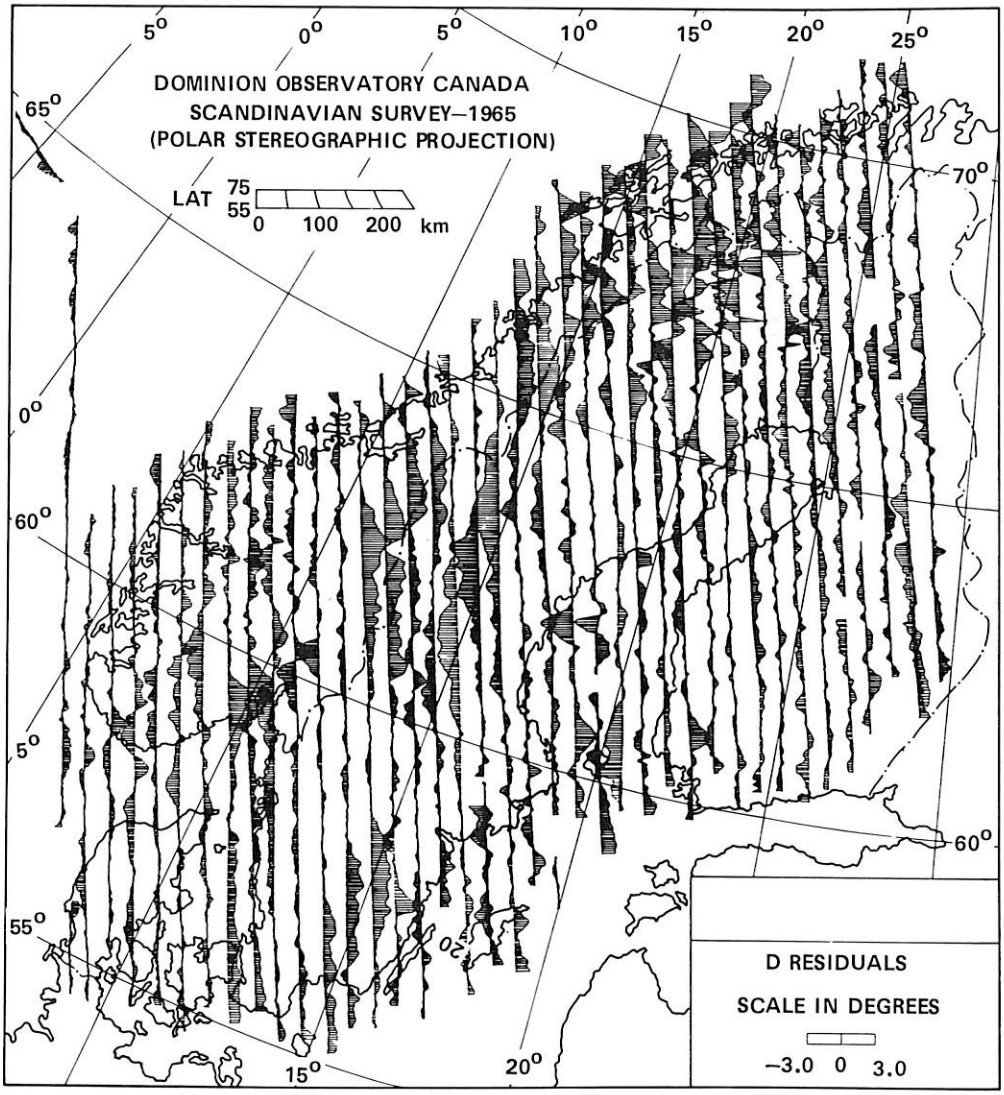

Fig. 10. Observed East Declination Minus Computed East Declination. Positive to the Right.

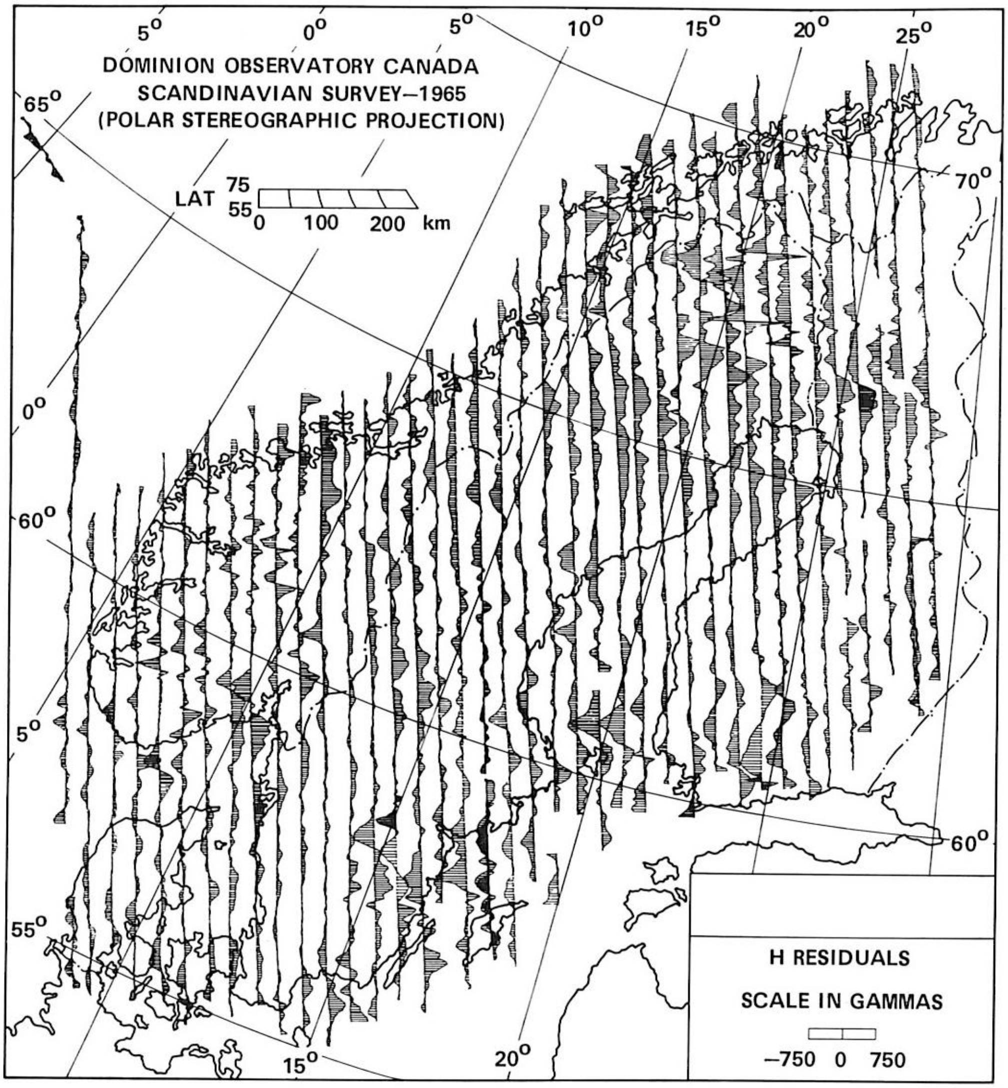

Fig. 11. Observed Horizontal Component Minus Computed Horizontal Component. Positive to the Right.

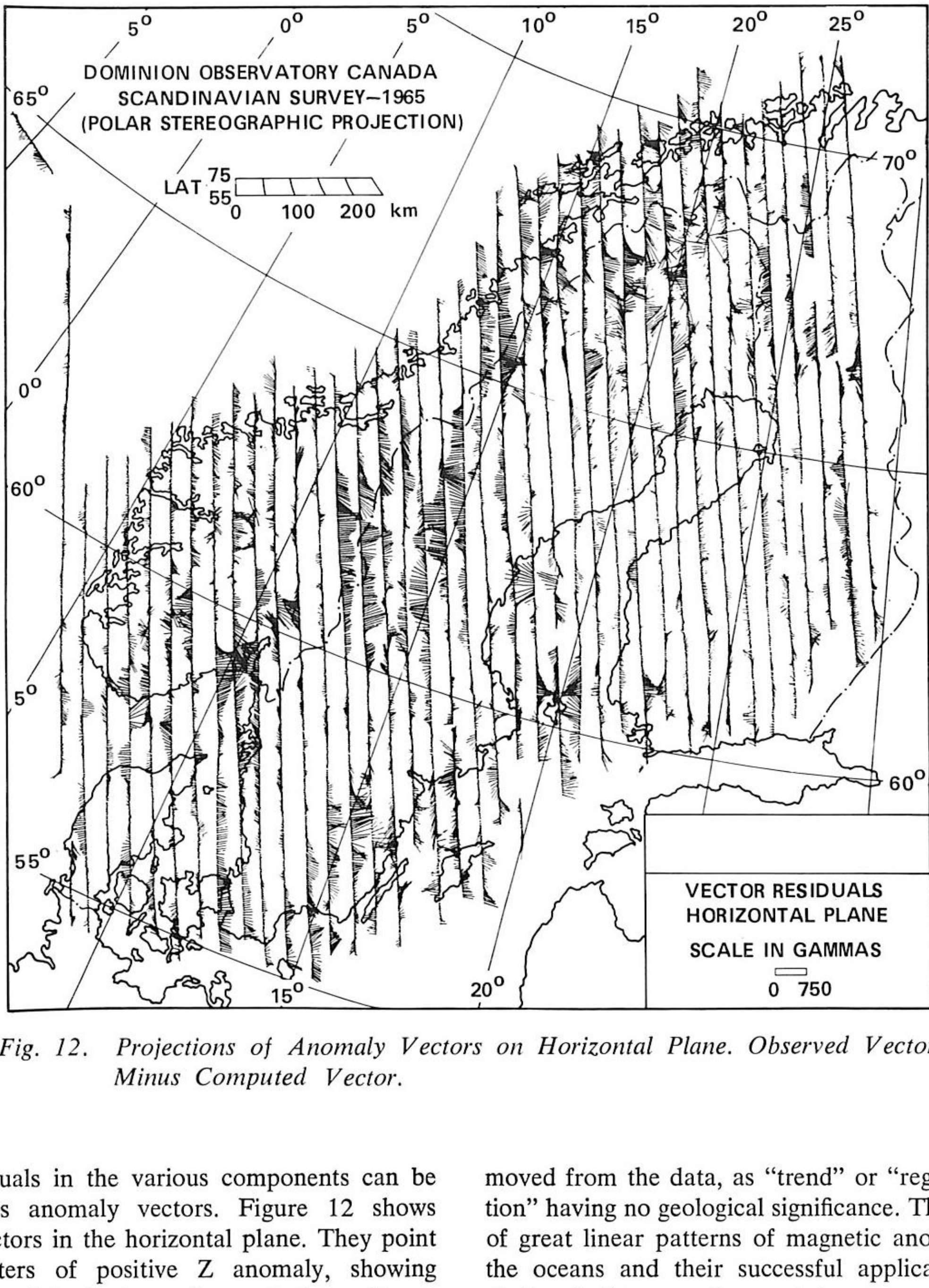

Fig. 12. Projections of Anomaly Vectors on Horizontal Plane. Observed Vector Minus Computed Vector.

The residuals in the various components can be combined as anomaly vectors. Figure 12 shows anomaly vectors in the horizontal plane. They point toward centers of positive Z anomaly, showing clearly many of the features discussed above. Figure 13 shows anomaly vectors in the vertical plane. The vector maps are also helpful in tracing long linear patterns of anomalies.

Until recently, the interest of the geologist in magnetic charts has been confined to the fine structure: anomalies with dimensions of 10 km or less that can be correlated with geological features visible at the surface or buried beneath a few km of sediments. Magnetic variations on a larger scale have been removed from the data, as "trend" or "regional variation" having no geological significance. The discovery of great linear patterns of magnetic anomalies over the oceans and their successful application in the study of the oceanic crust have encouraged the search for large-scale magnetic patterns over the continents.

The Geological Survey of Canada has recently compiled a magnetic anomaly map of Canada by combining 3400 detailed total intensity map sheets [*Morley et al.,* 1967]. The reference field is the Dominion Observatory F chart for 1965.0, which is roughly equivalent to a spherical harmonic fit of degree 50. The residuals, contoured at 200γ intervals,

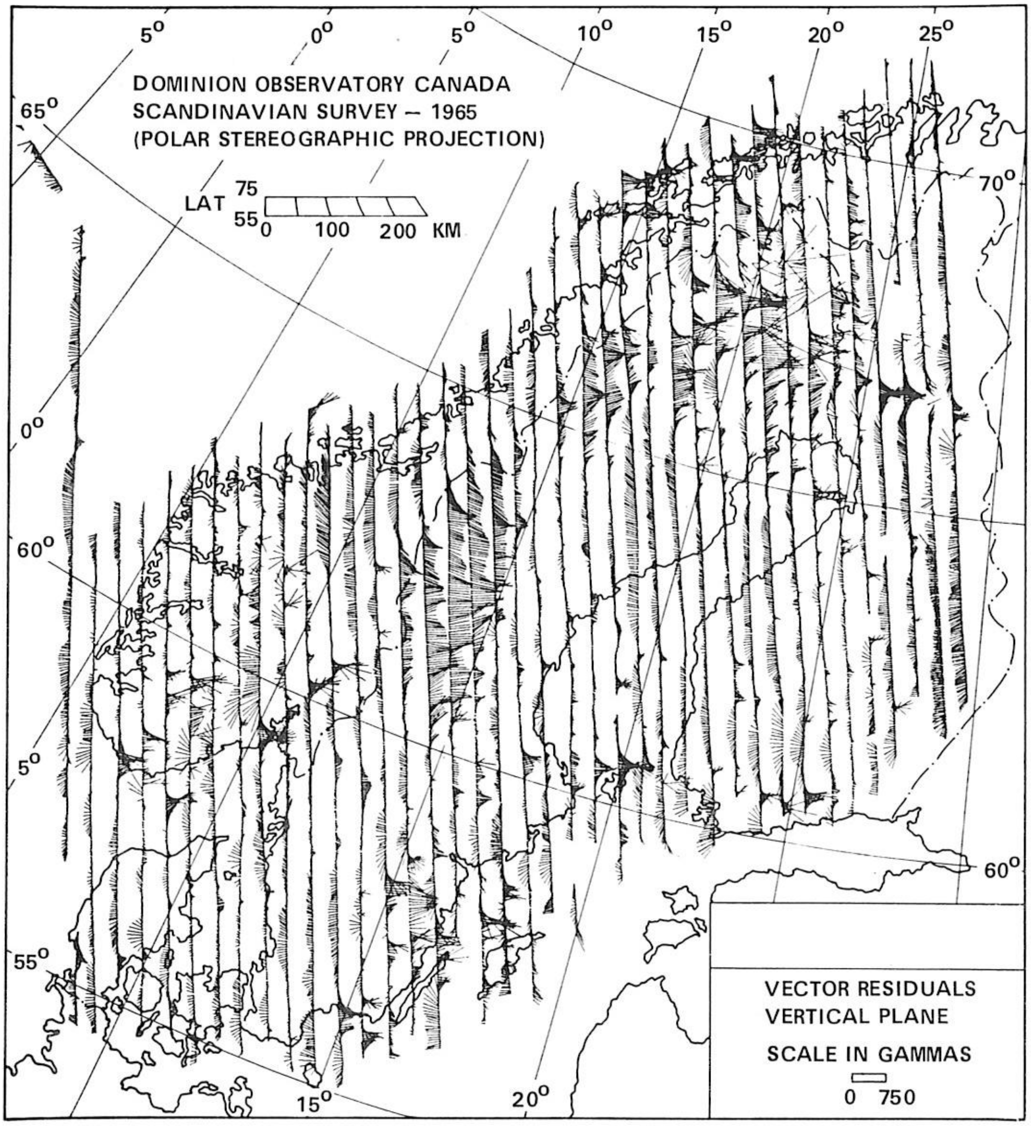

Fig. 13. Projections of Anomaly Vectors on Vertical Plane. Observed Vector Minus Computed Vector. Downward to the Right.

reveal many broad-scale features that are not at all evident from the original detailed aeromagnetic maps. Most striking are the long patterns of anomalies that follow the boundaries between adjacent geological provinces. It is easy to trace the anomaly associated with the boundary between the Superior and Grenville provinces for over 1000 km, from Lake Superior to central Quebec.

Clearly, the gap between the two classes of aeromagnetic surveys (detailed surveys for geological studies and broad-scale surveys for the study of the earth's field as a whole) is narrowing rapidly as geologists turn their attention to the deeper regions of the crust and the upper mantle. One may expect that the World Magnetic Survey will provide much new information of interest to crustal geologists and geophysicists. The adoption of an International Geomagnetic Reference Field may have an even more important impact on crustal studies, since it will make practical the use of a great quantity of existing data for the investigation of large-scale patterns of magnetic anomalies.

Summary

The present coverage of Canada and the Nordic countries by detailed aeromagnetic surveys of total intensity was illustrated. Examples were given of economically important discoveries of minerals that can be attributed to such surveys. Flight tracks of three-component airborne magnetic surveys conducted by the Dominion Observatory from 1953 to 1965 were shown. The latest version of the instrumentation was described briefly. Calibration procedures, the reduction of data, and final accuracy were discussed with special reference to the 1965 survey of the Nordic countries. Accuracies indicated were $\pm 0.4°$ in D, $\pm 70\gamma$ in H, $\pm 40\gamma$ in Z, and $\pm 40\gamma$ in F in high magnetic latitudes without correction for time variations. Polynominal representation of the magnetic field over large regions was discussed with examples of standard errors. Computer plots of large-scale anomalies were shown and their significance in terms of crustal structure considered.

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WORLDWIDE SURVEYS BY PROJECT MAGNET

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Introduction

The U.S. Naval Oceanographic Office has been publishing world magnetic charts since 1882, but its institution of a systematic and comprehensive magnetic measurement program is comparatively recent. For about 70 years, nearly all the data for the charts were collected by other organizations throughout the world. By 1950 it had become apparent that worldwide magnetic surveys, particularly of the oceans and polar regions, were required if the Oceanographic Office were to continue to fulfill its responsibility for the publication of world magnetic charts. After a thorough study of the problem, it was decided that airborne surveys offered the best solution, and Project MAGNET was established by the Navy in 1951.

Operational surveys commenced in 1953 in the North Atlantic area using a Neptune aircraft. The Neptune was retired from service in 1954, and its replacement, a Skymaster, became operational in 1955 and is still in service. The project's capability was more than doubled in 1958 with the assignment of an additional aircraft, a Super Constellation. This latter aircraft crashed on landing in Antarctica in 1960 and was a total loss. Fortunately, no one was killed in the accident, and most of the survey instruments were salvaged. Another Super Constellation commenced operational surveys in 1962 and is still in service with the Skymaster.

In addition to its primary mission of making magnetic surveys, Project MAGNET has collected other geophysical and oceanographic data during its operations. Cosmic ray measurements have been made for the Bartol Research Foundation of the Franklin Institute during essentially all flights of both Super Constellations [*Coxell et al.,* 1966]. Land gravity observations have been made at many places throughout the world during visits of the aircraft. This work is part of an international cooperative program of Study Group No. 5, International Gravity Commission, International Association of Geodesy. Sea surface temperature measurements and color and infrared photographs have been taken during low altitude flights at sea to support oceanographic studies.

Instrumentation

Project MAGNET's primary survey instrument is the Vector Airborne Magnetometer (VAM) developed by the U.S. Naval Ordnance Laboratory [*Schonstedt and Irons,* 1955]. The VAM is a self-orienting fluxgate system that measures the declination, dip, and total intensity of the earth's magnetic field. It is mounted inside the aircraft cabin. A vertical reference for the angular measurements is maintained by suspending the sensor as a damped pendulum. Directional reference is established through celestial observations. To minimize effects of aircraft motion, the angular measurements are averaged over a 100-second period. Permanent and induced aircraft magnetic fields that remain after extensive aircraft modification are compensated. Over the years the magnetometer system has undergone piecemeal modernization through alteration, replacement, or addition of various components. A digital magnetic tape recording system has been used on the Super Constellation since 1964, and a similar system has been obtained for the Skymaster, though it is not yet operational.

Since 1964 a metastable helium magnetometer (HEMAG) has been used to provide highly sensitive total intensity data. To achieve maximum sensitivity, the HEMAG sensor is housed in an aerodynamic vehicle and towed from the aircraft with a cable approximately 70 m long. To date only one HEMAG system has been in operation. It has been used mostly on the Skymaster although it was installed on the Super Constellation for one mission while the Skymaster was in overhaul. Procurement of a second HEMAG system is underway.

General World Surveys

During its 15 years of operation, Project MAGNET has flown 3,800,000 km of magnetic survey track. Approximately 75% of this effort has been devoted to general mapping of the earth's magnetic field. The basic survey plan consists of tracks spaced 300 to 400 km apart covering all accessible areas of the world. In many areas a considerably denser track spacing has been achieved. Data collection is continuous although data reduction is normally done for each 5-minute time interval. This provides observations spaced generally from 25 to 40 km along the tracks. Each complete observation consists of the magnetic elements that entirely define the magnetic vector and the required time and space coordinates. About one-third of these are not complete observations; declination is the element most commonly lacking because of weather conditions that precluded celestial observations required for determination of aircraft heading. Dip and total intensity are included in more than 90 and 95%, respectively, of the observations. Horizontal and vertical intensities are computed from the dip and total intensity measurements. Surveys completed through September 1968 will yield in excess of 100,000 data points. Probably more important than the number of data points is their distribution (Fig. 1). Flights have been made over all oceans and continents. The number of countries who have granted permission for landings or overflights is now approaching 100, and the aircraft have visited about 170 cities outside the United States. In addition to indicating the scope of operations, this attests to the excellent cooperation we have received throughout the world.

Surveys have been made of both north and south magnetic polar areas. North magnetic pole searches were made in 1955, 1960, and 1968. These have shown that, although the pole is moving, it is essentially a point at any particular time and not an area, as was previously thought by some investigators. A survey of the south magnetic pole in 1960 has shown that the magnetic characteristics of this area are very complex, and there are indications that there may be more than one pole. Another survey of this region is planned for late 1968, which we hope will provide more definitive information on the nature of the south magnetic pole.

Special Surveys

Project MAGNET has also made many special, more detailed surveys designed primarily to provide total intensity data for geologic studies. These have covered a total area of 7,500,000 km^2 and were generally flown at altitudes less than 500 m with line spacings of 1 to 20 km. Several important contributions to our knowledge of the seafloor have resulted from these surveys.

A seamount was discovered during a survey of the New England Seamount Chain in 1957. When the survey results were analyzed all but one of the characteristic anomalies could be correlated with known seamounts. At that time it was suggested that the uncorrelated anomaly, which had an amplitude of over 400γ, was associated with an unknown seamount, and a bathymetric investigation of the area was recommended. In 1967 bathymetric measurements by USNS *Kane* confirmed the existence of the seamount, which is 10 km in diameter and rises approximately 1000 m above the seafloor at geographic latitude 39°19′N, longitude 64°28′W. It has been named KIWI Seamount after the Skymaster which made the survey, and it is the only seamount whose discovery by an aircraft has been confirmed.

When Surtsey, a volcanic island near Iceland, was born in 1963, several profiles were flown in its immediate vicinity by the Skymaster, which was visiting Iceland at the time. In 1964 and again in 1966 detailed surveys were made of the area. There was

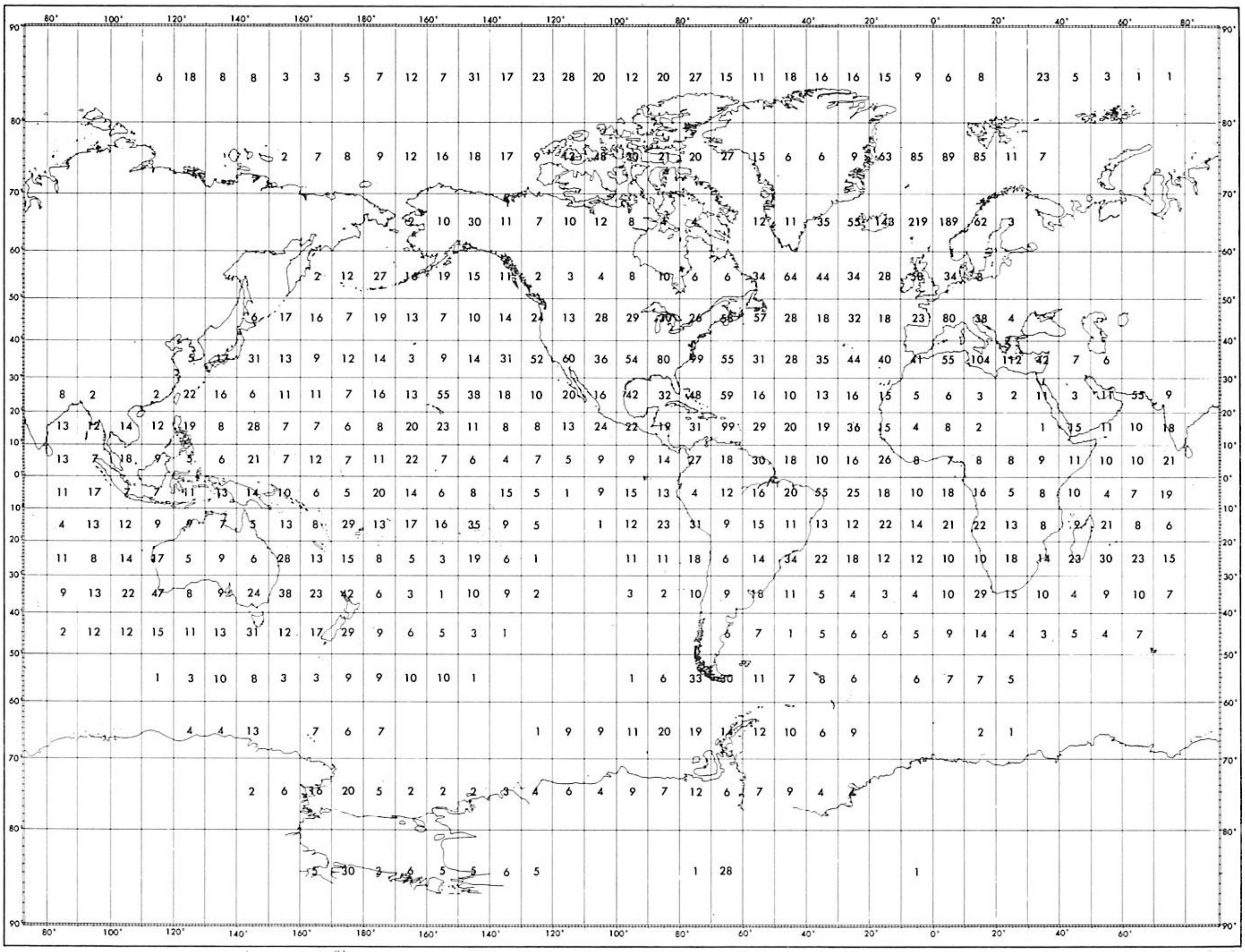

Fig. 1. Density of Magnetic Data (Data Points per 10^5 km^2) April 1953–May 1966, U.S. Naval Oceanographic Office Project MAGNET.

considerable volcanic activity during the time period between the surveys, and changes in the shape and size of negative anomalies were evident in the charts produced from the surveys. This may reflect alteration of the magma chamber. Another survey was made of this area in September 1968, but the data processing and chart compilation have not yet been completed.

An aeromagnetic survey of the United States Atlantic coastal region has completely defined, for the first time, the continental slope anomaly. This anomaly had been known for some time and had been previously thought to coincide approximately with the continental slope along the entire Atlantic coast. This survey has clearly shown that it turns westward across land near the Georgia-Florida border and is not related to the continental slope off Florida. It has been suggested by *Taylor et al.* [1968] that this anomaly outlines the edge of the continent as it was in pre-Paleozoic time.

Several Project MAGNET surveys have revealed the linear anomalies cited by many investigators as evidence of seafloor spreading. A classic example is the Reykjanes Ridge, a portion of the Mid-Atlantic Ridge southwest of Iceland. Here the alternating bands of positive and negative anomalies parallel the ridge axis and exhibit a striking degree of symmetry about the ridge axis.

Large linear anomalies are also present in the Norwegian Sea. Comparison of these anomalies with the model of *Heirtzler et al.* [1968], which has been used for worldwide correlation studies, indicates that there have been possibly as many as three separate periods of spreading with rates of 1.0 to 1.5 cm per year [*Avery et al.,* 1968]. The Norwegian Sea survey also provides evidence of four previously unknown major faults associated with the mid-ocean ridge, confirms the northwest-southeast direction of the Jan Mayen fracture zone, and indicates that the Great Glen and Minch faults of Scotland extend into the Norwegian Sea as far north as 64°.

Several profiles were flown in early 1968 over northeastern Brazil and western Africa in support of continental drift studies. Based on radiometric age dating of rocks, *Hurley et al.* [1967] found striking evidence that South America and Africa were once joined. Preliminary results of our aeromagnetic survey and correlation with other magnetic data from western Africa show linear anomalies that are similar in appearance (P. R. Vogt, private communication, 1968), but more work is needed before definite conclusions can be reached.

Although Project MAGNET data have been applied to studies concerned with exploration for petroleum and minerals, it was only recently, in the spring of 1968, that our first survey designed specifically for this purpose was flown. This survey was over the Formosa Strait and was in support of the development program of the United Nations Economic Commission for Asia and the Far East Committee for Coordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas. Interpretation of the data is not yet complete but the results support the existence of two large sedimentary basins separated by an arch through the Penghu Islands [*Meng,* 1968]. Proposals by the Committee for additional surveys of Asian offshore areas are under consideration for the future.

Future Plans

We are now preparing for procurement of a new instrument system that will include navigation, magnetometer, and data recording subsystems. An inertial navigation system will provide primary survey control. Additional navigation instruments to augment and update the inertial system will include Loran (both A and C), a star tracker, a doppler radar, a navigation radar, a VLF radio navigation system, and a satellite navigation system. Use of a laser altimeter to provide precise altitude is being studied.

The magnetometer will probably be a fluxgate, although a biased optical pumping magnetometer similar to those in use at observatories is also being considered. If the fluxgate is selected, it may be either an orienting type to provide angular measurements or a fixed orthogonal array to measure X, Y, and Z. Selection of the magnetometer type will be made after review of proposals submitted by prospective contractors. Stabilization of the magnetometer sensors and vertical and directional references for the magnetic measurements will be provided by the inertial system. A proton or optical pumping magnetometer will be included in the system for total intensity measurements.

Data will be recorded in digital form on magnetic tape. We plan to record outputs from both the magnetometer and navigation instruments, thus permitting data processing to be completely automated. Data processing will still be done in the Oceanographic Office, but we are considering inclusion of a small general purpose computer to provide a limited processing capability on the aircraft.

Expected accuracies of the new system, exclusive of navigation errors, are 3 minutes of arc for declination, 1.5 minutes of arc for dip, and 1γ for total intensity. Expected accuracy for geographic position is one nautical mile (1.85 km) worldwide. Position accuracy is expected to be better than this in areas of Loran-C coverage, and improvement in worldwide navigation accuracy is expected when additional navigation satellites are available.

As noted earlier, there are many areas, particularly in the southern oceans, that we cannot now survey because of aircraft range limitations. Plans are underway to obtain a new aircraft that we hope will largely alleviate this problem. The new aircraft, an Orion, is a modified version of the Electra that has been widely used by commercial airlines in recent years. A design study by the Lockheed Aircraft Corporation, manufacturer of the Orion, indicates that a survey range in excess of 9000 km might be realized. This would permit complete world coverage.

Upon completion of the basic world survey, repeat surveys will be undertaken to maintain the world magnetic data base. Plans for repeat surveys have not yet been established, but they may well include determination of secular change rates if anticipated accuracies of our new instrument system are achieved.

Summary

Project MAGNET has been engaged in worldwide airborne magnetic surveys since 1953. Surveys have been made in all accessible areas of the world and have provided data over all oceans and continents. The total distance flown is approximately 3,800,000 km of which about 75% has been on surveys designed for general mapping of the earth's magnetic field. These surveys provide data on all magnetic components along tracks spaced generally less than 400 km apart. Some 25% of Project MAGNET's effort has been devoted to special, more detailed, surveys designed primarily to provide total intensity data for geologic studies. More than 7,500,000 km² have thus been surveyed at line spacings of from 1 to 20 km. The special surveys have made many important scientific and economic contributions and are expected to continue. Future plans include the acquisition of new magnetometer systems and survey aircraft that should increase data accuracy and permit coverage of areas heretofore inaccessible because of aircraft range limitations.

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SATELLITE SURVEYS

INTRODUCTION

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Surveys by satellites formed part of an agreement announced at the United Nations between the Union of Soviet Socialist Republics and the United States. Some dates and actions are outlined in the following.

September 14, 1962. The United Nations Committee on the Peaceful Uses of Outer Space approved a report to the General Assembly (Document A/5181) that notes with approval the establishment of a World Magnetic Survey Program; and that requests all specialized agencies and member states to participate in this program in any way appropriate to their function and capability, and further requests Member States and scientific organizations concerned with obtaining and disseminating such data to arrange for especially complete and timely transmission of such data through established World Data Centers during the period of the World Magnetic Survey.

December 5, 1962. The United States and the Union of Soviet Socialist Republics announced at the United Nations an agreement on Cooperation in Peaceful Uses of Outer Space. The agreement included plans for a joint effort to launch artificial earth satellites to map the earth's magnetic field as part of the World Magnetic Survey.

December 14, 1962. The General Assembly of the United Nations having considered the report of September 14, 1962, of the Committee on the Peaceful Uses of Outer Space, adopted a resolution (Doc. A/Res/1802 (XVII)) that included an urging of all Member States and appropriate specialized agencies to give wholehearted and effective support to the international programs mentioned in the report and already under way, including the International Year of the Quiet Sun and the World Magnetic Survey.

December 15, 1962. Adlai E. Stevenson, the representative of the United States to the United Nations, announced the text of the agreement of June 8, 1962, between the United States and the Union of Soviet Socialist Republics, on Cooperation in Peaceful Uses of Outer Space. This agreement followed an exchange of views between Chairman Nikita S. Khrushchev and President John F. Kennedy and included plans for joint efforts to map the earth's magnetic field and plans for meteorological studies and satellite telecommunications. The agreement was circulated as U.N. Document A/C.1/880 and was also reproduced in Vol. XLVII, No. 1226, December 24, 1962, of the U.S. Department of State Bulletin.

The following persons participated in the discussions on the cooperation:

U.S.S.R. Representatives

Mr. Y. A. Barinov
Academician A. A. Blagonravov
Professor V. A. Bugaev
Professor Yu. D. Kalinin
Deputy Minister I. V. Klokov
Mr. G. S. Stashevsky

U.S. Representatives

Dr. Hugh L. Dryden
Professor Donald F. Hornig
Dr. John W. Townsend, Jr.

U.S. Consultants

Mr. Arnold W. Frutkin
Congressman James G. Fulton
Mr. Howard Furnas
Dr. James P. Heppner
Congressman George P. Miller
Dr. Richard W. Porter
Mr. Philip H. Valdes
Dr. Harry Wexler

Early plans for the Survey were discussed by *Vestine* [The survey of the geomagnetic field in space, *Trans. Am. Geophys. Union, 41,* 4, 1960] and Heppner [The World Magnetic Survey, *Space Sci. Rev., 11,* 315, 1963].

Five satellites directly applicable to the World Magnetic Survey were subsequently launched: the Soviet Union's COSMOS 49 (1964 69A) and the United States' OGO 2 (1965 81A), OGO 4 (1967 73A), OGO 6 (1969 51A), and 1964 83C. In addition to a discussion of these satellites, this section contains a review article on the findings of numerous other satellites.

GEOMAGNETIC SURVEY BY THE POLAR-ORBITING GEOPHYSICAL OBSERVATORIES

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Introduction

The only complete pole-to-pole survey of the geomagnetic field to date has been that performed by the polar Orbiting Geophysical Observatories OGO's 2, 4, and 6 [*Heppner*, 1963; *Ludwig*, 1963], satellites also unofficially referred to as "POGO's." Some of the characteristics of the orbits are as follows:

Satellite	*Launch Date*	*Inclination*	*Perigee(km)*	*Apogee(km)*
OGO 2 1965 81A	Oct 14, 1965	87.3°	410	1510
OGO 4 1967 73A	July 28, 1967	86°	410	910
OGO 6 1969 51A	June 5, 1969	82°	400	1100

The magnetic survey instruments used on these spacecraft were optically pumped, self-oscillating rubidium vapor magnetometers measuring the absolute scalar field [*Farthing and Folz,* 1967]. The sampling interval was 0.5 second for OGO's 2 and 4 and 0.288 second for OGO 6. OGO 2 acquired data from launch until October 2, 1967, whenever the orbit was in full sunlight; OGO 4 operated almost continuously from launch until January 19, 1969; OGO 6 operated almost continuously until August 29, 1970. Further data are being acquired one day a week until the equipment fails.

Since all the data have not been reduced, this report is limited to a summary of data from OGO 2 and 4 from October 14, 1965 until the end of 1967.

Accuracy of Observations

The accuracy of the instrument is better than 2γ [*Farthing and Folz,* 1967] as determined by direct comparison with proton magnetometers. The digitization "noise" resulting from measuring the frequency (frequency (Hz) = (4.66737)field(γ)) over a finite interval is $\pm 0.4\gamma$ for OGO 2 and 4 and $\pm 0.6\gamma$ for OGO 6. Extraneous magnetic fields from the rest of the spacecraft were tested prior to launch and found to be below 1γ at the rubidium vapor sensor, which is mounted on the end of a 6 m long boom.

A recent article by *Allen* [1968] indicated that single-cell rubidium magnetometers such as those used in the automatic surface observatories [*Alldredge and Saldukas,* 1966] could be in error as much as 7γ. No such drift error is possible with the units used on POGO since they are of the dual-cell type and automatically cancel such first-order errors (B. G. Ledley, private communication). There is a pair of such dual-cell instruments on each spacecraft, and the output frequency is a phase-locked sum of the signal from each. When the spacecraft happens to be in a spinning mode, the magnetic field vector alternately rotates through zones of insensitivity for each of the two instruments; at these times the output signal results from only one of the dual-cell units. Under these conditions it is thus possible to observe a small oscillation in the output data of about 2.5γ peak-to-peak amplitude. It is likely that the absolute error is less than this amount.

A source of error frequently comparable to that of the instrument is the absolute time assigned to any given observation. Since the field changes up to 40γ/sec due to the movement of the spacecraft, an error of 25 msec could be equivalent to a measurement error of 1γ. The timing accuracy is estimated to be generally better than 30 msec with rare excursions to 60 msec. It is thus likely that this source of error is also of the order of 1γ.

However, the instrumental and timing accuracies are overshadowed by the errors added due to uncertainties in the orbital position at the time of measurement. The effective accuracy of the observations can be no greater than the difference in field between the assumed and true position of the spacecraft at the time of measurement. Computations with geomagnetic field models show that an altitude error of as little as 40 m can give an effective error of 1γ,

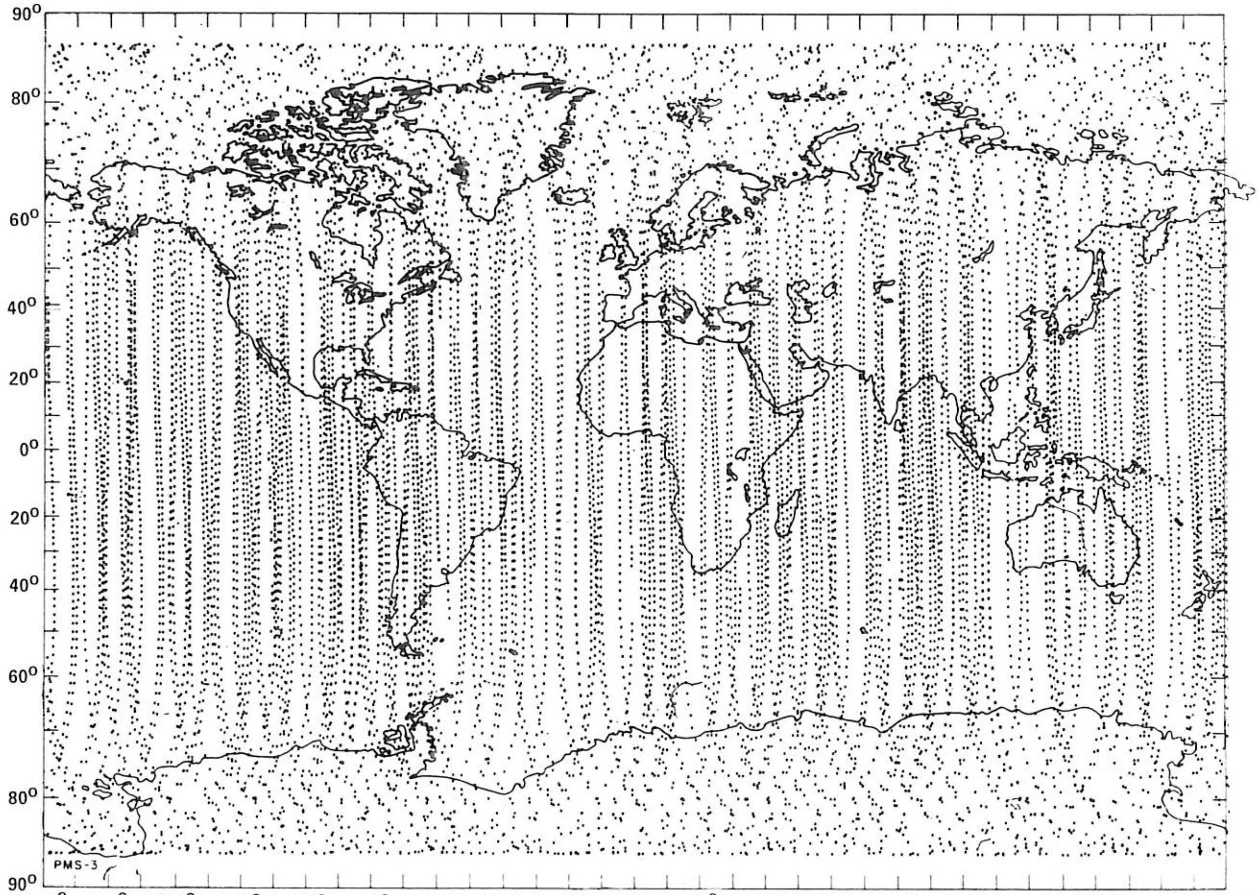


Fig. 1. Positions of the OGO 2 Observations Acquired during the First Ten Days from Launch.

whereas the horizontal uncertainty can be over 200 m for the same effect. The evaluation of absolute orbital errors is difficult since the quantity of tracking data for a spacecraft operating as low as POGO is barely sufficient to define an accurate orbit. We have attempted an estimate of errors by having two independent determinations of the orbit on the assumption that the computed difference in field gives an indication of the errors. The details of one of the orbital determinations and our accuracy evaluation are obtainable from the National Space Science Data Center (Greenbelt, Maryland, U.S.A.) as part of the reference material available to users of the OGO data. This evaluation was done on a daily basis and shows that for OGO 2 the difference is 5γ or less on about half the days and 10γ or less on 90% of the days. The other 10% show differences up to 20γ except for a few cases where one of the orbits used in the comparison obviously has large errors.

The corresponding positional differences range up to a few hundred meters vertically and one or two kilometers horizontally. The OGO 4 and 6 orbits have not been evaluated but since the tracking data are of the same type, one might assume that the errors would be no larger than for OGO 2.

Data Extent

The quantity of data acquired by the OGO magnetometers far exceeds the total for all other magnetic survey sources. Data acquisition for only about a two-week interval gives virtually complete global coverage. Figure 1 is a plot of the positions of the OGO 2 observations acquired during the first ten days from launch (one point is plotted every 37 seconds (~250 km)). Since the OGO satellites were long-lived, it was not necessary to follow the early recommendations [*Vestine,* 1961] to design the orbit so that the profiles from each day would evenly fill the

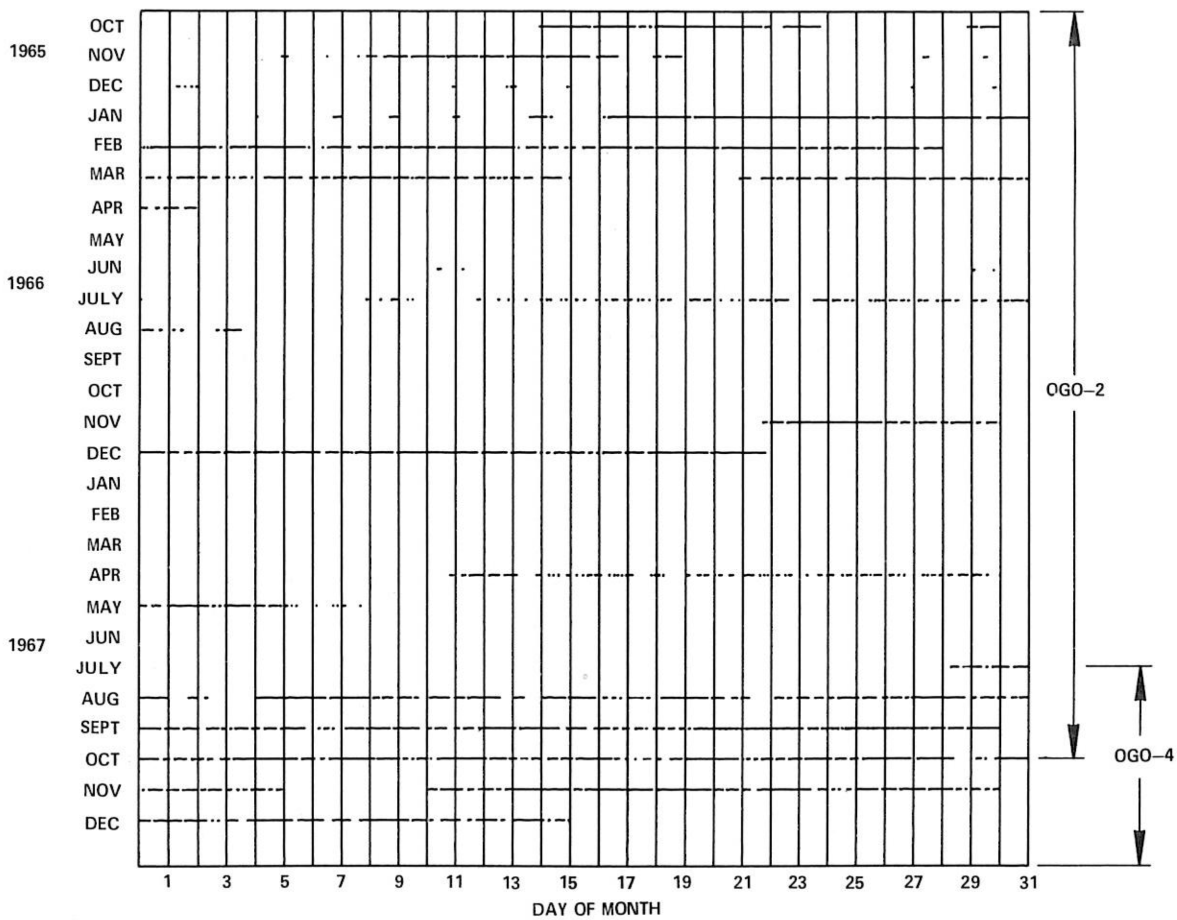


Fig. 2. Intervals of Data Acquisition Prior to December 15, 1967.

spatial gaps in longitude. The tracks are thus essentially random except that the locations of receiving stations available for reading out the recorded data have made the longitudes near 130°E and W slightly less well covered than others.

The intervals of time over which data were acquired prior to December 15, 1967 are given by Fig. 2. The solid horizontal lines for each month and day indicate continuous data acquisition with time gaps no greater than five minutes. The only contribution by OGO 2 after May 1967 was during the interval September 19 to October 2, 1967, when operation was very intermittent. When remaining OGO 4 data are reduced, they will cover almost all the dates from launch (July 28, 1967) until January 19, 1969, plus a few segments from July 17 through August 6, 1969.

The total data (about 12,200,000 observations) for OGO 2 are equivalent to approximately 2,000 hours or 50 million track kilometers. If one considers that the earth can be adequately covered in, for example, 100 orbits, OGO 2 has performed over ten complete surveys, whereas OGO 4 and 6 will each have performed more than double that number.

Having such a large base of data makes it feasible to go beyond the original concept of the World Magnetic Survey, which was to obtain the main field to an accuracy only of the order of 100γ [*Vestine,* 1960, 1961]. It becomes possible to look more carefully into the effect of external sources and time variations and may lead to a reference field whose accuracy is of the order of a few gammas. Also, it may be possible to follow the secular changes more accurately and with a finer time definition than ever before. It is thus useful to look into factors concerning data acquisition that may systematically bias the results at the 10γ level.

The most significant factor that is new and special to spacecraft surveys is that the plane of a satellite orbit moves very slowly in inertial space. Since the earth's rotation brings each longitude under the orbit plane, the data are globally well distributed. However, all observations at one latitude have nearly the same local time for several weeks. This movement is illustrated by Fig. 3 [*Langel,* 1967]. This diagram shows a plot (for the first few months from launch)

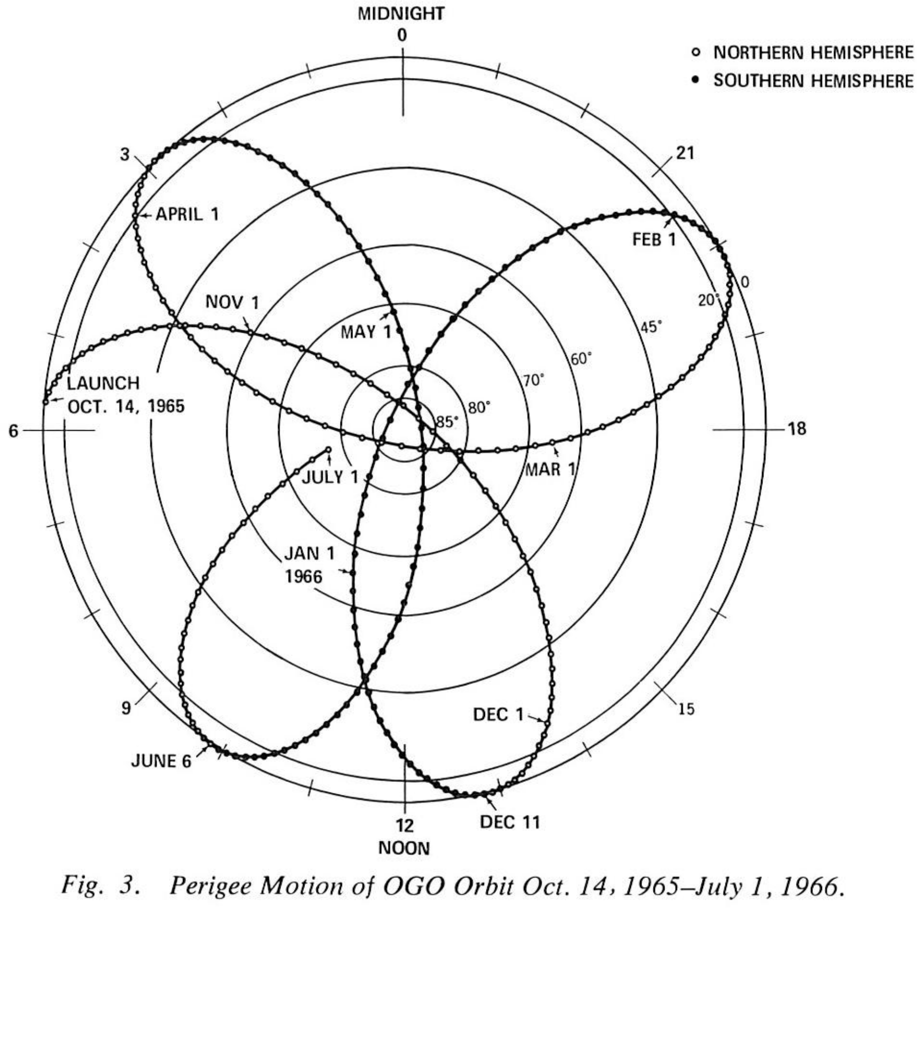


Fig. 3. Perigee Motion of OGO Orbit Oct. 14, 1965–July 1, 1966.

of the locus of perigee for OGO 2 as seen from above the north pole. The concentric circles are parallels of geographic latitude; the azimuth scale is hours of local time. The OGO 2 orbit at any epoch would project onto this diagram as a thin ellipse passing through the point given for perigee and the parallel of latitude equal to its inclination (87.3°). Thus, for the first ten days from launch, each observation equatorward of 60° latitude occurred between 4 and 6 o'clock (a.m. and p.m.) local time. Further, all the morning data were at a low altitude while the evening data were taken near apogee. Since both quiet-day and disturbance-time variations of the field have diurnal components, any analysis of the data neglecting such effects could contain systematic biases.

Of course, as the orbital plane rotates, data will normally be acquired at all local times. However, due to spacecraft malfunctions OGO 2 was only able to acquire data when the orbital path was almost fully sunlit. Thus, as seen in Table 1, less than 1% of the total OGO 2 data was obtained within two hours of noon and midnight, whereas the distribution for OGO 4 is much more uniform.

As shown in Table 2, for altitudes below 1000 km the quantity of OGO 4 data is more than triple that from OGO 2.

However, the interval during which OGO 2 was in operation was generally magnetically quieter than for OGO 4 as expected from the phase of the sunspot cycle. The percentage distribution of the data obtained below 600 km during intervals with a given magnetic Kp index is as follows:

Kp	*OGO 2* (%)	*OGO 4* (%)
0	22	9
1	30	24
2	21	27
3–5	26	39
6–8	1	1

TABLE 1

PERCENT DISTRIBUTION OF OGO 2 AND OGO 4 DATA IN LOCAL TIME (DATA EXCLUDED POLEWARD OF 80°)

Local Time Ranges (Hours)

	22–2	2–6	6–10	10–14	14–18	18–22
OGO 2	0.7	34	14	1	20	31
OGO 4	12	20	11	19	19	18

TABLE 2

DISTRIBUTION OF OGO 2 AND OGO 4 DATA BY ALTITUDE (ONE OBSERVATION TABULATED EACH 70 SEC)

	OGO 2	*OGO 4**
Below 600 km	30,000	91,500
600–1000 km	30,000	104,700
1000–1500 km	62,300	0
Total	122,300	196,200

* OGO 4 reduced data September 28, 1967 - May 28, 1968. Data were also acquired through January 19, 1969, but are not yet available.

Thus about half of the OGO 2 and a third of the OGO 4 data should be free of systematic variations due to magnetic disturbance. Of course, even on magnetically very quiet days one needs to make allowance for the few tens of gammas change in the level of the field due to external effects [*Sugiura,* 1964; *Sugiura et al.*, 1970].

Data Analysis

In using only total field data for magnetic mapping or modeling, one is faced with the question of whether a true vector field can be obtained from only scalar measurements. Although the theoretical basis is yet lacking, we have numerically demonstrated that this can be done with "perfect" data. That is, we have computed total field values on a 10° grid at one altitude from a finite set of spherical harmonic coefficients (g_n^m, h_n^m). Then, using the linearized least-squares technique as given by *Cain et al.* [1967] the original coefficients were retrieved to an accuracy comparable to the computer word-length round-off error (10^{-7}), using as initial conditions a $g_1^0 = -30{,}000\gamma$, with all other terms = 0.

In our original work with the OGO 2 data [*Cain et al.,* 1966] we found that it was possible to fit to within a 4γ rms residual a three-day span of magnetically quiet data with a harmonic series containing 143 internal coefficients (maximum degree and order of 11). However, satisfactorily reducing a longer span of data required allowing the coefficients to change with time to account for secular variation. Also, even by careful selection of the quietest intervals, the data still contain time variations from external magnetospheric sources and from ionospheric and induced currents internal to the shell of measurements.

An example of the results of fitting a longer span of data is contained in the POGO(3/68) set of coefficients submitted March 15, 1968, as a candidate for the International Geomagnetic Reference Field (IGRF) [*Cain and Cain,* 1968]. This fit was made to a set of OGO 2 and 4 data selected from the magnetically quiet days given in Table 3. The OGO 2 data were sampled at 60-second intervals on these dates whereas for OGO 4 the interval was 30 seconds.

TABLE 3

DATA SELECTION FOR POGO(3/68) COEFFICIENTS

Satellite	*Year*	*Date*	*Observations*
OGO 2	1965	Oct 12	1209
		Oct 16	693
		Nov 10	904
		Nov 12	964
		Nov 14	1162
		Nov 16	827
		Dec 14	93
		Dec 15	79
		Dec 17	61
	1966	Jan 12	18
		Jan 14	312
		Jan 17	760
		Feb 1	752
		Feb 9	769
		Feb 14	521
		Feb 28	607
		Mar 2	145
		Mar 7	696
		Jun 11	27
		Jul 18	182
		Jul 25	261
		Jul 31	391
		Aug 1	394
		Aug 2	74
		Nov 22	241
		Nov 23	908
		Nov 25	819
		Nov 26	432
		Dec 9	927
		Dec 11	140
		Dec 12	998
OGO 4	1967	Jul 31	2318
		Aug 1	2598
		Aug 2	403

Note that OGO 2 data were sampled at 60-sec intervals (~400 km) and OGO 4 at 30-sec intervals. Most data were taken when orbit planes were near twilight meridians.

Maps showing the distribution of data for each year (1965, 1966, and 1967) are given in Fig. 4. These 22,252 observations were fit with the 99 coefficients to a root mean square residual of 11γ. As shown in Table 4, the distribution of residuals from the fit is very symmetric.

Previous to the POGO(3/68) model the best estimate of the current geomagnetic field was given by the GSFC(12/66) set of coefficients [*Cain et al.,* 1967]. This prior analysis used a sample of OGO 2 data taken from the interval October 29 - November 15, 1965, plus the comprehensive selection of World Magnetic Survey data 1900-1963. However, as seen in Table 5 the POGO(3/68) model gives better fit to the whole set of POGO data than the GSFC(12/66) model. An inspection of plots of $\Delta F = F_{measured} - F_{calculated}$ for August 1, 1967 using these two models shows that the peak values using GSFC(12/66) range from +90 to −130γ; those using POGO(3/68) all lie within the band ±50γ. This day was one of the selected five quietest days for August.

TABLE 5

RMS DEVIATIONS BETWEEN EVENLY SELECTED POGO DATA AND MODELS

			Residuals(γ)	
Spacecraft	*Data Interval*	*No.*	GSFC *(12/66)*	POGO *(3/68)*
OGO 2	1965.8–1966.0	2150	17	12
OGO 2	1966.0–1966.9	8573	29	18
OGO 4	1967.6–1967.7	2784	44	20

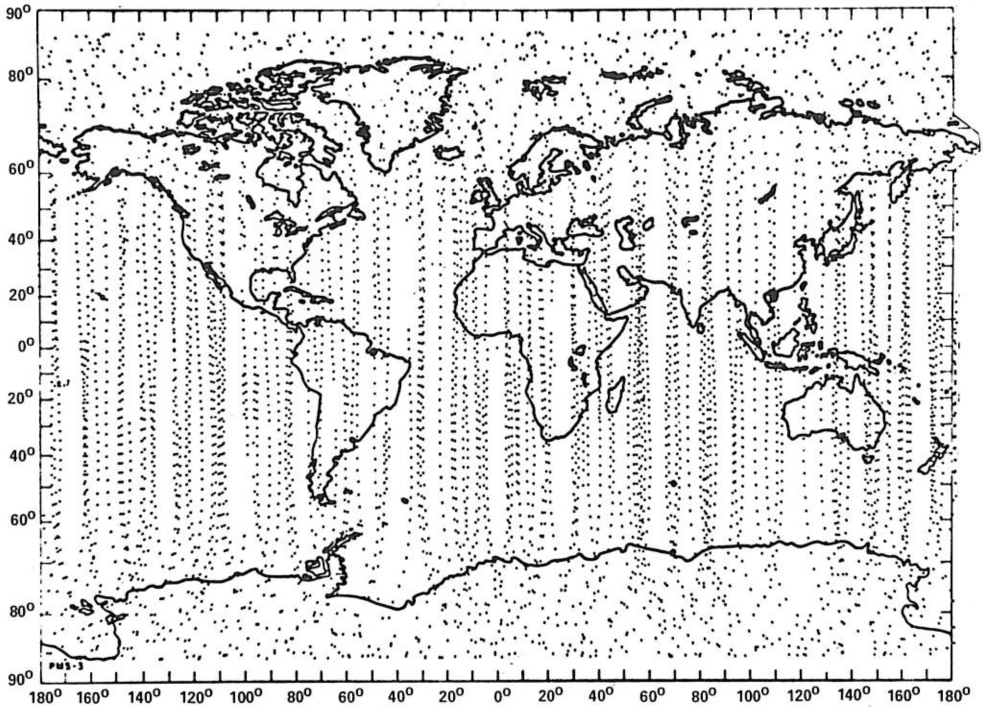
After having derived the POGO(3/68) fit for submission as an IGRF candidate, we also derived a more updated model. This was done with an improved set of 32,649 OGO observations. The resulting 143 internal spherical harmonic coefficients, labeled POGO(10/68) are listed in Table 6. The improvements in the data set over that used for the earlier model include:

1. The use of data that are more completely processed (having fewer erroneous values);

TABLE 4

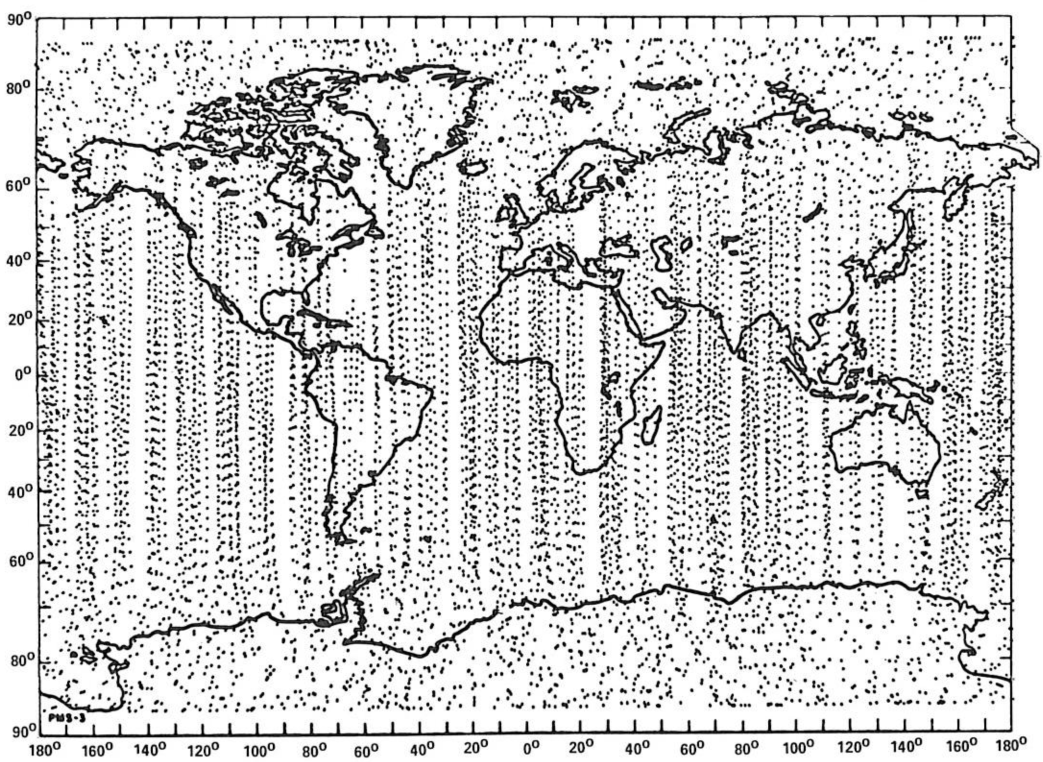
DISTRIBUTION OF RESIDUALS OF DATA FROM POGO(3/68) MODEL ($\Delta F = F_{(measured)} - F_{(computed)}$)

ΔF Interval (γ)	0		−10		−20		−30		−40		−50		−60		−70
Data		7303		2477		725		173		46		14		3	
ΔF Interval (γ)	0		10		20		30		40		50		60		100
Data		8360		2376		521		166		69		11		8	



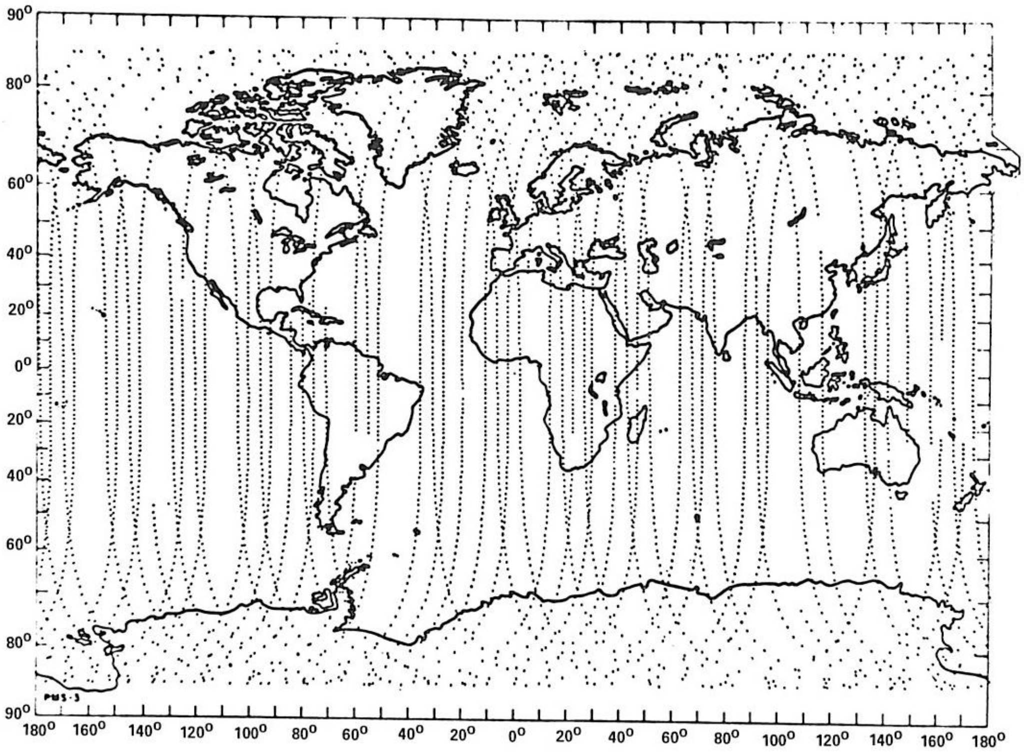
(a) OGO 2 (1965)

Fig. 4. Distribution of OGO Data Entering POGO (3/68) Model.



(b) OGO 2 (1966)

Fig. 4. Distribution of OGO Data Entering POGO (3/68) Model (continued).



(c) OGO 4 (1967)

Fig. 4. Distribution of OGO Data Entering POGO (3/68) Model (continued).

2. Extending the data selection for OGO 4 from launch through December 1967;
3. Selecting data from Kp = 0 or 0+ intervals (deleting those intervals following a disturbance that have high residual Dst) in place of whole selected quiet days; and,
4. Using more accurate orbital positions for the OGO 2 data.

The geographical distributions of data are very similar to those shown in Fig. 4 except that the OGO 4 data coverage (August - December 1967) is much more dense. Since the data were somewhat improved and the number of coefficients increased to 143, the residual of fit was reduced to 7γ with a percentage distribution as seen in Table 7.

We have compared the fields computed from the POGO and GSFC(12/66) models to see how well they extrapolate into the future and to see if surface components can be derived in practice from only total field measurements. The difference between GSFC(12/66) and POGO(3/68) at the surface and at 1000 km altitude is given in Table 8. The root mean square (rms) is obtained by differencing values computed on a grid 10° in latitude and longitude but weighting according to the area of the grid block. The maximum value is thus the largest absolute difference found on this grid. Since the two models contained overlapping data in 1965, the differences for that epoch are likely symptomatic of their inherent errors. The growth by a factor of three of the differences by 1970 is indicative of the discrepancies in their secular change coefficients. Indeed, the satellite-derived models reflect an annual decrease of the main dipole $\dot{H}_0$ of $27\gamma/yr$ whereas GSFC (12/66) predicts only $15\gamma/yr$. Although it is not clear whether this increase in rate of dipole collapse is a true feature of the internal field or only a short-term effect possibly due to external causes (see, e.g., *Chapman and Bartels,* 1940, p. 134) such results as given in Table 5 show that the change is necessary to fit the recent data. It is not now possible to judge which of these two models more accurately describes the surface component field at recent epochs, since the latest component survey data is epoch 1963 and the coverage is far from global.

TABLE 6

POGO(10/68) COEFFICIENTS, EPOCH 1960.0, DATA RANGE 1965.8 - 1967.9

n	m	$g_n^m(\gamma)$	$h_n^m(\gamma)$	$\dot{g}_n^m(\gamma/yr)$	$\dot{h}_n^m(\gamma/yr)$
1	0	−30465.0		25.42	
1	1	−2163.3	5791.0	9.88	−4.66
2	0	−1541.4		−23.90	
2	1	2976.3	−1977.2	3.50	−7.07
2	2	1607.5	156.6	−2.14	−10.70
3	0	1325.8		−5.59	
3	1	−1983.7	−445.3	−11.52	8.48
3	2	1316.9	233.4	−4.41	0.68
3	3	842.0	−94.9	2.87	−14.89
4	0	959.1		−0.62	
4	1	819.6	135.4	−2.51	3.45
4	2	486.4	−266.7	−1.22	−0.39
4	3	−372.4	20.7	−2.96	−0.87
4	4	256.2	−241.5	0.86	−6.52
5	0	−234.3		2.72	
5	1	357.7	16.9	0.48	0.05
5	2	233.9	113.3	3.17	3.00
5	3	−21.0	−128.7	−2.46	0.32
5	4	−147.1	−115.1	−0.89	3.11
5	5	−45.2	130.3	−3.15	−6.35
6	0	49.1		−0.61	
6	1	54.5	−9.6	1.06	−0.26
6	2	4.8	106.4	0.62	−0.48
6	3	−249.1	56.8	3.96	2.58
6	4	1.7	−27.2	−0.94	−0.80
6	5	−3.7	−14.9	1.49	0.50
6	6	−91.6	−4.3	−1.67	0.82
7	0	75.9		−0.89	
7	1	−52.4	−57.9	−0.21	−0.87
7	2	8.0	−25.0	−1.08	−0.46
7	3	10.0	−0.8	0.70	−1.02
7	4	−36.7	6.3	1.07	0.25
7	5	−8.3	9.5	0.96	1.88
7	6	6.6	−11.7	1.01	−2.43
7	7	−22.7	−37.6	5.23	2.32
8	0	7.4		0.61	
8	1	6.0	10.1	−0.12	−0.15
8	2	−8.1	−13.0	0.87	−0.10
8	3	−9.2	11.5	−0.33	−1.22
8	4	−0.8	−16.4	−0.14	−0.26
8	5	9.1	5.5	−0.85	0.15
8	6	−11.4	22.3	0.99	−0.37
8	7	7.9	−4.9	0.81	0.29
8	8	35.1	−26.2	−4.98	0.91
9	0	11.0		−0.24	
9	1	6.6	−20.4	0.30	−0.38
9	2	1.8	14.4	0.04	0.16
9	3	−12.5	0.6	0.04	0.67
9	4	15.8	−1.5	−0.40	−0.14
9	5	1.7	1.4	−0.28	−0.83
9	6	2.6	3.4	−0.57	1.30
9	7	8.7	14.8	−1.32	−0.33
9	8	5.1	2.4	−0.14	−0.38
9	9	−2.4	−0.9	0.50	0.99
10	0	−2.6		−0.01	
10	1	−2.0	1.1	−0.09	0.21
10	2	1.0	0.9	0.12	0.05
10	3	−5.5	−0.3	0.19	0.54
10	4	−0.7	7.5	−0.20	−0.26
10	5	7.5	−2.3	−0.02	−0.30
10	6	7.8	1.4	−0.43	−0.03
10	7	1.7	−0.5	−0.33	−0.39

TABLE 6.—CONTINUED

n	m	$g_n^m(\gamma)$	$h_n^m(\gamma)$	$\dot{g}_n^m(\gamma/yr)$	$\dot{h}_n^m(\gamma/yr)$
10	8	−5.3	4.3	1.03	−0.02
10	9	1.3	8.0	0.22	−1.04
10	10	−2.7	−13.7	0.46	0.79
11	0	2.3		0.03	
11	1	−1.8	−0.8	0.11	0.35
11	2	−2.1	4.4	0.05	−0.26
11	3	5.5	−0.1	−0.30	−0.17
11	4	−1.5	−3.9	0.01	0.17
11	5	2.4	−0.6	−0.34	0.18
11	6	−3.5	1.8	0.48	−0.50
11	7	−1.3	−3.2	0.52	0.23
11	8	2.5	0.8	−0.19	−0.34
11	9	−1.2	−5.9	−0.03	0.37
11	10	12.7	−1.7	−1.65	0.22
11	11	5.0	10.5	−0.40	−1.55

TABLE 7

DISTRIBUTION OF RESIDUALS OF POGO DATA (1965.8 - 1967.9 FROM POGO(10/68) MODEL)

$\lvert\Delta F\rvert\gamma$	0	10	20	30	40	70	100
%	85	13	2	0.4	0.2	0.04	

As might be expected for fits performed with a nearly common data base, the two POGO models give more similar results. As seen in the top line of Table 9, at an altitude of 1000 km and epoch 1966, the total field difference is only 17γ maximum and 5γ rms. This small difference is expected because of the common data volume. However, one can also see on this line that the differences in field components are considerably higher than these figures, which probably indicates that some of the previously mentioned systematic biases are affecting the results.

When the two POGO models are extrapolated to the earth's surface (lower half of Table 9) the differences between the components increase by a factor of three, whereas those for the total field show a ratio of six. Extrapolating into the future at this level gives quite large differences by 1972.

Conclusions

The global survey of the magnetic field by the OGO spacecraft that began near the close of the International Year of the Quiet Sun is expected to continue into 1970. Inasmuch as there are no other comprehensive data, it is likely that the models resulting from fits to these data give the best avail-

TABLE 8

ABSOLUTE MAXIMUM AND ROOT MEAN SQUARE DIFFERENCES IN FIELD COMPUTED FROM POGO(3/68) AND GSFC(12/66) MODELS

Epoch	|Maximum|						RMS					
	X(γ)	Y(γ)	Z(γ)	D(°)	I(°)	F(γ)	X(γ)	Y(γ)	Z(γ)	D(°)	I(°)	F(γ)
	1000 km Altitude											
1965	100	200	250	1.4	0.7	50	28	45	60	0.2	0.2	16
1970	230	290	460	13.5	1.5	160	73	94	143	0.5	0.7	67
	Surface											
1965	320	570	710	2.3	1.3	200	80	120	160	0.3	0.3	50
1970	530	770	1180	6.6	2.6	470	170	210	310	0.6	0.6	140

TABLE 9

MAXIMUM AND ROOT MEAN SQUARE DIFFERENCES IN FIELD COMPUTED FROM POGO(3/68) AND POGO(10/68)

Epoch	|Maximum|						RMS					
	X(γ)	Y(γ)	Z(γ)	D(°)	I(°)	F(γ)	X(γ)	Y(γ)	Z(γ)	D(°)	I(°)	F(γ)
	1000 km Altitude											
1966	90	180	260	1.7	0.7	17	20	40	50	0.2	0.2	5
1968	110	210	320	2.6	0.9	23	30	60	70	0.2	0.2	7
1970	170	370	490	3.0	1.1	43	50	80	100	0.3	0.3	13
1972	250	520	700	4.0	1.6	70	70	100	140	0.4	0.4	19
	Surface											
1966	290	610	780	1.5	1.4	100	70	120	150	0.3	0.3	30
1968	340	700	890	1.7	1.7	90	90	140	190	0.3	0.4	30
1970	470	930	1250	2.1	1.9	120	120	190	250	0.4	0.4	40
1972	690	1320	1810	3.3	2.6	150	160	240	320	0.5	0.6	60

able estimate of the field for the current epoch and for short extrapolations into the future. However, a truly accurate definition of the vector field and its secular change must yet include sorting out possible systematic biases in the data.

Comparing the OGO survey measurements with previously derived extrapolations based on earlier data makes it clear that to adequately follow the secular change irregularities the satellite surveys need to be repeated at frequent intervals. These results indicate that a hiatus in measurements of more than a year could lead to errors at the earth's surface exceeding 1000γ.

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THE SURVEY WITH COSMOS-49

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The geomagnetic survey with the satellite COSMOS-49 was carried out in accord with the international program of the World Magnetic Survey [*Dolginov et al.,* 1965]. The satellite was launched into an orbit with inclination 49°, perigee 260 km, and apogee 490 km. The orbit precessed westward at a rate of 4.5° per day; orbits (i) and (i + 77) had data points with similar latitude and longitude coordinates.

The measurements were made each 32.76 seconds during the interval October 24 to November 6 in 1964, a magnetically quiet period [*Dolginov et al.*, 1966] as shown by the values of the planetary index Kp:

October	24	25	26	27	28	29	30	31
Kp	8+	8o	23	13	10o	13	6o	3o

November	1	2	3
Kp	20+	19o	8o

A memory unit permitted sampling over a relatively large number of satellite positions, whose projections covered about 75% of the earth's surface.

The magnetometers and associated circuitry are discussed in detail in the publication by *Dolginov et al.* [1965], from which we extract some of the major characteristics on the nature of and errors in the measurements.

Two proton precession magnetometers were orthogonally mounted in the satellite which had no means for sustaining a specific orientation. For the region measured, the magnetometer frequency varied between 850 and 2100 Hz and its value was stored in the form of a coded number. It is well known that scalar intensities with the good accuracy of about 1γ are obtainable with proton magnetometers under conditions of good signal-to-noise ratios, conditions that among other factors depend on the orientation of the sensor axis with respect to the geomagnetic field. To enhance the signal-to-noise ratios a narrow-band amplifier and automatic range switching were employed. During part of the free nuclear precession period the circuitry seeks and analyzes the optimum signal that, if large enough, interrupts the search, at which time the precession frequency is measured. For each measurement the position for the optimum is remembered and forms the starting point for the next sequence. If a sensor is unfavorably oriented, the signal has low quality, no measurements are normally taken, and the frequency meter shows zero reading.

Ground measurements showed that an accuracy of about 2γ was achievable with the sensor axis at 45° to the field and with the use of the electronics to pick the optimum range out of the 11 available. This limit relates to the following: (1) The PM-4 magnetometer measured the number N of impulses of a quartz oscillator for a time T which equalled the interval for 512 cycles of the nuclear precession, not for the 1024 cycles common for ground magnetometers. With satellite data, an increase in T cannot increase the accuracy of the measurements. (2) The time of measurement was unknown to within the search-time period, which varied from 0 to 0.65 second, for finding the optimum range.

The sequence of operation is as follows. On command from an accurate program-timing device aboard the satellite, polarization current is applied to the one magnetometer for $t_1 = 1.92$ seconds and then the sensor coil is connected to the amplifier input. After a delay of $t_2 = 0.18$ second, the search for the optimum range begins and lasts for $0 \leqq t_3 \leqq 0.65$ second, depending on the field intensity and the previous reading. The frequency measurement occurs in a period between 0.24 and 0.6 second, depending on the field value, and is then kept for 8 seconds, the time needed for recording by the on-board memory device. The second magnetometer starts operating 32.76 seconds after the first one started and follows the sequence earlier discussed. Time marks are made by the satellite program-timing device and subsequently correlated with time markers registered on the ground during the telemetering of satellite data. The time of the measurement is uncertain to ±0.5 second.

The magnetometers are mounted 3.3 meters from the center of the satellite, whose magnetic effects are compensated to an accuracy of 2γ by an array of permanent magnets producing a homogeneous compensating field at the sensor locations. The effectiveness of the compensation was checked in preflight tests by rotating the satellite around horizontal and vertical axes, motions that produced no modulations of the satellite magnetometer outputs, and by tests wherein the satellite was moved translationally with respect to a special fixed magnetometer.

In addition to the uncertainty of ±0.5 second earlier discussed, errors in satellite position existed that could reach 3 km in the direction of the flight path and 1 km in altitude as well as in the direction of the normal to the satellite orbit. Random errors due to unfavorable orientation of one of the magnetometer sensors were rejected at the first stage of the data processing through comparison of the field gradients measured by each magnetometer.

The most effective means of control in data processing appeared to be comparing ΔF values, in the measured field intensity minus the computed one, at the "repeated" revolutions i and i+77 [*Dolginov et al.,* 1966]. The values $\delta F = \Delta F_i - \Delta F_{i+77}$ could differ from zero for any of the following causes: orbit errors, different levels of magnetic activity, phase difference due to the diurnal variation, inaccuracy of computed field, and random errors of measurement. The statistics of the δF's for all the repeated revolutions show that the mean δF equals ≈ 30γ; thus, any real field could differ from that measured by at least $\delta F/2$ or ~15γ [*Dolginov et al.,* 1966]. Quiet-day effects due to external sources such as trapped particles and magnetopause currents produce fields estimated to be 10 - 20γ at the satellite altitude. Thus, δF may reach 25 - 30γ, values that may be considered as characteristic of the total error with which COSMOS-49 surveyed the field due to internal sources.

The usable scalar intensity values totaled 18,000 and were published in catalogue form [*Dolginov et al.,* 1967] where the entries include Moscow time, satellite coordinates, measured and computed intensities, and the difference ΔF. The computed field was obtained from a set of spherical harmonics with 48 coefficients, up to n = m = 6, based on the analysis of the U.S.S.R. World Magnetic Charts of 1960 and incorporating the effects of the secular variation manifest in the first three harmonics.

From an examination of the ΔF's, *Adam et al.,* [1967] found the following:

a. Harmonic analysis of the 1960 World Charts did not take into account the earth's oblateness; thus, resultant errors in the g_1^0 and g_3^0 coefficients could produce errors of about 100γ in the computed field value.

b. Large ΔF values occur over ocean areas, just where the charts were less reliable.

c. Fourier analysis confirmed the predominance of low over high harmonics in the ΔF field. Consequently, spherical harmonic expansions based on the accurate and evenly distributed satellite data, made within a relatively short period of time, should be improvements over those using results from ground surveys.

The satellite data were made within a relatively small range of altitude and could be reduced to a common altitude of, say 400 km, using the vertical gradients [*Dolginov et al.,* 1967]. These reduced F values were used to compile a "residual field chart"—F measured minus F dipole due to uniform magnetization. The chart clearly illustrated that at 400 km the residual field maintained the inherent features of the surface field: epicenters of global anomalies and regions of high gradients maintained their respective geographical positions. The invariability with altitude of the epicenter position justifies approximating the field by a number of radial dipoles. The single minimum of the Brazilian anomaly was investigated by *Konovalova et al.* [1967] using COSMOS-49 data and by Dr. J. C. Cain and colleagues using the GSFC 12/66-1 analytical field model, with both approaches yielding similar values for the position and magnitude of the minimum:

Konovalova et al.	23°S	47.5°W	20,100 - 20,300γ
Cain	23.3°S	47.5°W	20,190γ

The satellite data were subjected to spherical harmonic analysis using an iterative method for computing the coefficients [*Tyurmina,* 1968; *Osipov et al.,* 1967; *Tyurmina and Cherevko,* 1967a,b]. The oblateness of the earth was taken into account (flattening f = 0.00335238918; equatorial radius a = 6378.178 km) and 99 coefficients were determined (up to n = m = 9) in each of four separate analyses with each analysis based on an independent set of 4000 values of the scalar intensity. The analytic model labeled "IZMIRAN" was the mean of these four sets and fit the COSMOS-49 data to an rms of 22γ.

To investigate possible sources of the field values where $\Delta F = F(\text{COSMOS}) - F(\text{IZMIRAN}) > 60\gamma$, or thrice the rms error, the ΔF's at revolutions (i) and (i+77) were examined, with ΔF in this case the observed value minus the value computed by the IZMIRAN model. The examination showed the following:

a. These ΔF's are not connected with geographic position, as they varied between revolution (i) and (i+77); and thus are not due to sources of origin internal to the earth.

b. It would be difficult to construct an external source to produce ΔF's of such magnitude.

c. It appears that these ΔF's are probably related to erroneous field values obtained when signal-to-noise ratios are below the threshold value [*Dolginov et al.,* 1965]. These values are to be rejected.

Kolomiytseva et al. [1968] investigated the use of satellite data to improve the value of the secular variation and concluded that improvements are possible if effects of transient variations and surface anomalies are eliminated.

To check the reliability of the IZMIRAN model for removing trend or representing the "normal field," computed values were compared with surface observations which included those from the *Zarya* surveys. The anomalous field patterns remaining after subtracting the model field contain a background residual with a wavelength spanning about 30° and amplitude 100 - 200γ. This residual could be approximated by a harmonic of order 10 [*Benkova et al.*, 1970].

Investigation of the COSMOS-49 data led to some suggestions regarding field sources located externally to the earth. Analysis of values of $\delta F = |\Delta F_i| - |\Delta F_{i+77}|$ for the subequatorial region revealed the existence of a source of a uniform field and located above the satellite apogee; and sources at the satellite altitudes. *Dolginov et al.* [1966] discussed the possible contribution of the fields of the equatorial electrojet and of currents in the ionospheric F-2 layer.

From the results of four different analyses using data measured on different days and using values of horizontal component of intensity at the surface, comparisons of values of g_1^0, ΔF, and the horizontal component show that even on magnetically quiet days, some influences of external sources exist. These external sources could be identified with the permanently existing ring current.

The following definitions apply to the quantities in Table 1:

$\Delta g_1^0 = g_1^0 - \bar{g}_1^0$ where $\bar{g}_1^0$ is the mean value for the four analyses.

ΔF′ = algebraic mean difference between F measured and F computed with IZMIRAN model.

ΔH = difference between absolute value of H averaged over the whole period of satellite measurements minus those averaged over the interval for each analysis.

TABLE 1

COMPARISON OF VALUES DETERMINED IN VARIOUS ANALYSES [*Tyurmina,* 1968]

Analysis Number	*1*	*2*	*3*	*4*
Period Covered	*0400 Oct 24 - 1200 Oct 26*	*1200 Oct 26 - 1800 Oct 28*	*1800 Oct 28 - 0500 Oct 31*	*0500 Oct 31 - 1000 Nov 3*
Δg_1^0, γ	+30	−83	+12	+45
ΔF′, γ	+3	−3	−1.5	+1.5
ΔH, γ	+8.5	−7.5	−4	+4

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SATELLITE 1964 83C

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Satellite 1964 83C was launched on December 13, 1964, into an orbit with inclination 89.992°, period 106.2 minutes, perigee 1040 km, and apogee 1089 km. The satellite contains a rubidium-85 vapor magnetometer produced by Varian Associates of Palo Alto, California, a permanent Alnico V magnet with moment 1.475×10^5 gauss cm³, and a calibration magnet of moment 6.85×10^3 gauss cm³.

The satellite is magnetically stabilized; that is, geomagnetic torques align the magnetic axis of the satellite along the local field direction. The optical axis of the magnetometer sense head makes an angle of 45° with the satellite magnetic axis so that data are potentially receivable (1) at the maximum signal-to-noise ratio and (2) throughout the orbit with only one magnetometer. The head attaches near the end of a gas-actuated, telescoping boom, which is manufactured by the Raymond Engineering Laboratories of Middletown, Connecticut, and is used as an antenna on Project Mercury capsules. When fully extended, the boom length is 4.88×10^2 cm (16 ft). *Radford* [1967] and *Zmuda et al.* [1968a] give additional characteristics of the satellite.

The satellite telemetered a total of 350,000 usable data points to a network of 16 stations from those in the following groups: TRANET, Atlantic and Pacific Missile Range, and NASA STADAN. Power and voltage limitations confined the data periods inside the intervals December 13 - 31, 1964, and April 10 to June 26, 1965, and relatedly to the local time epochs 0300 - 0800 and 1500 - 2000. Observations exist for four storms, a mixture of smaller disturbances, and undisturbed conditions. The data refer to middle and low latitudes since a design shortcoming precluded meaningful observations for higher latitudes. The nonstorm-time data were used by *Heuring et al.* [1968] and *Zmuda and Heuring* (see paper in this book) to evaluate harmonic coefficients for the International Geomagnetic Reference Field (IGRF), and by *Zmuda et al.* [1968b] to plot the isodynamic contours. *Zmuda et al.* [1968a] also considered storm-time variations and *Zmuda et al.* [1968b] compared quiet-time surface and satellite field changes.

For a fixed latitude, the observations lie within the geocentric radial range 7405 and 7465 km and within a set of narrow longitudinal bands. The data distribution permits an easy computation of spatial gradients and a reduction to a single geocentric distance, which equals 7450 km for the lines of constant magnetic intensity shown in Fig. 1. With the earth's surface as a spheroid of semimajor axis 6378.4 km and flattening 1/297, the geocentric distance of 7450 km corresponds to a height above the surface in the range, for example, from 1072 km at 0° latitude to 1077 km at 30°. In the area called the South Atlantic (or Brazilian, or South American) magnetic anomaly, many of the lines form either closed loops or segments of what would probably become a closed loop, with the center (a field minimum) of the entire system at about 20°S and 45°W, slightly different from the center at 350 and 450 km ($\approx$ 23°S and $\approx$ 47°W) determined by *Konovalova and Nalivayko* [1967] with COSMOS-26 and -49 data.

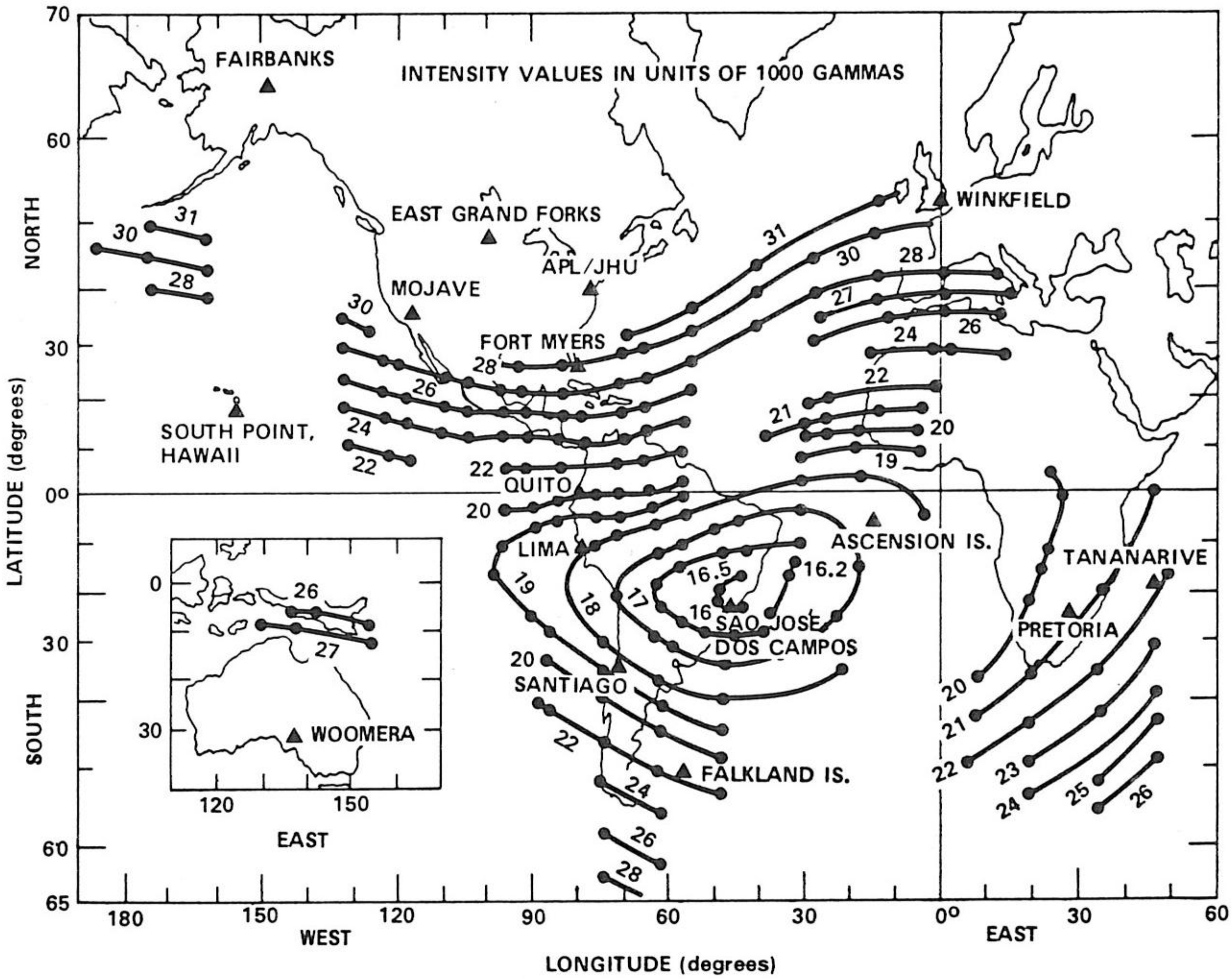

Fig. 1. Isodynamic Lines at a Geocentric Distance of 7450 km with the Intensity Values in Units of 1000 Gammas and the Locations of the Ground Stations.

We agree with Konovalova and Nalivayko that a single minimum exists in the anomaly, in opposition to the double minimum at 1000 km reported in a preliminary study by *Muzzio et al.* [1966], using a combination of electron gyrofrequency resonances and magnetic data.

Figures 2a and 2b show the differences, or residuals, between the observed scalar intensity, F_G, and that computed, F_T, for a number of satellite passes relevant to the magnetic storm of 1312 UT April 17, 1965. Figure 3 shows the Dst(H) values for this storm and the times of the satellite passes. With respect to the data in Fig. 2, the residuals have a latitudinal variation indicative of errors in a few harmonic coefficients. Note, however, that each storm-time (recovery-phase) group of ΔF values lies considerably below its quiet-time counterpart. This lowering results from a decrease in the total geomagnetic intensity (F_g), owing primarily to the superposition of an oppositely directed horizontal storm-field on the main geomagnetic field, considering the changes detectable with a scalar magnetometer and the direction of the main field in the equatorial region.

The storm-time decrease reaches -46γ for the pass of 1644 UT, April 19 and -60γ for that of 2351 UT, April 19, where there also are temporal variations near the dipole equator and where each of these passes is considered with respect to its non-storm-time complement. These diminutions compare favorably with those of (surface) Dst(H) for corresponding times, -47 and -56γ, respectively (see Fig. 3), and the similarity shows that the storm ring current lies considerably above the satellite position,

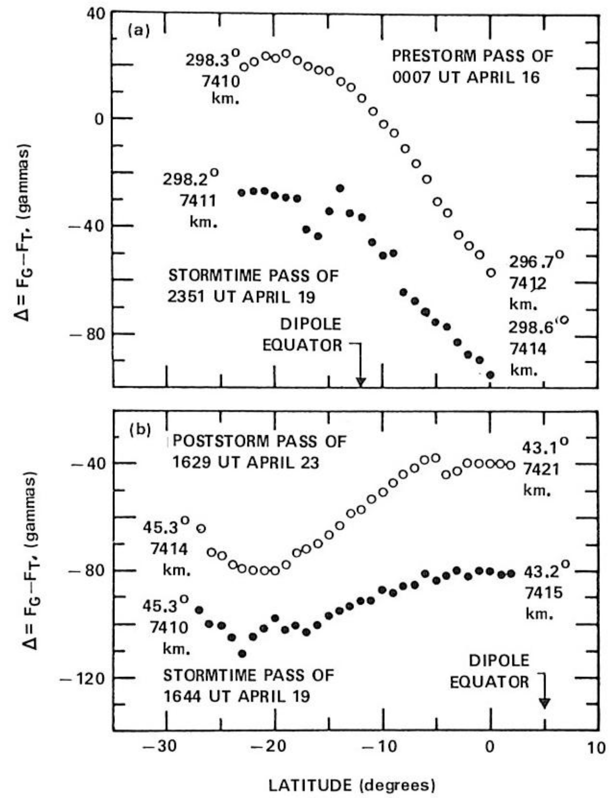

Fig. 2. The Field Residuals for Storm-Time and Nonstorm-Time Passes. The Longitude and Altitude of Each End Point are Also Noted.

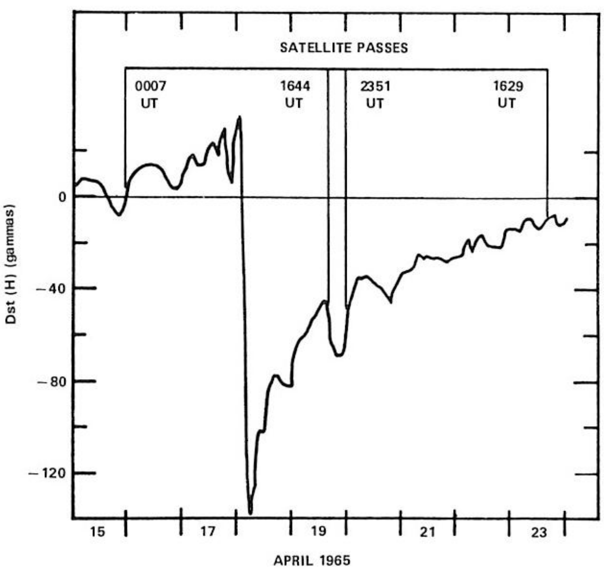

Fig. 3. Dst(H) Values for the Storm of 1312 UT, April 17, 1965, and the Times of Some Low-Latitude Passes of Satellite 1964 83C.

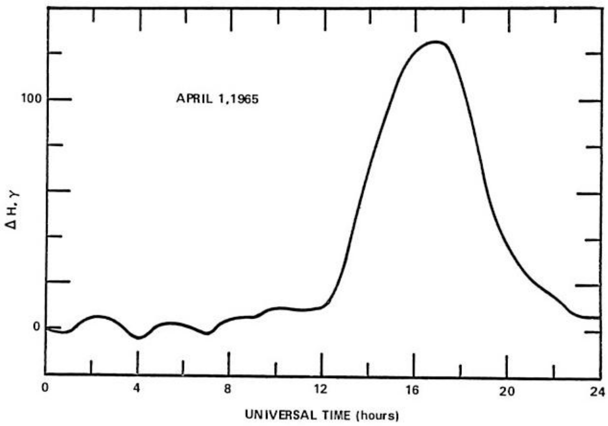

Fig. 4. An Example of the Diurnal Variation of the Horizontal Component at Huancayo, Peru.

which at the equator has a value of McIlwain's shell parameter L = 1.17. Thus, our data are in accord with but also add a little to one of *Cahill's* [1966] findings for this storm: that the ring current during the recovery phase has its maximum on the McIlwain shell parameter L = 3.5 with reduced effects down to at least L = 2.

In relation to the data in Fig. 2a, we examined the magnetograms for Huancayo, Peru, at the dipole equator and at 22°07′S and 65°35′W, geographic. For the period between the satellite equatorial passages, the Huancayo decrease in the horizontal component equalled -45γ, practically that (-42γ) in F at the equator at the satellite altitude. Thus, in this case, at 1944 local time, the evening ionosphere below the satellite has essentially no effect on the disturbance field in the recovery phase of the storm.

Quiet-time field changes observed at the satellite altitude (~ 1100 km) were correlated with field changes observed at the Huancayo, Peru, observatory. Figure 4 shows an example of the well known diurnal variation of the horizontal component of intensity, normalized to the value at 00 UT. The satellite data used for comparisons were obtained (1) while the satellite was within 0.03° in latitude and 4° in longitude of Huancayo, and (2) within the time periods 2100–2400 UT and 0000–0400 UT, periods well removed from that normally associated with the equatorial electrojet.

Though there is a spread in the satellite observations, the trend is clear that field changes at 1100 km altitude are comparable to those occurring at the surface, as shown in Fig. 5a, with the fit improved if

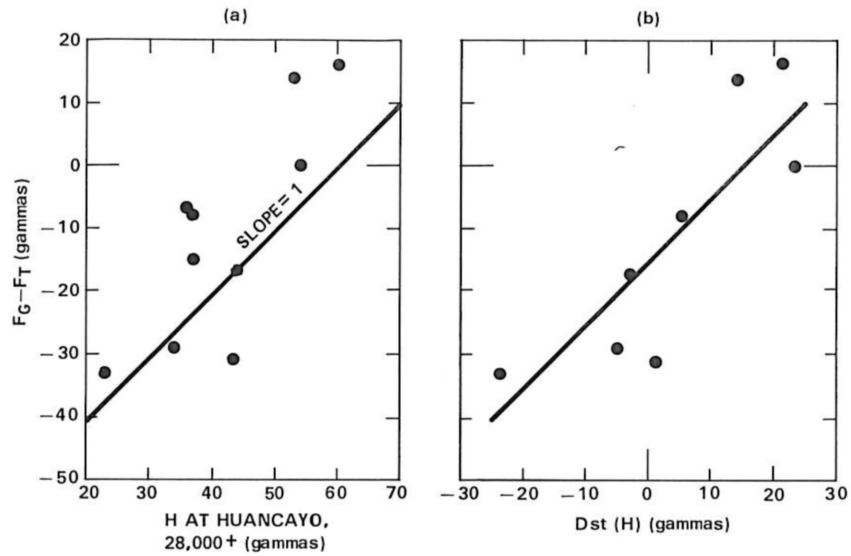

Fig. 5. Comparison between Field Changes Observed at 1100 km Altitude and at the Earth's Surface.

the Dst(H) values averaged over 2.5 minute intervals are used, as in Fig. 5b. In both cases, the satellite and surface field changes are both due to field sources above the satellite altitude of 1100 km.

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RESULTS OF MAGNETIC SURVEYS OF THE MAGNETOSPHERE AND ADJACENT REGIONS*

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Introduction

The continuous plasma flow in the solar wind confines the geomagnetic field in a limited volume of space surrounding the earth. This region is called the magnetosphere because the magnetic field, to a large extent, controls the behavior of the charged particles contained therein. The outer boundary of the magnetosphere is termed the magnetopause. The solar wind carries with it a magnetic field, and the velocity of its flow exceeds that of a magnetosonic wave in the medium, thus creating a detached bow shock ahead of the magnetopause as in a supersonic flow of a fluid in the presence of a blunt body. The region between the bow shock and the magnetopause

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is referred to as the magnetosheath, or the transition region, in which the plasma flow and the magnetic field contain varying degrees of irregularity. The confinement of the geomagnetic field in the magnetosphere results in a distortion of the geomagnetic field, and the interaction between the solar wind and the geomagnetic field leads to a formation of a long geomagnetic tail. These two consequences of the solar wind necessitate an extensive magnetic survey by spacecraft. The past several years have witnessed significant advancements in the exploration of this type. The major features of the achievements in this field are summarized in the present brief review.

Observations of the magnetopause, the bow shock, the magnetosheath, and the tail are discussed in this paper. Results of a recent study of the OGO 1 and 3 satellite data taken in the near tail region, the magnetic field disturbances observed in the magnetosphere, and brief acounts of quantitative models of the magnetosphere are also given. The magnetic field structures in the magnetosphere are largely determined by the mutual interactions between the plasmas and the magnetic field, and hence the effects of plasmas are discussed wherever appropriate, though the paper is primarily concerned with the magnetic observations. It is mentioned here that the scope of the present review is limited mostly, if not entirely, to the results obtained by workers in the United States.

The Magnetopause

Early measurements aboard Pioneers 1 and 5 indicated a termination of the earth's magnetic field beyond some distance from earth [*Sonett et al.*, 1960; *Coleman et al.*, 1960a, b], but because of the incompleteness of the measurements neither the magnetopause nor the bow shock was identified. The first definitive identification of the magnetopause on the basis of the magnetic field and plasma measurements was made by Explorer 10 launched in March 1961, on the evening side near the meridian of 21 hours local time [*Heppner et al.*, 1963; *Bonetti et al.*, 1963]. The observation showed that the magnetopause flares out on the evening side. Explorers 12 and 14 mapped the magnetopause from near the noon meridian to the dawn flank, and the observations indicated a similar flaring-out of the magnetopause on the dawn side [*Cahill and Amazeen,* 1963; *Cahill*, 1964a, b]. Observations by Explorer 18, launched in November 1963, identified the standing bow shock several earth radii upstream from the magnetopause [*Ness et al.,* 1964]. The existence of such a (collision-free) shock had been predicted theoretically by *Zhigulev* [1959], *Zhigulev and Romishevshii* [1960], *Axford* [1962], and *Kellogg* [1962].

Complete identifications of the magnetopause and the bow shock require observations of certain characteristics both in the magnetic field and plasma: for the magnetopause, a discontinuity in the magnetic field and the absence of streaming (solar wind) ions inside the discontinuity; and for the bow shock, a discontinuity both in the magnetic field and in the flux of the solar wind plasma. However, under normal conditions an observation of either the magnetic field or the plasma often suffices to locate the magnetopause or the bow shock. An abrupt termination of the quasi-trapped particles has also been used to identify the magnetopause. Recent studies of crossings of the magnetopause and the bow shock based primarily on magnetic field observations include those made with the data from Explorer 12 [*Cahill and Patel,* 1967], Explorer 18 [*Ness et al.,* 1964; *Ness,* 1965], Explorer 21 [*Fairfield and Ness,* 1967], Explorer 28 [*Ness,* 1967], OGO 1 [*Holzer et al.,* 1966; *Heppner et al.,* 1967], and Explorer 33 [*Behannon,* 1968]; more data are being accumulated by OGO 3 and 5 and other satellites. Determinations based on plasma and/or energetic particle measurements have been made on Explorer 12 [*Freeman et al.,* 1963], Explorer 18 [*Bridge et al.,* 1965; *Wolfe et al.*, 1966], Vela 2A and 2B [*Gosling et al.,* 1967], and OGO 1 and 3 [*Vasyliunas,* 1968]. In particular, *Gosling et al.* [1967] have made a detailed statistical study of the positions of the magnetopause and the bow shock by the Vela satellites at about 17 R_e (earth radii) and at ecliptic latitudes up to $\pm 63°$.

Summarizing these observations the following general remarks are made concerning the positions of the magnetopause and the bow shock. The average shapes and positions of the magnetopause and the bow shock are in general agreement with theoretical results based on gas dynamical models [*Ness,* 1967; *Heppner et al.,* 1967; *Gosling et al.,* 1967]; for theoretical models see *Spreiter and Briggs* [1962a, b], *Midgley and Davis* [1963], *Mead and Beard* [1964], *Mead* [1964], *Spreiter et al.* [1966], and *Dryer and Faye-Petersen* [1966]. The magnetopause and the bow shock are frequently in motion, often resulting in multiple crossings by a satellite on any one orbit [*Holzer et al.,* 1966; *Heppner et al.,* 1967; *Gosling et al.,* 1967]. There appears to be an east-west asymmetry in the average shapes of the magnetopause and the bow shock; the line with respect to which these shapes are symmetric deviates from the earth-sun line toward west by 2 to 4° This tilt is roughly in agreement with that expected from the aberration of the solar wind flow direction due to the earth's orbital motion about the sun [*Gosling et al.,* 1967]. Since geomagnetic activity as expressed by Kp is related to the solar wind [*Snyder et al.,* 1963], a question immediately arises as to whether or not the position of the magnetopause is related to magnetic activity. The answer to this question has been given in both affirmative [*Gosling et al.,* 1967] and negative [*Patel and Dessler,* 1966; *Heppner et al.,* 1967]. This is due to the circumstance that the position of the magnetopause at any instant of time depends in a complex way on a number of parameters both in the solar wind and in the magnetosphere, beside the most obvious dependence on the solar wind velocity. The magnetic pressure in the (magnetosheath) solar wind and the nonuniform plasma pressure inside the magnetosphere are examples of the factors that are likely to contribute significantly in determining the position of the magnetopause. Thus, though the average position of the magnetopause is related to magnetic activity as has been reported by *Gosling et al.* [1967], its instantaneous position is not always related to magnetic activity. However, there are cases such as times of sudden commencements or sudden impulses in which the solar wind pressure changes abruptly, and, therefore, a corresponding adjustment of the magnetopause position is obviously expected [*Heppner et al.,* 1967; *Gosling et al.,* 1967].

Figure 1 shows the magnetopause and bow shock encounters by the OGO 1 satellite; the positions are projected onto the solar ecliptic plane by rotating the radial distances along circles in earth-centered solar-ecliptic meridian planes. The plotted crossing points

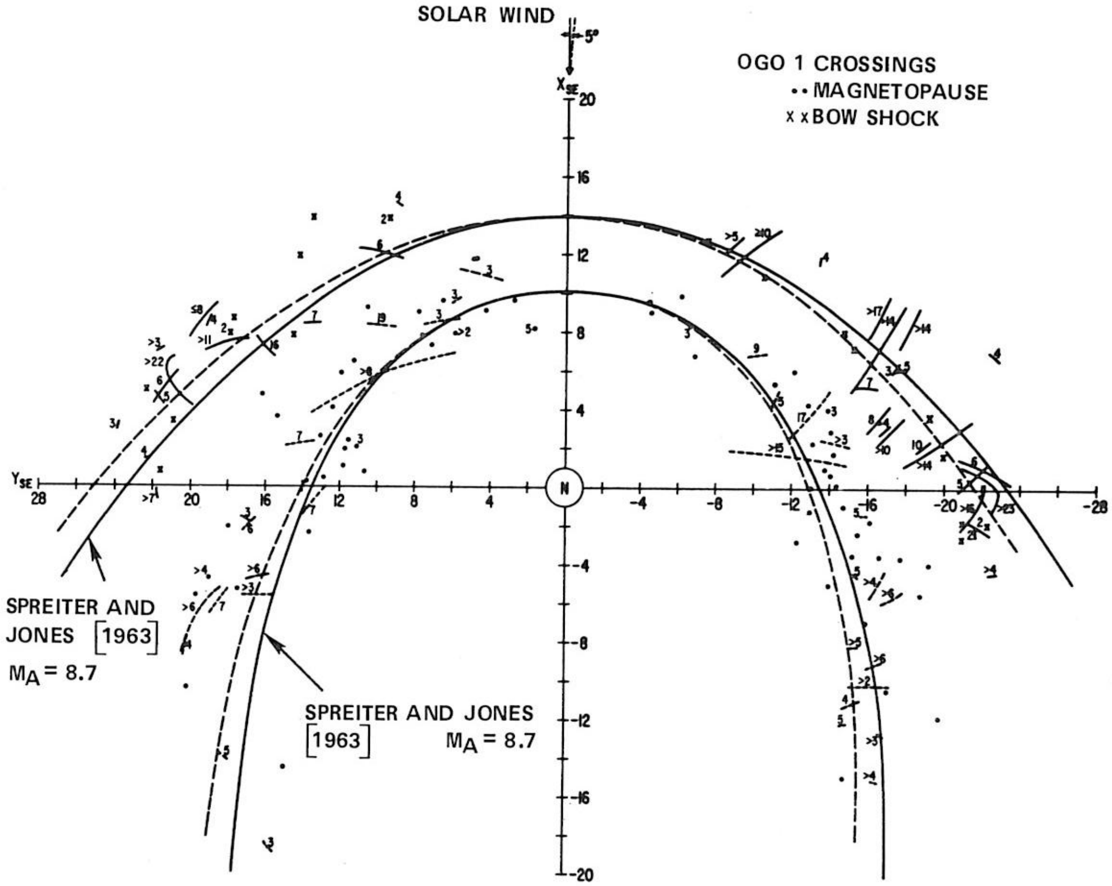

Fig. 1. The Magnetopause and Bow Shock Encounters by the OGO 1 Satellite. The Positions are Projected onto the Solar Ecliptic Plane by Rotating the Radial Distances along Circles in Ecliptic Meridian Planes. The Solid Curves Represent the Magnetopause and Bow Shock Positions Calculated by Spreiter and Jones [1963]. To Take into Account the Average Aberration Angle of 5°, the Solid Curves are Rotated about the Earth by 5° to Produce the Dashed Curves.

are corrected for variations in the geomagnetic latitude χ_{ss} of the subsolar point, using an expansion factor $K = (1 + 3 \sin^2 \chi_{ss})^{1/6}$; see *Ness et al.* [1964] for the meaning of this factor.

A magnetopause crossing typically involves a time scale of about one minute, but because of the motion of the magnetopause the crossing time can be considerably shorter. Although it is not possible to determine the thickness of the magnetopause from a traversal by one satellite, a study of numerous crossings by OGO 1 indicates that the thickness must be of the order of 100 km under normal conditions; this scale length is nearly the cyclotron radius of the ions in the average solar wind [*Heppner et al.,* 1967]. At the magnetopause the solar wind particles are reflected away by the combined effects of the Lorentz force and the polarization electric field; the latter is created because of the larger mass-charge ratio for the protons than for the electrons. If the initial velocities of the ions and electrons in the solar wind are equal and unidirectional, the thickness of the boundary layer is of the order of the characteristic electron cyclotron radius, c/ω_{pe}, where c is the velocity of light and ω_{pe} $(= \sqrt{4\pi e^2 n_e / m_e}$ where e, m_e, and n_e are the charge, mass, and number density of the electrons, respectively); ω_{pe} is the electron plasma frequency [*Ferraro,* 1952]. If the electron density is 1 to 10 cm^{-3}, this scale length is 5.3 to 1.7 km, which is shorter than the value estimated from the observations by one or two orders of magnitude. This seems to mean that the electrostatic field in the boundary layer is short-circuited by the thermalized electrons. According to the OGO 1 and 3 observations, the magnetic field transition from the magnetosphere to the magnetosheath is sometimes smooth, but at other times involves considerable irregularity. Under normal conditions, changes in the magnitude and the direction of the magnetic field characterize the transition. At times the transition takes an exceptionally long interval of time during which the magnetic field magnitude changes rather gradually but with irregularities superimposed on the gradual change. *Gosling et al.* [1967] have reported that there are magnetopause traverses in which the magnetosheath solar wind "gradually builds up or fades away over a rather long period." *Sonnerup and Cahill* [1967] have studied the Explorer 12 magnetopause crossings and have shown that the magnetopause is generally a tangential discontinuity, that is, a discontinuity in which the magnetic field component normal to the discontinuity surface is zero. However, they have found a few cases in which the normal component was substantial; in these cases the magnetopause is a rotational discontinuity. Recently *Aggson et al.* [1968] have observed large electric field fluctuations in a wide range of frequencies below several hundred Hz in the magnetopause; whether or not there exist large electrostatic fields there is not certain. In summary, the structure of the magnetopause and the precise nature of the interaction between the solar wind and the magnetosphere are not as yet known.

The Bow Shock

Observations of the bow shock positions have been mentioned in the preceding section. According to the OGO 1 results, the time involved in crossing the shock is generally 1 to 10 sec. Movements of the shock appear to be more frequent and with greater speed than those of the magnetopause. With the OGO 1 observations the average velocity of the shock has been estimated to be a few to 10 km/sec and the average amplitude of the oscillation to be a few thousand km; these statistical estimates are based on an idealized model in which the shock oscillates between two extreme positions with a constant velocity [*Heppner et al.,* 1967]. Similar estimates have been given by *Holzer et al.* [1966] on the basis of their observation of AC magnetic fields.

At the shock and in its vicinity, coherent waves of frequencies near 1 Hz and irregular fluctuations of frequencies greater than several Hz are often observed in the magnetic field [*Heppner et al.,* 1967]. Recent electric field observations on OGO 5 by *Aggson et al.* [1968] are consistent with the earlier interpretation that waves near 1 Hz are wave packets generated in the shock and propagating upstream in the solar wind in the whistler mode [*Heppner et al.,* 1967]. The mechanisms of the generation of these coherent waves and irregular fluctuations are not as yet understood. The structure of a collision-free shock has been a subject of intensive study by plasma physicists, and several theoretical models have been promulgated [*Fishman et al.,* 1960; *Auer et al.,* 1962; *Camac et al.,* 1962; *Kellogg,* 1964; *Tidman,* 1967; *Kennel and Sagdeev,* 1967a, b]. However, neither the observations nor the theories appear to be adequate to clarify the physical picture of the magnetosphere bow shock.

The Magnetosheath

The region between the bow shock and the magnetopause is called the magnetosheath or the transition region. Observations of the magnetic field behaviors in this region have been made extensively [*Cahill and Amazeen,* 1963; *Ness et al.,* 1964;

Coleman, 1964; *Holzer et al.,* 1966; *Siscoe et al.,* 1967; *Heppner et al.,* 1967]. The magnetic field in the magnetosheath is generally characterized by the predominance of irregularities. The degree of irregularity, however, varies considerably in different regions of the magnetosheath and at different times. Observed field fluctuations have periods, in spacecraft reference frames, from a fraction of one second to several minutes or even longer. Average power spectral densities have been estimated [*Holzer et al.,* 1966; *Siscoe et al.,* 1967], but their generality has not been adequately tested. Interpretations of such power spectra are difficult since spatial field irregularities convected by the magnetosheath solar wind (to be mentioned below) cannot be distinguished from temporal fluctuations generated in the magnetosheath. Although the magnetosheath field can be generally characterized by the presence of irregularities, there are times when the magnetic field is so quiet and steady that without plasma data it is difficult to identify that region with certainty; examples of such cases have been found in the OGO 1 and 3 observations.

By simultaneous observations on two satellites in interplanetary space, identifiable signatures in the magnetic field have been found to be convected downstream by the solar wind plasma, indicating that the magnetic field is "frozen" in the plasma; this feature has been demonstrated with the observations by Explorer 28 and Pioneer 6 [*Ness,* 1966] and by Explorers 18 and 21 [*Fairfield,* 1967]. It has been shown further that the interplanetary magnetic fields are convected into the magnetosheath and wrap around the magnetosphere, the lines of magnetic force tending to align themselves tangent to the magnetopause [*Fairfield and Ness,* 1967; *Fairfield,* 1967]. It thus appears that the background magnetic field in the magnetosheath is essentially ordered as in interplanetary space and that irregular fields are generated in the magnetosheath and are superimposed on the ordered field. This picture is in general agreement with the theoretical results using gas dynamical models [*Dryer and Faye-Petersen,* 1966; *Spreiter et al.,* 1966; *Alksne,* 1967].

The Magnetosphere Tail

The Explorer 10 magnetic observations made in 1961 showed that the earth's magnetic field at large distances was greatly distorted on the night side, being stretched out and, below the ecliptic plane, pointing away from the earth [*Heppner et al.,* 1963]. Observations by Explorer 14 indicated in 1962 that the direction of the earth's magnetic field was predominantly away from the earth beyond some distance to apogee at 16.5 R_e near the midnight meridian [*Cahill,* 1964b, 1966a]. The Explorer 18 observation, made in 1965, provided a detailed mapping of the magnetic field of the magnetosphere tail [*Ness,* 1965]. An important aspect of this observation is the finding of a sheet-like region, near the solar ecliptic plane, in which the magnetic field magnitude is extremely small and often near zero. This region has frequently been referred to as the neutral sheet, and across the neutral sheet the magnetic field direction is nearly reversed. *Speiser and Ness* [1967] have studied the magnetic field near the neutral sheet and deduced an equivalent current system in the neutral sheet. The Explorer 33 data have shown that the tail extends to at least 80 R_e in a well defined form [*Ness et al.,* 1967; *Behannon,* 1968; *Mikalov et al.,* 1968]. The observations on Pioneer 7 have indicated that the tail may extend to 1000 R_e [*Ness et al.,* 1967; *Fairfield,* 1968a]. *Wolfe et al.* [1967] described their plasma observations at these large distances by Pioneer 7 as a "wake" because of the lack of a well developed, steady feature.

Increases in the tail field observed by Explorer 18 during periods of high geomagnetic activity were interpreted as being an indication that additional field lines are transferred from the magnetosphere proper to the tail [*Behannon and Ness,* 1966]. With the magnetic field observations from three satellites, OGO 1 located deep in the tail and Explorer 28 and Explorer 33 both situated outside the bow shock, evidence for such a transfer of an additional magnetic flux to the tail at the time of a sudden commencement has been presented [*Sugiura et al.,* 1968a]; here the Explorer 28 and Explorer 33 observations provided the position of the interplanetary discontinuity (responsible for the sudden commencement) outside the magnetosphere, and OGO 1 observed a magnetic field increase in the tail before the interplanetary discontinuity reached this distance behind the earth. According to the energetic electron ($\geqq$ 280 kev) observations on the APL satellite 1963 38C, the low-altitude, high-latitude electron trapping boundary in the midnight meridian collapses toward lower latitudes simultaneously with an increase in the tail field observed by Explorer 18, and these observations have been interpreted as being due to the flux transfer [*Williams and Ness,* 1966]. Thus the magnetic field in the tail is directly related to the solar wind compression of the magnetosphere.

The neutral sheet region as defined by magnetic observations is thin, being only a fraction of one earth radius [*Ness,* 1967]. The existence of this region of weak magnetic field implies a presence of plasmas with sufficient density. Early observations of electrons by *Gringauz et al.* [1960a, b], *Freeman* [1964], *Frank* [1965], and *Vernov et al.* [1966] are, retrospectively, suggestive of the existence of an equatorial plasma sheet. The observations by the Vela satellites of electrons and protons with energies greater than 100 ev in the tail have now established the existence of such a plasma sheet across the tail [*Bame et al.,* 1966, 1967]. According to the Vela observations, the electrons in the plasma sheet typically have a broad, quasi-thermal energy spectrum, peaked anywhere between a few hundred ev and a few kev, with a non-Maxwellian high-energy tail. The thickness of the plasma sheath in the tail is 4 to 6 R_e at the distance of $\sim$17 R_e, and the sheet flares out to about twice that thickness toward the dawn and dusk boundaries. Recent plasma observations by *Vasyliunas* [1968] and *Frank* [1967a, b] on OGO satellites have shown that the nightside plasma sheet extends well into a magnetosphere from the flanks to the front side.

The Near Tail Region

While the overall shape of the magnetosphere is determined by the pressure balance between the earth's magnetic field and the solar wind, the magnetic field structure inside the magnetosphere, in particular, at geocentric distances beyond several earth radii is, to a great extent, dependent on the plasmas in the magnetosphere. Behaviors of the plasmas in the near tail region appear to play an important role in the dynamics of the magnetosphere and in high-altitude disturbance phenomena. The term "near tail region" is used here to refer to the region near the (earthward) tip of the plasma sheet where the ratio, β, of the plasma kinetic energy density to the magnetic field energy density is nearly unity or greater. The following discussions on the magnetic field structure in the near tail region are mainly based on the OGO 1 and 3 observations.

Figure 2 shows an example of the variation in the magnitude, B, of the magnetic field along an inbound orbit of OGO 3, covering distances from about 16 to 6 R_e. This figure (as well as Fig. 3) also shows the magnetic index Kp, the McIlwain L-shell parameter, the local time of the subsatellite position, and the geomagnetic, or dipole, latitude. The steady field from beyond 16 R_e to about 11.3 R_e is the tail field under relatively quiet conditions. The steady field is abruptly terminated by a sudden decrease in B and is followed by a region of irregular field. Sudden changes and irregularities in the magnetic field in the near tail region, shown in Fig. 2, are generally not associated with any notable magnetic variations on the ground and are interpreted as being spatial structures [*Sugiura et al.,* 1968b]. However, near the magnetic midnight meridian a sudden field change is often observed in this region following the onset of a negative bay on the ground; such a change has been taken to mean a magnetic field collapse in the near tail region caused by the bay [*Heppner et al.,* 1967; *Sugiura et al.,* 1968a], as will be discussed in the following section. The spatial structures discussed here should be distinguished from these temporal variations associated with bay disturbances. The beginning of the irregular field at about 11.3 R_e is interpreted as the satellite's entrance into a high β region. Whether or not the sudden magnetic field change that often characterizes the beginning of an irregular field corresponds to the plasma sheet boundary remains for future studies. However, a preliminary comparison of the magnetic field data with plasma observations indicates that when β becomes nearly equal to, or greater than, unity, magnetic field irregularities seem to appear [*Sugiura et al.,* 1968b]. Hence this threshold need not be precisely the boundary of the plasma sheet, and the former may be the surface within which $\beta \gtrsim 1$. Normally only one large, sudden field change is observed in one pass, but there are passes in which more than one such change is encountered. This suggests that the magnetic field in the near tail region has shell-like structures and that the large sudden changes are magnetic field discontinuities between successive shells. The orbital characteristic, i.e., the inclination of 31° of the OGO 3 satellite, is probably the reason for its normally passing one discontinuity on each inbound orbit; the latitude of the satellite was too high to see these discontinuities on its outbound passes during the first several months after launch. Figure 3 shows a magnetic field profile frequently observed when the satellite passes the geomagnetic equator in the near tail region. The region of the large, box-like depression of the magnetic field is taken to be the central part of the plasma sheet.

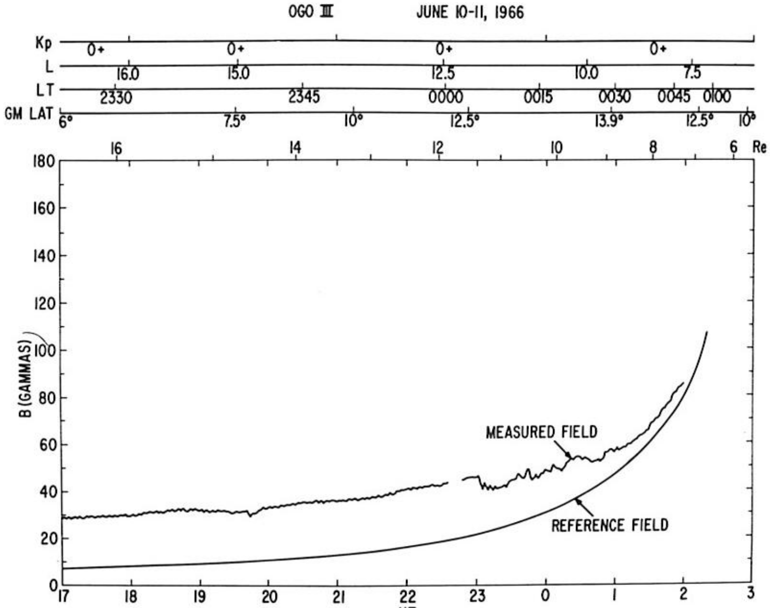

Fig. 2. An Example of the Profile of the Magnitude B of the Magnetic Field along an Inbound Orbit of the OGO 3 Satellite. The Sudden Decrease in B near 23 Hours UT Represents a Shell Discontinuity in the Near Tail Region.

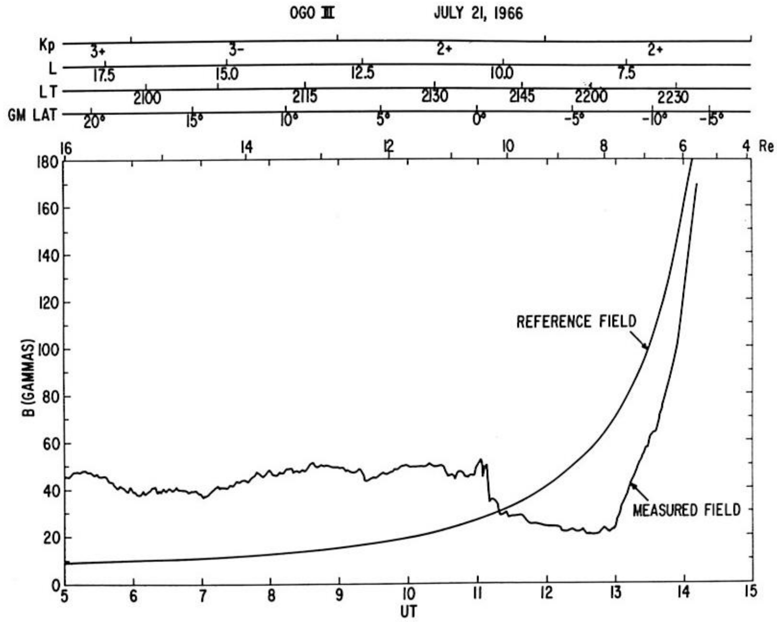

Fig. 3. An Example of a Sudden Magnetic Field Decrease Observed When the OGO 3 Satellite Crosses the Geomagnetic Equator in the Near Tail Region.

Figures 4 and 5 summarize the structure of the magnetosphere discussed in this and preceding sections, the two figures showing the main features in the equatorial cross section and in the noon-midnight meridional cross section, respectively. The shell-like discontinuities discussed above are indicated in Fig. 5. The region containing the discontinuities is likely to be connected to the auroral belts by the lines of magnetic force.

Disturbance Field Variations

The Storm-time Ring Current. Early satellite observations of the magnetic field decrease produced by a storm-time ring current include those made by Lunik 1 and 2 [*Dolginov et al.*, 1961; *Dolginov and Pushkov*, 1963], Explorer 6 [*Smith et al.*, 1960; *Smith and Sonett*, 1962], Explorer 10 [*Heppner et al.*, 1963], Explorers 12 and 14 [*Cahill and Amazeen*, 1963; *Cahill*, 1964a, b], and Elektron 2 [*Eroshenko et al.*, 1965]. More recently, *Cahill* [1966b, 1968] has made an extensive survey of the ring current field with Explorer 26 and has shown that the region of large field decrease varies from one storm to another, ranging from L = 2.5 to 5.3.

Low energy protons (150 kev < E < 4.5 Mev) were observed by Explorer 12 [*Davis and Williamson*, 1963]. On the basis of these data *Akasofu et al.* [1962] constructed a model ring current. The observation of the proton belt was confirmed by

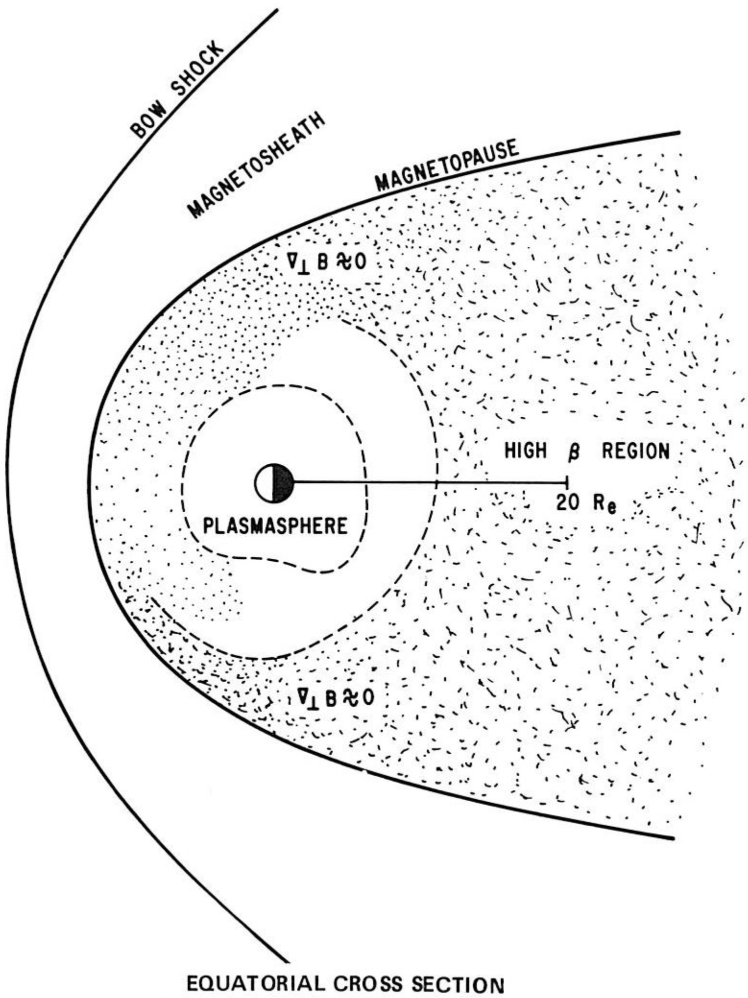

Fig. 4. Illustration of the Magnetosphere in the Equatorial Cross Section. The Dotted Region Represents That Containing Higher Energy Plasmas.

Explorers 14 and 15 [*Davis,* 1965]. The most complete observations of the charged particles of the ring current are those made by *Frank* [1967c] on OGO 3. As an example, for the storm of July 8, 1966, he observed enhanced fluxes of 200 ev - 50 kev protons between L = 3 and 7 with a peak at 3.7, and electron fluxes in the same energy range from L = 3 to beyond 7.5. It was shown that the energy spectra and spatial distributions of the protons and electrons in the ring current vary with time in a complex manner.

A ring current has been found to exist even during magnetically quiet periods [*Davis and Williamson,* 1963; *Frank,* 1967c]. The magnetic field decrease at the earth's surface due to the quiet-time proton belt has been estimated by *Hoffman and Bracken* [1965] to be 9γ using the proton data from Explorer 12.

Magnetic Bays (or Polar Substorms). The OGO 1 and 3 satellites have provided observations of magnetic variations in the near tail region associated with magnetic bays, or polar substorms [*Heppner et al.,* 1967; *Sugiura et al.,* 1968a]. In a summary of their results, the important features are as follows. A sudden change is observed in the near tail region in association with a magnetic bay if the satellite is nearly in the same meridian plane as the center of the bay disturbance on the earth. The onset of the bay at the earth's surface precedes the sudden

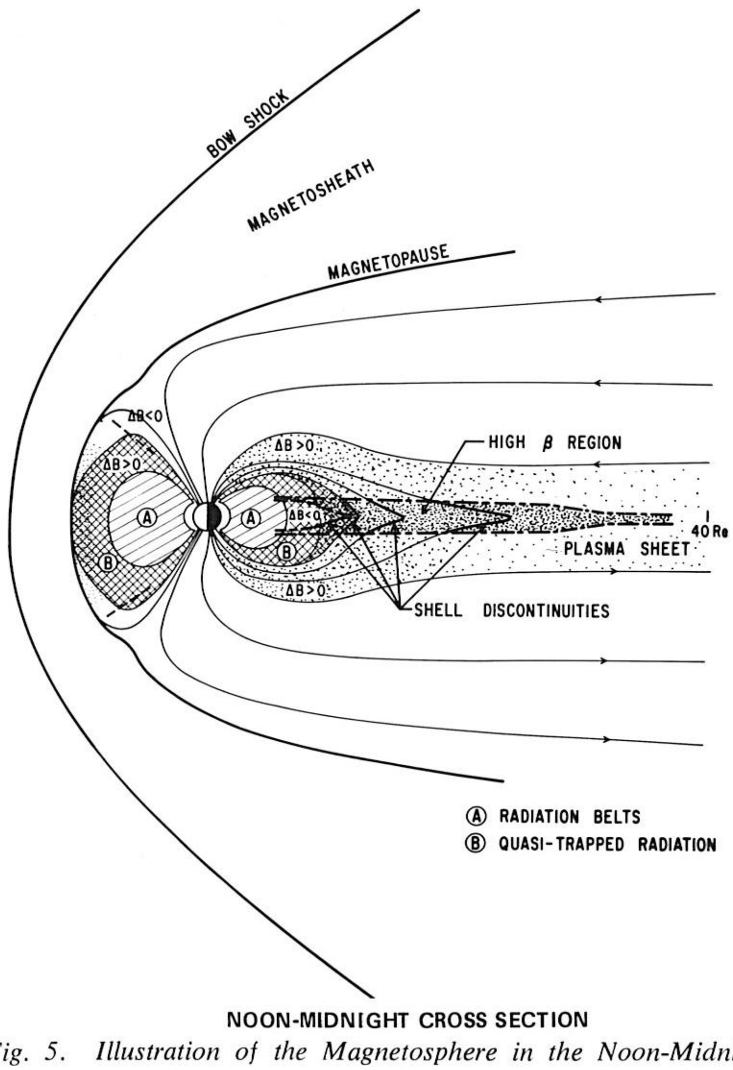

Fig. 5. Illustration of the Magnetosphere in the Noon-Midnight Cross Section. The Dotted Region Represents That Containing Higher Energy Plasmas. ΔB *is the Difference Field, i.e., the Observed Minus the Reference Field.*

change in the near tail region. If the satellite is in the region away from the equator where normally ΔB(= the observed minus the theoretical field) > 0, the change is a decrease in B; whereas if the satellite is in the equatorial region where normally $\Delta B < 0$, the change is an increase. The change in the direction of the magnetic field is such as to approach the theoretical dipolar field. These features are interpreted to mean that the tubes of magnetic force passing the equatorial near tail region collapse, following the bay onset; the tubes of force initially collapsing are probably those that are connected to the ionosphere in the general area of the bay onset, i.e., the region in which the negative bay begins abruptly. After the collapse of these flux tubes a rearrangement of the neighboring tubes must take place to adjust to a new pressure balance, but a sudden large change in the field is observed only in the collapsing tubes. It is thought that the plasma is drained from these tubes of force partially by precipitation into the ionosphere and partially by convection into other regions of the magnetosphere. According to *Cummings et al.* [1968], recent observations by the ATS 1 satellite in a synchronous orbit at 6.6 R_e indicate a magnetic field depression in the dusk-to-midnight sector during magnetic bay activity. This is interpreted by these authors as being due to a "partial ring current". The creation of the partial ring current may be related to the drainage of the plasma in the near tail region mentioned above. The picture of the magnetic field collapse in the near tail region at the time of a bay is consistent with the observations of the electron behavior in the tail plasma sheet by the Vela satellites at about 17 R_e [*Hones et al.*, 1967].

Transverse magnetic field perturbations have been observed by the APL satellite 1963 38C [*Zmuda et al.*, 1966, 1967] and are suggestive of field-aligned currents [*Cummings and Dessler*, 1967]. These variations are found at the satellite altitude of 1100 km along the auroral oval. Significance of large-scale field-aligned electric fields and currents is now being recognized, but no direct observations of them have so far been presented.

Magnetosphere Models

Unlike the description of the geomagnetic field near the earth's surface, usefulness of an analytical representation of the magnetic field in the magnetosphere will be greatly limited unless spatial as well as temporal variabilities are in some way incorporated. Several attempts have been made to represent the magnetospheric field analytically. *Mead* [1964] and *Midgley* [1964] expressed the scalar magnetic potential of the field from the magnetopause surface current in spherical harmonic series. *Williams and Mead* [1965] expressed the magnetic field in the trapping region as the sum of the main (dipole) field, $\mathbf{B}_d$, the field from the magnetopause surface current, $\mathbf{B}_s$, and the field from the neutral sheet current, $\mathbf{B}_T$, to obtain a theoretical model for the diurnal variation in the trapped electrons. In their model $\mathbf{B}_T$ is given by an infinitely thin sheet current in the equatorial plane in the back of the earth; the current flows from infinity to infinity in the direction perpendicular to the sun-earth line, the direction of the current being from the dawn to the dusk side so as to create the tail field. The (uniform) current intensity and the positions of the front and rear edges of the current sheet are taken to be adjustable variables to fit the observation. The adiabatic motion of energetic particles in such a model magnetospheric field has been investigated by *Mead* [1966] and *Roederer* [1967]. While this model represents several gross average characteristics of the magnetic field in the trapping region, there are intrinsic limitations in its applicability both from the geometric and physical idealization of the neutral sheet current.

Based on the extensive magnetic data from Explorers 18, 21, and 28, *Fairfield* [1968b] has derived an average configuration of the magnetic field in the outer magnetosphere between 5 and 18 R_e. In particular, he drew contours of equal magnetic field magnitude in the equatorial plane and attempted to establish, from the consideration of flux conservation, the relationship between the equatorial crossing points of lines of magnetic force and the positions of their intersection with the earth's surface. This "graphical" model represents some average features of the magnetospheric field configuration, but the spatial coverage of the observational data used is not adequate to bring out the effects of the plasmas in the equatorial region.

Summary

Gross features of the magnetic fields in the magnetosphere and its vicinity have been explored in the past several years by extensive spacecraft observations. The positions of the magnetopause and the bow shock have been mapped at various latitudes below about 63° and their frequent movements have been inferred. The interplanetary magnetic field is convected into the magnetosheath and comprises the ordered background field in the magnetosheath; irregular fields are superimposed on the ordered magnetic field. The magnetopause thickness is estimated to be of the order of one cyclotron radius. The observed general characteristics of the magnetospheric field have been found to be in gross agreement with the theoretically expected distortion of the geomagnetic field by the solar wind. The magnetospheric tail is now known to extend well beyond the moon's orbit, and may reach 1000 R_e in a wake-like form. A region of weak magnetic field near the solar ecliptic plane, which is often called the neutral sheet region, separates the earthward field in the northern half of the tail from the oppositely directed southern half. The existence of a plasma sheet in the magnetosphere and in the tail has been established. The plasma sheet occupies a larger volume than the magnetically defined neutral sheet and extends well into the magnetosphere. The magnetic field in the near tail region often shows shell-like structures with well defined discontinuities between neighboring shells. Both the magnetic field and the charged particle content of a ring current have been measured during magnetic storms. A proton belt of lesser intensity has been observed even during magnetically quiet periods. The diamagnetic effects of the plasmas have been observed, indicating that the magnetic field configuration of the magnetosphere is distorted appreciably by the plasmas. Therefore, in a magnetic field model for the magnetosphere the effects of the plasmas must be taken into consideration. Sudden magnetic variations are observed in the near tail region near the magnetic meridian following the onsets of magnetic bays.

While the overall configuration of the geomagnetic field in space is known, detailed magnetic field structures and dynamical processes operating in the magnetosphere are not as yet well established. Outstanding fundamental questions that are still awaiting definitive answers include, for instance, the precise nature of the solar wind-magnetosphere interaction at the magnetopause; the structure of the bow shock; the reason for the existence of the extended tail; the origin of the plasmas in the magnetosphere and in the tail; the processes causing high latitude disturbances; and various particle acceleration mechanisms. Some of these problems appear to be interrelated, but some may be related to still other important processes that have so far escaped our observation.

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The discussions given here are partly based on the studies of the OGO 1 and 3 magnetic data made jointly with Dr. J. P. Heppner, Mr. T. Skillman, and Dr. B. Ledley. I wish to express my appreciation of the benefit I received from these studies; in particular, I wish to acknowledge valuable discussions with Dr. J. P. Heppner.

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COVERAGE BY LAND, SEA, AND AIRPLANE SURVEYS, 1900 - 1967

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The worldwide coverage of the earth by land, sea, and airplane magnetic surveys since the beginning of the 20th century is illustrated in the accompanying figures, which were produced by plotting the position of each measurement with a microfilm plotter. This technique results in heavily surveyed regions appearing as completely darkened areas (India and U.S. in Fig. 1, and Europe, western U.S.S.R., Japan, Madagascar, and New Zealand in Fig. 2) or heavy lines as in the closely spaced measurements along ship tracks in Fig. 4. The data file used to derive these plots was assembled by the U.S. Coast and Geodetic Survey from available sources. The file contains measurements at about 100,000 land stations, airborne measurements at over 90,000 points, and marine measurements at over 25,000 points. The marine measurements cover over 1,000,000 km of trackline.

For the survey period 1900 - 1930 (Fig. 1) there is very good coverage for both land and oceans excluding the polar areas. The most significant ocean surveys were conducted during the period 1905 - 1929 by the ships *Galilee* and *Carnegie* of the Carnegie Institution of Washington, D.C., U.S.A. Over 600,000 km of trackline were traversed and measurements made at over 6000 points in the ocean areas at spacings of approximately 100 km between measured points. In all, ten cruises were made by both ships. The ocean cruises were discontinued in 1929 when the *Carnegie*, which had

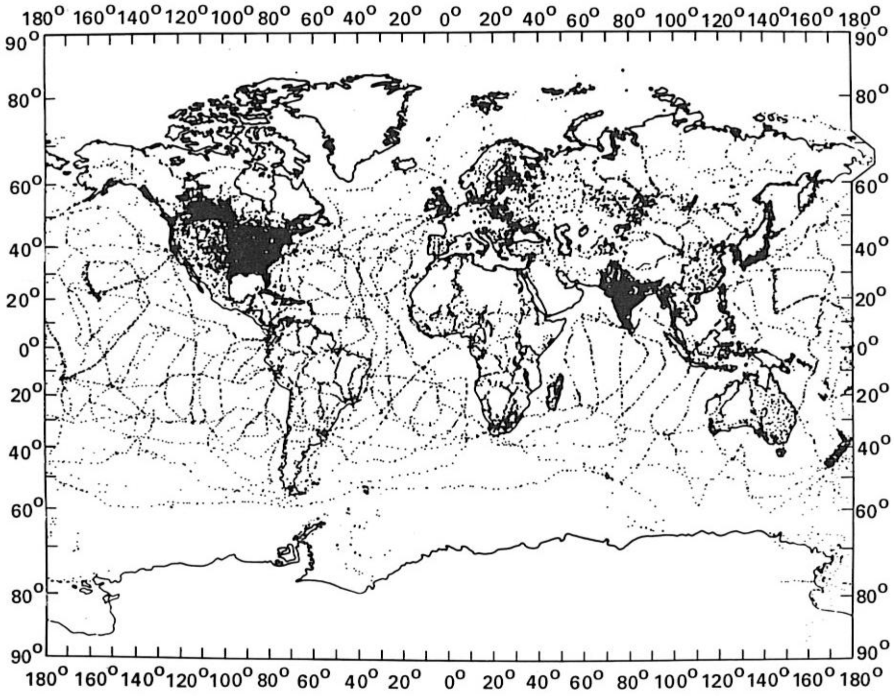

Fig. 1. Surface Survey Data (1900–1930).

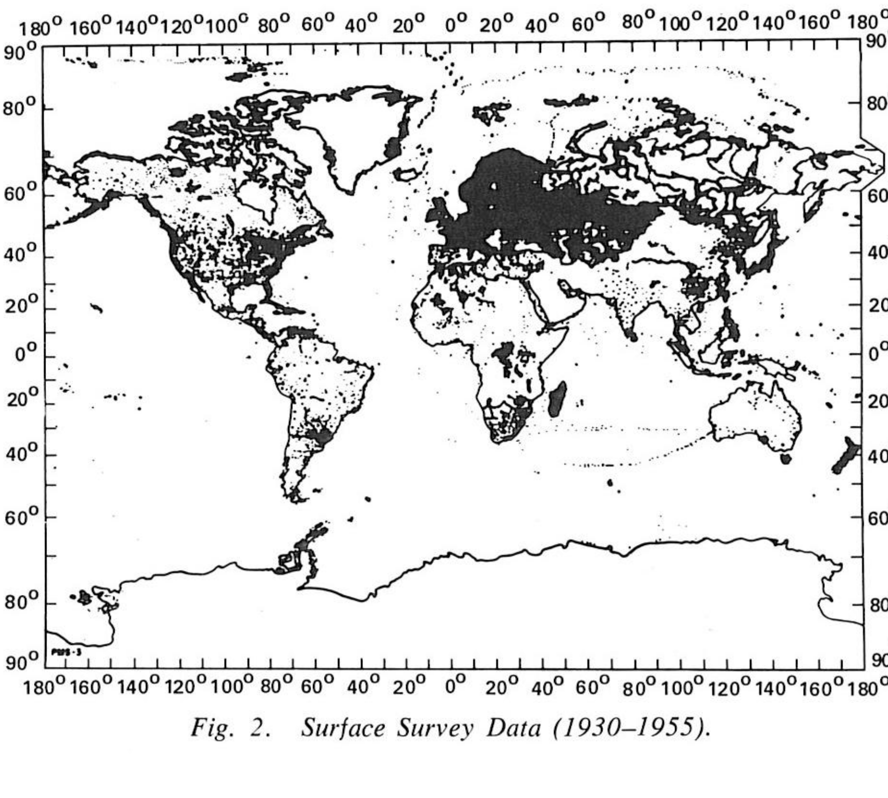

Fig. 2. Surface Survey Data (1930–1955).

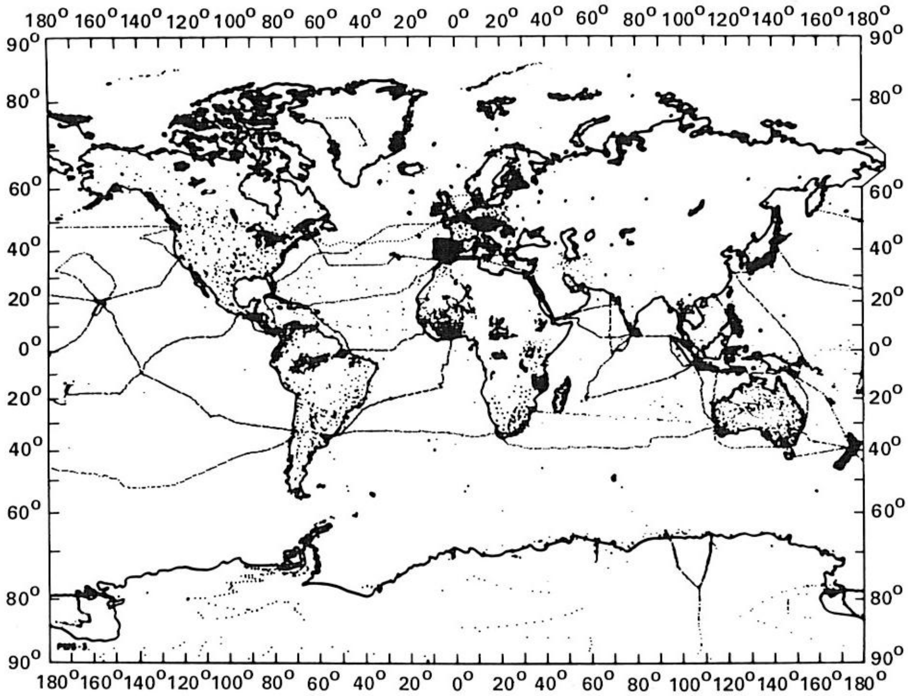

Fig. 3. Surface Survey Data (1955–1967).

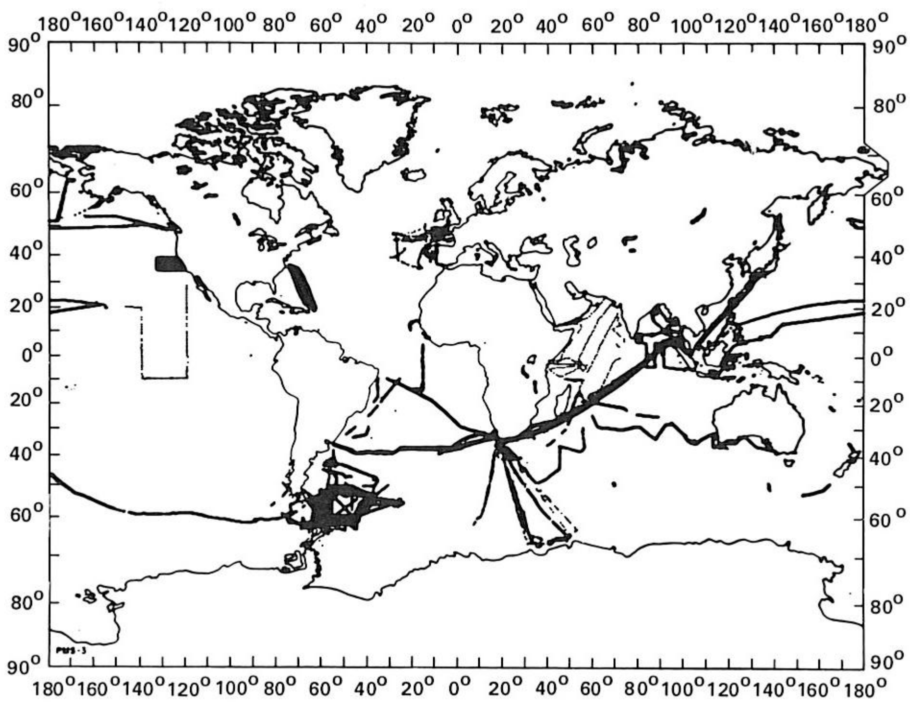

Fig. 4. Ship-Towed Magnetometer Surveys.

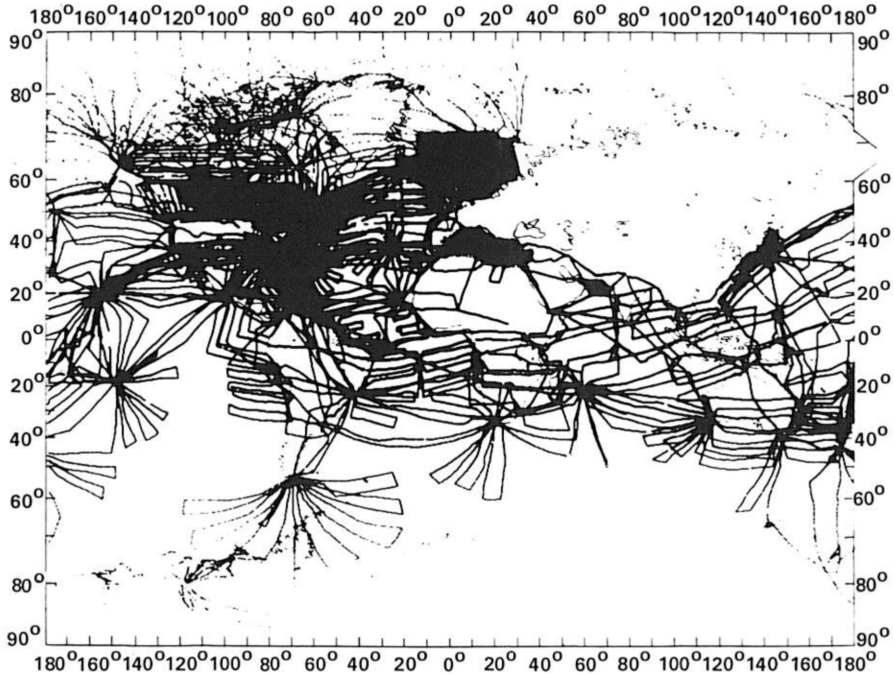

Fig. 5. Airborne Survey Data (1953–1966).

replaced the *Galilee,* was destroyed by fire at Apia, Samoa. In addition to the marine surveying it conducted, the Department of Terrestrial Magnetism, Carnegie Institution of Washington, also was responsible for the occupation of over 6000 land stations throughout the world up to 1944.

Other extensive land surveys done during the period 1900 - 1930 were India (7000 stations), United States (6000 stations), and western Canada (15,000 stations).

For the period 1930 - 1955 (Fig. 2) there is relatively good coverage in the land areas but an almost complete lack of ocean measurements. Coverage for the polar regions was still extremely sparse. Some of the most extensive surveys during this period took place in Europe and, particularly, in Russia. Most of the Russian survey activity occurred during the period 1931 - 1942 when about 22,000 stations were occupied. The measurements made north of the 70th parallel in the eastern hemisphere were made by the U.S.S.R. on the various ice islands.

Surface survey data for the period 1955 - 1967 (excluding ship-towed total intensity data) are shown in Fig. 3. One of the most important surveys conducted during 1956 - 1963 was that undertaken by the U.S.S.R. ship *Zarya.* Measurements were made of the components D, H, Z, and F at more than 2500 points in the various ocean areas. New *Zarya* data, which are not shown in this illustration, indicate measurements at about 1000 additional points up to May 1967.

Something of the order of 1000 measurements were made during this period in the Antarctic. Most of the observations were for scalar total intensity only, but at about 100 points the vector field was measured. Coverage for some parts of Africa and large areas within Asia is very sparse.

Figure 4 shows the available marine magnetometer measurements derived from towed instrumental equipment that recorded only scalar total intensity (F). Most of these measurements were made subsequent to 1956. The survey work off the west coast of the United States represents tracklines of the ship *Pioneer* (ESSA, U. S. Coast and Geodetic Survey, United States). Most of the surveys conducted in the southern hemisphere were undertaken by the ships *Vema* (Lamont-Doherty Geological Observatory, Columbia University, United States), *Soya* (National Antarctic Committee, Japan), *Zapiola* (Argentina-United States cooperative program), and *Shackleton* (British Antarctic Survey, United Kingdom). A considerable amount of marine magnetic survey data is not reflected in this figure. In general, these data are held by the separate agencies which conducted the surveys.

Tracklines of the vector airborne data available for the period 1953 through May 1966 are shown in Fig. 5. These surveys were conducted by the United States (Project MAGNET), Canada, and Japan. Generally, magnetic vector measurements were made at points spaced 30 km apart. This figure shows about 4,000,000 km of trackline with measurements being made at about 90,000 points.

The airborne coverage for the northwest quadrant is quite dense. The region between the equator and 40°S shows comparatively good coverage with the exception of that part of the Pacific Ocean that is included in this sector. The most conspicuous gaps appear in Asia, Central Europe, and in much of the southerly regions beyond 45°S.

EFFECT OF MAGNETIC FLUCTUATIONS ON SURVEY DATA

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GENERAL REMARKS

Superimposed on the earth's main field and its secular change are the time variable magnetic signals propagated to the site of the magnetic survey, whether at earth, satellite, or ground level. Such signals arrive more or less continuously. On a few days per year they are particularly intense, and these are called magnetic storm days, which may total as much as twenty a month. Storms tend to be on an average larger near or just following a sunspot maximum than they are at a sunspot minimum. The disturbance is most marked and irregular within the auroral oval, which has a dipole latitude of about 67° at local midnight and about 78° at local noon.

Another variation is the solar daily variation (S_q) caused by electric currents flowing at altitudes of about 110 km in the E-region of the ionosphere. The electric conductivity becomes enhanced near noon so that the field change then tends to be greatest. At local midnight the ionospheric currents are usually small, and their field contribution to the survey data is minimal. Since most measurements are made in the daytime, when certain fluctuations are large, it is suggested that a better measure of the main field may be provided by correcting the measurement to the midnight value for that station. For instance, if at the site of measurement a portable magnetic observatory were available, we could correct the result measured, say, at 2 p.m. to the value for the previous or following midnight (or to the mean of the two midnight values, if desired). Ordinarily such magnetic information is unavailable to land survey parties, and observatories, though there are about 200 of them, may not be close enough to the station to provide the required correction directly. The improvement in the main field value may be substantial since the correction for S_q may be as great as 200γ or so for a land survey station near the equator. Since the ionizing influence of the sun upon the E-region decreases with increasing solar zenith angle, S_q varies also with season as well as from day to day by amounts as great as 50% or even more, and by a comparable amount with sunspot cycle [*Vestine et al.,* 1947]. This is therefore a major "noise" item affecting the land magnetic survey measurements.

A lunar magnetic variation (L) remains in the survey value but is usually only a few gammas in magnitude, although it may at certain hours be as much as 20γ near the magnetic equator [*Chapman and Bartels,* 1940].

In addition to S_q and L, which vary with solar electromagnetic radiation, upper air tidal motions, and winds, there are variations due to magnetic disturbance that affect the survey value. The simplest of these is conveniently discussed in terms of the daily means of disturbance as the post perturbation (P) of storms or the ring current field. The lowering of values of horizontal intensity represented by P is associated with transient lowering in field disturbance Dst starting near the beginning of a storm and often continuing 10 hours or more with subsequent recovery, often at a rather uniform rate over a period of days. Except for some 5 - 20 days of storm per year, for which correction of the survey data is presently not very practical, it may in principle be possible to make a correction for P.

There are some other transient variations such as geomagnetic fluctuations superimposed on the main and recovery phase of a magnetic storm, on a geomagnetic bay, and on a pulsation, for example. Outstanding geomagnetic variation anomalies have been found in a number of countries in recent years [*Rikitake*, 1966a], so that attention should be paid to the fact that a geomagnetic variation sometimes differs considerably from station to station even if the distance between the stations is not large, for example, less than 50 km.

ACCURACY OF MAGNETIC OBSERVATIONS

Techniques for measuring a weak magnetic field have been developed in recent years. It is customary for a regional magnetic survey to make use of a magnetometer having an accuracy of $\pm 1\gamma$ for the three-component measurement [*Whitham,* 1960]. A Geographical Survey Institute (GSI) magnetometer, which has been widely used for field surveys in Japan and other countries, satisfies, for instance, a condition that the standard errors of a single observation are less than ± 0.1 minute of arc for the declination (D) and inclination (I) and $\pm 1\gamma$ for the horizontal intensity (H) at middle latitudes [*Tsubokawa,* 1951; *Tazima,* 1968].

Use of proton precession and optical pumping magnetometers for land, air, ocean, and satellite surveys has now become commonplace. Most of these magnetometers are designed for measuring the total intensity only. Although some of the magnetometers have a higher sensitivity, an accuracy of $\pm 1\gamma$ is usually required for a field survey.

OVERALL ACCURACY OF FIELD OBSERVATIONS

A regional magnetic survey aims at obtaining magnetic field values free from transient variations that could be eliminated, in some cases, in the following simple way.

Considering a reference magnetic observatory, a magnetic element observed there at a time t is defined by $M_k(t)$. A quantity $C_1(t)$, which represents the difference in the value of the element between $t = t_o$ and $t = t$, is then defined by

$$C_1(t) = M_k(t_o) - M_k(t). \qquad (1)$$

Let us suppose that a value $M_i(t)$ is obtained for the same element at a station not very far from the reference observatory. The element value reduced to epoch $t = t_o$ is then given by

$$M_i^r(t) = M_i(t) + C_1(t). \qquad (2)$$

When $t - t_o$ is not very large, it is assumed that $M_i^r(t)$ gives an approximate value of $M_i(t_o)$.

In the above procedure of epoch reduction, it is assumed that the effect of the geomagnetic variation anomaly on $M_k(t)$ is the same as that on $M_i(t)$. Such an assumption is a poor one for surveys in a country like Japan. Figure 1 shows how the three geomagnetic elements behave at observatories in Japan at the time of a geomagnetic bay. We notice in the figure great differences in the vertical component between the respective observatories, although the horizontal components are distributed fairly regularly over Japan.

In the case of an actual magnetic survey in Japan, it has been planned not to make use of data on disturbed days. *Tazima* [1968] argued that the reliability of the first-order magnetic survey results in Japan is roughly given as

$$\Delta D = \pm 0.4', \Delta I = \pm 0.3 \text{ to } 0.4', \Delta H = \pm 3 \text{ to } 4\gamma, \qquad (3)$$

the Kakioka Magnetic Observatory in central Japan having been taken as the reference observatory. *Rikitake* [1966a] pointed out that even S_q is distributed in an anomalous way in Japan so that reduction of survey data, even if they are taken on a quiet day, cannot be of high accuracy. The overall accuracy of a magnetic survey in other countries may be higher if no intense anomaly of geomagnetic variation exists there, but there are usually few observatories that may work as reference ones in most countries.

More elaborate ways for epoch reduction have sometimes been discussed. In the author's opinion, however, no drastic improvement of overall accuracy seems possible with existing methods.

EXTREMELY ACCURATE COMPARISON OF MAGNETIC FIELD VALUES

Attention has recently been drawn to an extremely accurate comparison of magnetic field values between two stations in relation to detectability of a

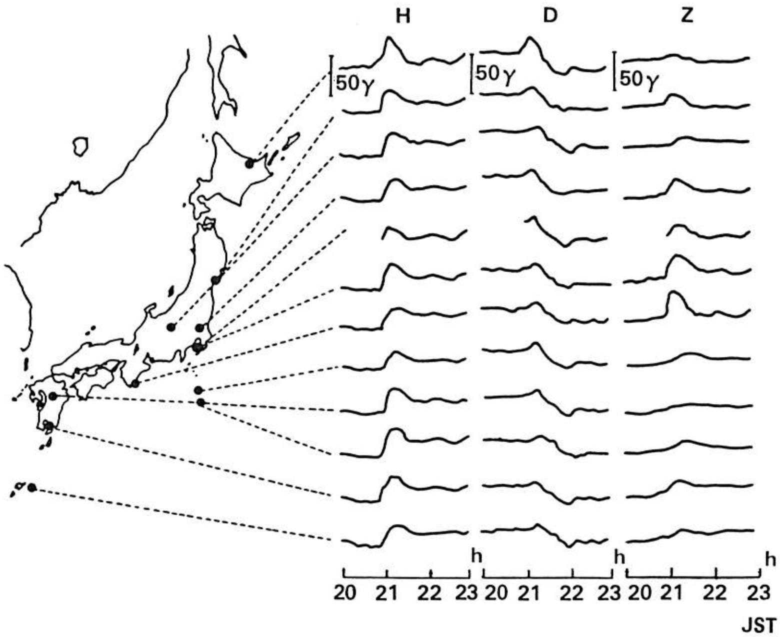

Fig. 1. Changes in the Three Geomagnetic Components at the Time of a Bay as Observed at Twelve Observatories in Japan on April 18, 1958.

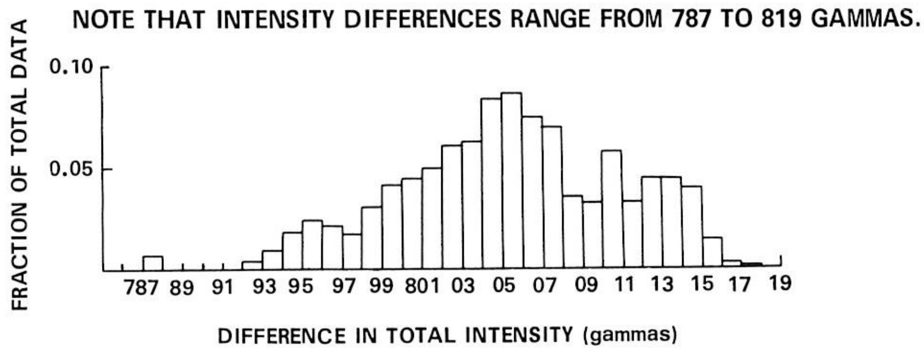

Fig. 2. Histogram of Differences in the Total Intensity between Two Stations on an Island South of Tokyo on January 8, 1967, a Moderately Disturbed Day. The Number of Cases Totals 1402.

seismo-magnetic effect that is as small as 10γ or so in most cases. Statistics of total intensity values taken by proton precession magnetometers lead to a conclusion that the standard deviation of a simple difference value between two stations several tens of kilometers apart amounts to 0.85γ in England [*Stacey and Westcott,* 1965] and 3 to 4γ in Japan [*Rikitake,* 1966b; *Rikitake et al.,* 1968]. *Rikitake* [1966b] proposed a technique for eliminating the nonlocal transient field using weighted differences for nighttime data. In a country like Japan where the geomagnetic variation anomaly is extremely large, however, no standard deviation smaller than 2γ has ever been reached in spite of such a technique.

In the case of field surveys, the number of observations at a station is necessarily limited. The standard deviations for these observations would hence be larger than those for fixed stations as mentioned above.

It is really surprising that geomagnetic changes at relatively near stations are sometimes quite different. As an example for the worst case, Fig. 2 shows a histogram of differences in the total intensity value between two stations separated by only 7 km and located on a small island about 100 km south of Tokyo. The data were taken every minute by a digitalized proton precession magnetometer on a moderately disturbed day. The scattering of the difference values is so large that the standard deviation amounts to 6γ or so. It is also known that the standard deviation becomes 2γ or so on a quiet day. Such a large difference in the magnetic field value is certainly caused by the magnetic fields produced by electric currents induced in the sea surrounding the island.

CONCLUSION

The influence of S_q on survey data may amount to as much as 200γ, on L about 20γ, and on P about 50γ on a day other than a storm day. Other time variations such as bays, pulsations, and daily variations on disturbed days also appreciably affect survey data. These effects may be corrected by a conventional means with an accuracy of ± 3 - 4γ at middle latitudes. Care should be taken to eliminate an effect due to geomagnetic variation anomalies, recently found in survey data in many countries.

ACKNOWLEDGMENT

This article was prepared on the basis of a draft manuscript which seemed to have been written by the late Dr. Ernest Harry Vestine; the draft was found in the office of the WMS Board.

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CHARTS

BRITISH WORLD MAGNETIC CHARTS

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HISTORY

The present series of world magnetic charts produced at the Royal Observatory and published by the British Admiralty can claim a long and distinguished history going back as far as the first world magnetic chart produced by Edmond Halley in 1702. (Responsibility for the magnetic department has recently passed from the Royal Greenwich Observatory to the Institute of Geological Sciences. However, the staff remains the same and will continue to work at Herstmonceux for the next few years.)

The connection between the Observatory and the Admiralty dates from 1675, when the observatory was founded by Charles II with the purpose of improving methods of navigation. The data used for the preparation of Halley's chart were mainly those that he obtained while master of an Admiralty "pink." He later became the second Astronomer Royal, the title given to the director of the Royal Observatory.

The first of the modern series of Hydrographic Office magnetic charts was that of Evans for epoch 1858. Like its predecessor it was largely based on observations by ships of the British Navy, supplemented by "magnetic surveys undertaken of late years by British and Foreign Governments." In this chart the isogonals were extended over land as well as sea, and an inset indicated secular variation. Since this chart there has been a fairly steady stream of Admiralty charts, with various modifications and improvements incorporated from time to time. These are summarized in Table 1.

TABLE 1
INNOVATIONS IN ADMIRALTY CHARTS

Epoch	*Innovations*	*Element*
1871	Secular Variation (s.v.) chart printed outside the world chart. Polar regions added.	D
1880		D
1907	Small world charts of I, H, and Z in cgs units.	D,H,Z,I
1912	3 large sectional charts in addition to the world chart.	D
1917	Isogonals in color.	D
1922	Full size H and I charts, including $\dot{H}$ and $\dot{I}$. Later subjected to spherical harmonic analyses by *Dyson and Furner* [1923].	D,H,I
1927		D
1932		D
1937		D
1942	Later subjected to spherical harmonic analysis by *Jones and Melotte* [1953] (using both spherical and ellipsoidal models).	D,H,Z,I
1947		D
1955	First set of charts for which spherical harmonic analysis was used as an aid to compilation [*Finch and Leaton,* 1955]. Charts for all 7 elements.	D,H,Z,I,X,Y,T
1960	s.v. overprinted in wash instead of inset. Separate polar charts. Prepublication comparison with U.S. Coast and Geodetic Survey charts.	D
1965	Extensive use of electronic computer for data reduction, spherical harmonic analysis [*Leaton, Malin, and Evans,* 1965].	D,H,Z,I,X,Y,T

GENERAL CONSIDERATIONS

The present policy is to publish D charts (world, three mercator sections, and polar regions) at 5-year intervals, and the other six elements (one chart each) at 10-year intervals. The last complete set of charts was for epoch 1965.0, and the next set of charts (D only) will be for epoch 1970.0.

The main purpose of the charts, at least from the point of view of the Admiralty, has always been as an aid to navigation, and for this purpose the D charts are the most important. They are issued to ships in the British and other Navies and are also widely used by British and Foreign merchant ships and by yachtsmen. They are also used for aircraft navigation, particularly for the final approach to an airfield. The size of the charts makes them less convenient to use in the restricted space of an aircraft cabin, and they may be replaced with grid-point values stored in a small airborne computer. These grid-point values will, however, be based on the chart values. Large-scale land maps usually have D information included, often in the form of a marginal compass rose, indicating the current value of D and its rate of change. This information is commonly extracted from the world D chart.

For navigational purposes it is clearly desirable to have data for a current epoch, and for this reason, the magnetic charts are "forecast" charts, compiled and published before the epoch to which they refer. This restriction is undesirable from the point of view of the cartographer, who would prefer the accuracy of a definitive chart. For this reason, most cartographers will welcome the opportunity to collaborate in the production of the WMS chart, which will be definitive rather than forecast.

The present charts owe more to their predecessors than mere tradition. Each new set of charts, although largely a new estimate of the field, is very directly related to its predecessors in a way that will become obvious when the method of preparation is described. Another more tenuous but equally important inheritance is the chart lore and knowhow that have been accumulated and passed on over the years. An example of this is the policy of smoothing. Obviously a world chart cannot present all the details of local anomalies, so some degree of smoothing is necessary. However, it has long been our policy to spend a great deal of time "polishing" the final charts to produce smooth curves and uniform gradients. The original philosophy was that, if a chart could not be accurate, there was no reason why it should not be aesthetic. However, time and again the smoothed chart has proved to be a better fit to subsequent observations than the initial wavy one. Effectively, this policy means that each observation is allowed to influence the pattern of isopleths over a considerable area rather than just locally. In 1960, for example, much of the Indian Ocean pattern was shifted to accommodate a few good observations near the Australian coast, and the revised pattern was largely confirmed when *Zarya* observations became available.

In the past, isolated observations have been very carefully evaluated before deciding on the weight they should be given. This is very important to ensure the accuracy of the final chart but is becoming more difficult with the current plethora of observations. Fortunately it is less important to vet the individual values when there are sufficient data to outweigh the few wild values; however, it is considered to be important to try to maintain a check on the data being used, particularly now that computer techniques are generally used and it is very easy for improbable values to be fed into the machine without detection.

PREPARATION OF CHARTS

The "working charts" for one epoch are the published charts for the previous epoch. The charts are corrected to agree with recent data straddling their epoch, and as a final stage the corrected charts are adjusted to the new epoch.

Before any observation can be plotted on the working chart, it must first be corrected to the epoch of the working chart using an estimate of the secular variation (s.v.). Since most of the new data will be observed within a few years of the epoch of the working chart, the correction will be small and it will usually be adequate to use the estimated s.v. for the appropriate epoch as published in the most recent charts. When the observation is plotted on the chart, a mark is made to show how far the nearest isopleth should be moved to accommodate the new value, assuming no change of gradient. When all the points have been plotted, the revised isopleth is drawn through the marks, having regard for the confidence that can be placed in the original isopleth (i.e., the quantity and quality of the data that determined its position when the previous chart was drawn) and the varying quality of the new data.

Where intensive surveys have taken place, it is not possible to plot all the observations. In such cases, the mean of several observations may be taken, or, if the persistence is very high, a selection may be made (e.g., every twentieth value from a towed magnetometer). The mean of a string of observations should not be taken when the gradient of the field changes appreciably over the range of the mean.

Where airborne observations are available, these often provide a high density of points, and it is convenient to take the mean of all values falling within a small tessera. This must then be corrected to ground level, which is done by computing the difference between the ground level value and the aircraft altitude value, from a sixth-order spherical harmonic model of the main field. The correction is usually small, so it is not necessary to use a particularly refined model.

When the new data are available only in the form of local charts, these are corrected to the required epoch, smoothed, and transferred to the working charts. In such cases it is usual to assume that the local cartographer has done his job well, and his values are accepted without modification, except to adjust the ends of the lines to conform with the surrounding pattern. However, it sometimes happens that two such charts for adjacent, or overlapping, areas tell different stories. (This has even occurred on the Canada/U.S.A. border in 1955, and there was a classic earlier example when different Japanese authorities produced widely different pictures of the magnetic field over their islands.) In such cases, if the anomalies cannot be resolved by correspondence, the cartographer has to act as arbiter and decide for himself where the curve should go.

Having produced a revised chart as described above, it is usually valuable to perform a spherical harmonic analysis, or series of such analyses. There are several reasons for this:

1. It indicates what adjustments are necessary to produce a chart that represents a potential field of purely internal origin. In regions where the observations are sparse such adjustments may be made without prejudicing the overall fit to the initial data, and the process may then be repeated.

2. It indicates what adjustments are necessary to make the charts of different elements mutually compatible.

3. If the iterative method described by *Leaton* [1957] is used, it allows observations in one part of the world to indicate adjustments to be made in different parts of the world.

4. It permits the use of satellite data for defining the main magnetic field at ground level.

5. It provides a method of smoothing.

The use of spherical harmonic analysis (s.h.a.) for these various purposes has been the subject of a great deal of study by many people, and it is not practical to go into any detail here. However, the value of such analyses cannot be too strongly emphasized.

The final stage in the preparation of the charts is the correction to the new epoch. For this we require the best possible estimate of secular variation, partly because any errors in s.v. will introduce systematic errors into the final chart, partly because this estimate of s.v. will be used by customers to correct chart values to the epoch they require; also this s.v. will be used to correct subsequent data to epoch when the next charts are prepared.

The preparation of final s.v. charts is left until the end so that the most recent data can be used and the length of the extrapolation kept to a minimum. The most reliable sources of s.v. data are observatory annual means, and great care is taken to obtain the best possible values for these and to eliminate discontinuities [*Roy. Obs.*, 1967]. Unfortunately the geographical distribution of observatories leaves much to be desired, and it is necessary to fill in the gaps from other sources. Of these, repeat stations are usually good, but sometimes give rise to wild values. In some cases one has to resort to comparisons of surveys of different epochs, or even ships' compass readings over a number of years on a regular shipping route. These last methods are very much inferior to observatory data or repeat stations, but, particularly in the southern oceans, they are sometimes the best available. Again s.h.a. is a valuable tool for use in constructing the s.v. charts.

PROSPECTS

Most of the discussion so far has related to the preparation of past charts. It is, perhaps, of more immediate interest to outline the methods intended for use in the future.

Since the 1965 charts were produced, a great wealth of total field data from satellites has become available, together with practical methods for the use of these data to give vector information. Indeed, it seems possible that the main magnetic field may soon be better defined from satellite data alone than from all the past surface and airborne data. However, there may be some pitfalls. For instance, the satellites orbit above the level of the ionized layers where S_q, S_D, etc., probably originate and may include some external (with respect to the earth) sources as part of the main field. Also, because of the short time for which satellites have been operating, they provide little information on s.v. Although great claims have been made for the Rb magnetometers used, *Allen* [1968] has raised doubts concerning their stability. In spite of these objections, satellite data will be the main source from which the main field of the next charts will be derived, via a spherical harmonic analysis, allowing for the earth's oblateness, to about twelfth-order and degree.

The spherical harmonic coefficients will be carefully compared with those from an analysis of surface and airborne data to see if any unacceptable differences exist (the criterion of "acceptable" being based on the standard deviation).

The main value of the surface data will be for the s.v. information they contain. The proposed method of s.v. analysis was described by *Malin* [1967] at the Herstmonceux WMS colloquium (1966) and may be summarized as follows.

1. Using only long-running observatory data, a number of preliminary models of s.v. will be constructed at intervals of five years, back to 1940.

(Differences between these models should give the best available estimate of secular acceleration.)

2. Using this preliminary s.v., data observed between 1940 and 1955 will be corrected to epoch 1950; data observed after 1955 will be corrected to epoch 1960.

3. Spherical harmonic analysis will be performed for 1950 and 1960. The difference between the coefficients for the two epochs should be the best estimate of s.v. for the interval 1950 to 1960, and may be adjusted to a more recent epoch using (1).

Part 1 has been completed [*Malin*, 1969]. Progress on the first part of stage 2 is greatly hampered at present through shortage of suitable staff, but steps are being taken to rectify this.

To summarize, the main field will be derived from satellite data, s.v. will be derived from survey and observatory data, and secular acceleration has been derived from observatory data, all via the medium of spherical harmonic coefficients, and converted to chart form with a computer and graph-plotter.

All of this is very far removed from the "dividers and drawing board" methods for the earlier charts, but it is hoped that many of the qualities, standards, and skepticism of our predecessors may still percolate through and help to control the quality of the machine age charts.

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MAGNETIC CHART COMPILATION BY THE U.S. COAST AND GEODETIC SURVEY

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Shortly after the compilation and publication of the isogonic chart of the world (1960), which was a joint effort of the U.S. Navy Hydrographic Office and the U.S. Coast and Geodetic Survey (USC&GS), the planning in the Geomagnetism Division of the Coast and Geodetic Survey was modified to provide for compiling the next (1965) series of world charts through analytical procedures rather than primarily by the graphic techniques of plotting means of observed values and drawing isolines by hand.

A number of mathematical descriptions of the field using spherical harmonic coefficients have been derived since Gauss' [1838] first effort. Most of these, however, used uniformly spaced data points obtained by interpolating between the isolines of charts compiled by the conventional graphic methods, and the work was thus an analysis of the charts and only indirectly of the magnetic field. The analyses were often used (for example, by *Finch and Leaton* [1957] in Great Britain) in a feedback process for modifying and adjusting the hand-drawn isolines before final positions of the lines were adopted for publication.

A project was established in the USC&GS, with Louis Hurwitz as its guiding geophysicist, to develop a procedure that would use the basic data observed throughout the world since the beginning of the 20th century and would yield a set of spherical harmonic coefficients to the highest practicable degree and order. The objective was to produce an analysis of the observations from which the loci of the isolines could be computed directly and plotted automatically with suitable computer-controlled plotting equipment. The product was to be a set of world charts comparable in detail with the earlier world charts but more accurate and more nearly consistent with natural laws that govern the field. Many of the theoretically obvious procedures had to be modified or adapted to available equipment. For example, the memory capacity and speed of the computers initially available to the USC&GS put an economic limit on the scope and detail of the analysis that could be considered.

In the meantime other workers in the field (*Cain et al.* [1965] at NASA and *Fougere* [1965] at Air Force Cambridge Research Laboratories) performed spherical harmonic analyses on the data, following procedures that employed other methods for selecting data to be used—data from selected sources and for selected (later) years. Fougere used only data from magnetic observatories, thus having only about 82 data points. Cain also introduced another variable, time, with the objective of completely eliminating the requirement for graphical methods in the preparation of his basic data.

Observational data used by Hurwitz in his analysis were reduced to epoch 1965.0 by the method adopted in the USC&GS some twenty years ago, and described by *Walker and O'Dea* [1952]. This procedure involved the idea of secular change "impulses," an empirical device that approximated the behavior of the secular change patterns as derived from the records of magnetic observatories and the observations at magnetic repeat stations throughout the world. The reduced values were then averaged in 1° by 1° quads. These 1° quads were subjected to a presmoothing routine that suppressed much of the local detail and generated grid values appropriate for further processing. In the regions near the dip poles, the presmoothing also involved (for the horizontal components of the field) a special procedure to insure that the grid values would be free from systematic distortion such as might otherwise arise from the peculiarities of the D and H patterns in these regions [*Knapp,* 1967]. The grid values resulting from the presmoothing covered most of the globe, though with some areas of known weakness and leaving some gaps.

The grid values were next subjected to two successive spherical harmonic analyses, to degree 8 and 12, respectively, the first being used only to synthesize missing values for input to the second. The two-stage analysis was done for each of the components X, Y, and Z, those for X and Y being coupled and that for Z being independent.

It has been found that this procedure affords a fairly satisfactory new approach toward filling in the gaps, while maintaining a suitable resolution in the well-surveyed areas [*Hurwitz et al.,* 1966]. For the 1970 charts, gaps will be filled in via interpolation with local models.

The coefficients obtained in the higher order analysis were then used to compute the loci of all the isogonic, isoclinic, and isodynamic lines (in H, Z, and F) that were to be presented on the series of world charts. The principal computing was done on an IBM 7030 computer (known as STRETCH) then being operated by the U.S. Weather Bureau. The plotting was done from the taped positions of points on the loci by a plotter made available to the USC&GS at the U.S. Naval Oceanographic Office (the new name for the U.S. Navy Hydrographic Office).

The procedures have now been improved and refined so that when the next series of world charts is compiled the program will include the following modifications:

1. Adapt the analysis to a spheroidal earth rather than a spherical earth.
2. Introduce the time variable, through spherical harmonic analyses of the station rates of change at appropriately spaced intervals of time to reduce or eliminate the dependence on graphical methods of reduction to epoch.
3. Apply an altitude correction for all surface observations, as is now done for airborne and higher level observations.
4. Adopt some method of assessing the value of original observations with suitable selection and weighting of data.

Spherical harmonic analyses of degree and order 12 cannot depict details of the field having physical sizes smaller than ~2000 miles, the wavelength of the twelfth harmonic. Thus this type of treatment is less suitable for regional charts such as the magnetic charts of the United States. Hurwitz has described in some detail the methods that were used in compiling the U.S. charts. Essentially they consisted of deriving polynomial expressions for the distribution of the field in overlapping areas a few square degrees in extent. The degree of the polynomial chosen depended partly on the density of available observations. The data were screened, partly by computer techniques, partly by hand, to eliminate "wild" values due to errors or to sharp local anomalies that might have an undue influence on the resulting coefficients. From the adopted coefficients the loci of the isolines were then computed and used for controlling the operations of the automatic plotters.

The objective of the work for the U.S. charts, like that for the world charts, was to produce a set of magnetic charts comparable in detail with the earlier series, but with improved accuracy through reduction or elimination of the influences of the cartographer's skill (or lack of skill) and personal judgment (which inevitably varies from one person to another).

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THE U.S.S.R. CHARTS FOR THE EPOCH 1965

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The compiling of world geomagnetic charts, as well as geomagnetic charts for the U.S.S.R., is traditionally done in the Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation.

At present a complete set of geomagnetic field charts for the epoch 1965 has been compiled; it contains the charts for the following: the declination (D), the magnetic field intensity (F or T), the horizontal component (H), and the vertical component (Z).

The charts are prepared to the scale 1:10,000,000 on the basis of results of magnetic measurements and then scaled down to 1:85,000,000.

For the preparation of charts three kinds of survey data were used: airborne, marine, and land. About 100,000 measurements were used for each of the components; they include about 15,000 land, about 20,000 marine, and about 65,000 airborne measurements. In addition, for the preparation of the total intensity chart 19,000 measurements of F were used, obtained with towed magnetometers by the ships of the U.S.A., Great Britain, Japan, and other countries.

For some countries, previously compiled charts were used if they were available to us. World magnetic charts are usually compiled on the basis of observations made since 1950 in order to avoid errors related to the uncertainties in the secular variation. In poorly surveyed regions the charts for the epoch 1960 were used, prepared on the basis of the measurements made since 1900.

On the world oceans regular observations from the Soviet expeditionary ship *Zarya* were used. In 1956 - 67 the surveys in three oceans (the Atlantic, Indian, and Pacific) were performed from this ship. A continuous record of the geomagnetic elements was obtained on board the *Zarya.* The results were plotted on the chart at 2-hour intervals, corresponding to the distance of about 20 - 25 km. The accuracy of measurements is as follows: D, $\pm 0.5°$; F, $\pm 50\gamma$; H and Z, of the order of $\pm 100\gamma$.

Project MAGNET of the U.S. Oceanographic Office provided most of the airborne data. We used 52,000 data points taken during the period 1953 - 1963. In addition to MAGNET data, 13,000 values of the absolute airborne magnetic survey carried out by the Canadian Dominion Observatory during 1953 - 55 and 1957 - 61 were utilized.

The number of the ground measurements used is considerably less than that of airborne and marine ones. Their distribution over the world is very uneven. The major portion of measurements falls within Europe; the smaller amount, within Antarctica. Approximately 200 values of magnetic field measurements made on different islands scattered about the oceans, as well as the data from all the observatories, were used.

It is essential to note that recent magnetic surveys in the oceans by the Soviet nonmagnetic ship *Zarya* and the airborne magnetic survey of the U.S.A. and Canada, covering vast, previously unsurveyed areas of the oceans and the continents by a network of routes, secured a considerable improvement of magnetic charts. The southern hemisphere, however, especially in latitudes south of 40°, is poorly surveyed, and the charts of this region are less reliable.

For the construction of charts a graphical method of plotting isomagnetic lines was used with an interpolation between the observed magnetic values. For the regions where the earlier charts were used, the lines were moved a distance proportional to the summary value of secular variations. These are the territories of the Soviet Union, Finland, Germany, China, Italy, and some water areas.

The coordinates of the north magnetic pole, 75.1°N and 100.8°W, are given on the basis of observational results obtained by the Canadian expedition of 1962. The coordinates of the south magnetic pole, 67.5°S and 140.0°E, are given by the New Zealand expedition of 1962.

In order to coordinate world magnetic charts we compared a Z-chart compiled from the observed points with a Z-chart compiled on the basis of Z-values computed from F and H values read off from corresponding world magnetic charts. A good agreement was found between these charts.

In the northern hemisphere but excluding areas adjacent to the pole the accuracy of the F-, H-, and Z-charts may be estimated as $\pm 200\gamma$ on the average; D is $\pm 0.5°$. In the southern hemisphere the accuracy of each chart is considerably less due to insufficient data coverage. The charts of Antarctica are the least reliable ones.

World magnetic charts are widely used both in theory and in practice. On the basis of these charts the space structure of the geomagnetic field is studied, various kinds of analyses are made, and the separation of fields for geological purposes is performed. The charts are also essential for navigation. Besides the compiling of world magnetic charts, the less smoothed geomagnetic charts and the normal field charts for the U.S.S.R. are regularly compiled.

ORIGIN OF THE GEOMAGNETIC FIELD

DYNAMO THEORY

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INTRODUCTION

The dynamo theory of the earth's magnetic field suggests that the field is produced by a self-exciting dynamo in the earth's core. It is supposed that the material of the core is an electrically conducting fluid that is kept in motion by forces whose nature is quite uncertain. The fluid moves through the magnetic field producing an electromotive force (emf) that drives electric currents within the core. These currents produce the field.

There is no direct evidence of the correctness of the theory or that the suggested process does occur in the earth's core. Nevertheless, it is widely accepted perhaps because it is qualitatively the right sort of theory and because it is capable of detailed development from the fundamental laws of physics. The difficulty of providing an alternative theory and the fact that no other view seems likely to explain the magnetic fields of the sun and stars have also encouraged belief in a dynamo within the earth.

The theory can be developed in many directions; we consider the present state of the main aspects.

QUALITATIVE PLAUSIBILITY

On a small scale, a scale of tens of kilometres, the variations in the earth's magnetic field from place to place are related to geology, but on a large scale of thousands of kilometres, they are not. The small scale correlation with geology is irrelevant for our purpose; it is due to the magnetisation of near-surface rocks and has no relation to the origin of the main field itself. A satisfactory theory must invoke causes within the earth and in a region deep enough to be unaffected by geology. Again the time scale of magnetic change is quite different from the time scale of geology; at London the compass swung through 35° to 250 years, and from paleomagnetic studies we know that the field has repeatedly reversed in the past, a reversal being completed in a few thousand years. This time scale strongly suggests that the cause of change must lie in the liquid core. It is inconceivable that any large scale change, dynamical, chemical, or thermal, can occur in the mantle or crust in so short a time. Some kind of repeated catastrophe might be invoked to explain the reversals, though not, I think, with much plausibility, but the secular variation that we see today must be produced by the normal workings of the mechanism that generates the field.

The core is too hot to be ferromagnetic and, in any case, liquids are never ferromagnetic; it is therefore to be expected that the field is produced by electric currents in the core. A rough estimate can be made of the conductivity of an iron core; the value usually taken is 3×10^{-4} ohm^{-1} m^{-1} though *Stacey* [1967] has argued for a value ten times higher. With such conductivities, currents will decay in a period of the order of 10^4 to 10^5 years. Since this time is very short compared to the age of the earth, it is necessary to suppose that the currents are sustained by applied emf's. These might be of thermoelectric, chemical, or dynamo origin. Little consideration has been given to thermoelectric or chemical theories, but it appears difficult to get large enough emf's from the former, and the latter would have difficulty in explaining rapid changes and reversals.

Another type of theory supposes that the laws of electromagnetism require modification when applied to large bodies and that such bodies acquire a spontaneous magnetisation. The occurrence of reversals appears to present an insuperable difficulty to such views. Before reversals were generally accepted *Blackett* [1952] proposed a theory of this kind in which the magnetisation of large bodies was associated with their rotation; this theory predicted a decrease of the horizontal intensity with depth that was not confirmed by observations [*Runcorn et al.*, 1951]. A further difficulty of such theories is that they are too simple. At the earth's surface the dipole field predominates, but not overwhelmingly, the root mean square (rms) value of the vertical component of the nondipole field being 21% of that of the dipole. If the cause of the field lies within the earth, the nondipole field will increase rapidly with depth and, if it lies as deep as the surface of the core, it will there be comparable with the dipole field. A theory that modifies the fundamental laws of physics would need a subsidiary mechanism, perhaps a dynamo, to produce the complexity of this field and of the secular variation.

The absence of magnetic fields on the moon and Mars is no doubt due to their having no cores or only small ones [*Runcorn*, 1968]. From its density

Venus must have a core much like the earth's and might be expected to have a magnetic field; the fact that it has not is presumably connected with the slowness of its rotation, which will profoundly affect the motions. Little is known about the interiors of the outer planets, but it is likely that the material in their interiors is converted to a metallic form by pressure, and dynamos may well exist and be able to account for the field observed on Jupiter.

NONDYNAMO THEOREMS

There are two classes of theorems that restrict the systems that can function as dynamos. One restricts the symmetry of the fields that can be produced; the other restricts the field of flow.

Cowling [1934] proved that a dynamo could not produce a field symmetrical about an axis. This theorem may also be expressed in the more general form that a field cannot be produced by a dynamo if it contains a closed line of force or a closed line of zero field around which the curl of the field has always the same sign. It seems difficult to obtain any significant extension of this theorem. The theorem itself is less restrictive than it might appear, since fields in three dimensions do not, except in special cases, possess closed lines of force; the lines of force are usually space-filling curves.

The nondynamo theorems about the velocity field state that for a dynamo to sustain a field in a sphere the velocity vectors cannot be everywhere in parallel planes or on spheres concentric with the boundary. It has recently been shown by G. Roberts (unpublished) that there do exist dynamos whose velocities are symmetrical about an axis. This unexpected result shows how necessary it is to require strict proof of nondynamo theorems; it was rather easy to suppose that axially symmetric velocities could produce only axially symmetric fields and would therefore be excluded.

A very curious theorem has been proved by *Braginskii* [1964a]. He considered dynamos that have approximately axisymmetric velocities and fields and proved that, in the limit when the ratio of the symmetric to the asymmetric part of the velocity becomes very large, there can be no dynamo unless some term in the spherical harmonic expansion of the asymmetric part of the velocity field contains the sine and the cosine of a multiple of the longitude. This result has been proved to the second order in the ratio by *Tough* [1968] and *Tough and Gibson* [1969], but there is no reason to suppose that it is true for finite values of the ratio.

PROOF OF THE POSSIBILITY OF DYNAMOS

That dynamos exist is a commonplace; they can be bought in shops. Such dynamos, however, cannot plausibly be supposed to exist within the earth. The earth's core is a simply connected body of fluid with a high degree of symmetry. In fact, to a close approximation it has full spherical symmetry; such dynamos are called "homogeneous dynamos." For many years there were serious doubts whether motions in such a body could act as a dynamo. The engineers' dynamos are multiply connected and of low symmetry: is this essential or merely an engineering convenience? It was shown by *Backus* [1958] and by *Herzenberg* [1958] that a sphere of fluid can act as a dynamo. The central feature of both proofs is to show that a dynamo that is possible when only smoothly varying fields are considered is not destroyed by the inclusion of shorter wavelengths, that is, to show that an expansion in orthogonal functions converges. Herzenberg did this by confining the motion to two small parts of the fluid; the higher terms in the expansion of the field in one region due to motion in the other then fell off rapidly and convergence could be proved. This argument is typical of most of the work on dynamos that has led to rigorously proved theorems; some parameter in the problem is supposed small, and an expansion in this parameter is attempted. For Herzenberg the parameter is the ratio of the size of the two small regions, within which the motion is confined, to their distance apart; for Braginskii it is the ratio of the asymmetric to the axisymmetric field. In the proof of dynamo action by Backus the motion is supposed stopped at intervals to allow the shorter wavelengths to decay; the ratio of the times with and without motion then becomes an adjustable parameter. The theory of the Herzenberg dynamo has been further developed by *Gibson* [1968; 1969].

In recent years much work has been done on dynamos in unbounded fluids. *Braginskii* [1964b] has shown that dynamo action can occur in an infinite plane layer of fluid, and *Lortz* [1968] has obtained an exact dynamo solution for a helicoidal motion in an infinite three-dimensional fluid. *G. Roberts* [1970a] has shown that "almost all" three-dimensional motions periodic in space can act as dynamos. The field vanishes at infinity but has a scale larger than the wavelength of the motion. This is true for all values of the resistivity and all magnitudes of the velocity. The apparently paradoxical result is presumably restricted to infinite dynamos where the natural rate of decay can be reduced by enlarging the scale of the field until slow motions and low conductivities are sufficient to maintain the field. *G. Roberts* [1970b] has also shown that some, but not all, three-dimensional motions varying periodically in two orthogonal directions and constant in the third can act as dynamos.

Results for finite bodies of fluid have been obtained by *Childress* [1969] and by G. Roberts (unpublished); both have succeeded in fitting what were initially conceived as dynamos in infinite bodies of fluid into finite spheres.

The results of this recent work are of great interest; they suggest that large classes of motions, perhaps most sufficiently fast motions, will act as dynamos provided the known nondynamo theorems are circumvented.

A dynamo of the type postulated by Herzenberg has been constructed by *Lowes and Wilkinson* [1963; 1968].

NUMERICAL WORK

If it is desired to explore in detail the properties of a particular dynamo with a specified velocity field, then it is necessary to solve Maxwell's equations. Except in special cases, such as that of *Lortz* [1968], this can only be done numerically.

The equations for the field **B** are

$$\dot{\mathbf{B}} = \frac{1}{\mu k} \nabla^2\mathbf{B} + \text{curl}\,(\mathbf{v} \times \mathbf{B})$$
$$\nabla \cdot \mathbf{B} = 0$$

where μ is the permeability, k the electrical conductivity and **v** the velocity. The boundary conditions require **B** to be continuous at the surface of the conducting fluid and to join onto an external field that vanishes at infinity at least as rapidly as does a dipole field. This latter requirement cannot easily be met by a solution using finite differences on a bounded grid of points. It is, however, very easily dealt with for spherical bodies if the field is expanded in spherical harmonics. The equations for a steady dynamo then become a set of ordinary, second-order, linear, differential equations giving the radial functions of the spherical harmonics as a function of radius. The boundary conditions are homogeneous and linear and involve only the radial functions and their first radial derivatives. If the dynamo is not steady, the radial functions depend also on the time, and there is a term in the first time derivative. The general theory has been developed by *Elsasser* [1941, 1946, 1947] and by *Bullard and Gellman* [1954]. Except in trivial cases the set of equations is infinite. The steady dynamo presents an eigenvalue problem that determines the magnitude of the specified motion.

The equations can only be solved if they are truncated to a finite set, that is, if all harmonics of degree and order above some limit are ignored. Many methods may be used for solving the resulting finite set, but the only ones that have actually been employed are expansion in power series, expansion in orthogonal functions, and finite differences on a set of radial points. Orthogonal functions are clearly superior to power series; for a given accuracy they probably require about half the unknowns that finite differences do, but this advantage is partly compensated by the need to compute the functions. It is probable also that the eigenfunctions obtained by finite differences give a better warning if insufficient radial detail is being included.

The main problem that has been considered is to take a dynamically plausible velocity field and to attempt to obtain the magnetic field of the corresponding steady dynamo. The difficulty is to be sure that the results for the truncated set of equations resemble those for the infinite set and in particular to be sure that the eigenvalue of the velocity is near an eigenvalue of the infinite set. The equations are not self-adjoint and do not necessarily possess any real eigenvalues; an apparently satisfactory solution of the truncated set cannot be taken to imply the existence of a solution of the infinite set. On the other hand sufficiently good convergence as the truncation level is raised would strongly suggest the existence of a solution.

The first solutions were those of *Bullard and Gellman* [1954]. They took a motion with two rising and two sinking currents evenly spaced around the equator together with an angular velocity decreasing with radius. Solutions were obtained for various velocity fields of this kind including harmonics up to degree and order 2, 3, and 4. The eigenvalue showed no rapid increase as the truncation limit was raised from 2 to 4 and was widely regarded as encouraging. The work was done with one of the earliest electronic computers and could not be taken further until both speed and storage had increased. Both are now about 1000 times greater than they then were and *Gibson and Roberts* [1969] have taken the computations to degree and order 5. The results for a particular flow were:

Degree and order	2	3	4	5
Eigenvalue	66	83	76	143

It cannot be said that these suggest convergence.

Braginskii's work suggests a reason for the poor performance of this dynamo. The variation of the rotation with radius has been taken to be large compared to the radial velocities which is an approach to the limit considered by Braginskii, where the axially symmetric part of the velocity is large compared to the asymmetric part. Since the asymmetric part of the Bullard-Gellman dynamo contains only terms in cos 2φ (where φ is the longitude), we know that no solution exists in the limit, and it is likely that for the actual velocity field the solution will either have a large real eigenvalue or none at all.

Lilley [1970] has attempted to get better convergence by adding terms in sin 2φ. As the radius is divided into smaller intervals the convergence is excellent, and as the degree and order are increased up to 6 it is also much better than before, as is shown in Table 1 of the reference. It is scarcely possible to take the solution further by the direct calculation of the eigenvalues, since the amount of arithmetic becomes prohibitive; if, however, the solutions are already somewhere near their limiting form, it should be possible to use perturbation methods to improve them.

The solutions are interesting in that the field is predominantly toroidal. The poloidal part, including the dipole field, changes greatly and even reverses as the approximations are improved. It seems likely that the essential mechanism of Lilley's dynamo involves only toroidal fields and that the dipole field is a byproduct which is not essentially involved in the generation and maintenance of the field.

Rikitake and Hagiwara [1968] have considered nonsteady Bullard-Gellman dynamics including only harmonics up to the second degree.

DYNAMICS OF DYNAMOS

So far we have considered only kinematic dynamos, that is, dynamos in which the velocity of the fluid is specified. In fact the motion will be driven by forces and will be determined by the equations of hydrodynamics containing the electrodynamic force. These equations are

$$\rho\dot{\mathbf{v}} + 2\,\rho\Omega \times \mathbf{v} = \nabla p + \mathbf{I} \times \mathbf{B} + \eta\,\nabla^2\mathbf{v} + \mathbf{F}$$

where ρ is the density, Ω the angular velocity, p the pressure, $\mathbf{I}$ the electric current, η the viscosity, and $\mathbf{F}$ the applied force. The $\dot{\mathbf{v}}$ term is certainly negligible and so is the viscous term except perhaps in a boundary layer. We are therefore left with a balance between the applied forces, Coriolis force, the electromagnetic force, and the pressure. Since the curl of the pressure is negligible, the curl of the applied force is given by

$$\text{curl}\ \mathbf{F} = \text{curl}\ (\mathbf{B} \times \mathbf{I}) + 2\,\rho\ \text{curl}\ (\Omega \times \mathbf{v})$$

and can be found for any kinematic dynamo for which the velocity is specified and the field found from Maxwell's equations.

Such a calculation has not been made and would not, in itself, be of much interest. The physically interesting problem is to assume that the forces are those predicted from some theory and then to solve Maxwell's equations and the hydrodynamic equations simultaneously. A possible approach to this is to guess a velocity field, solve the kinematic dynamo problem, compute the forces, and then to adjust the solution empirically or by some systematic calculation until the required forces are obtained. No attempts at such a procedure have been made, and it would undoubtedly be a very large, perhaps an impracticably large, undertaking.

Two types of forces have been considered, thermal convection and precession [*Malkus*, 1968]. In the absence of any detailed development of the dynamical theory it is possible only to say that neither seems excluded as a dynamo mechanism. Even more important than the doubts about the nature of the forces are the doubts as to the scale of the motion. Even if the forces varied smoothly over distances of a thousand kilometres, it does not follow that the motion has the same scale or that the field has the scale of either the forces or the motion. It is usually argued that, as the electromagnetic forces are sufficient to stop the motion of a fluid element a few hundred kilometres across in a very short time, such small scales of motion will not occur. This is an example of the well known supression of turbulence by a magnetic field. This argument is plausible but, in the absence of a detailed discussion, it is impossible to say whether the result is correct. It may be that calculations such as those of Bullard and Gellman are wrongly based and that we should consider some kind of statistical dynamo involving turbulence in a magnetic field.

The only dynamos for which we have a detailed dynamical theory are disc dynamos. The simplest of these consists of a conducting disc rotating in a magnetic field parallel to its axis. Current is drawn by brushes in contact with the edge of the disc and with the axle and fed to a coil which provides the field. A single dynamo of this kind driven by a steady torque performs very curious oscillations [*Bullard*, 1955] but does not give reversals of field. In the presence of noise, however, it does reverse. Two dynamos with the disc of one connected to the coil of the other do show reversals [*Rikitake*, 1958; *Allan*, 1962]. The analogy between such simple systems and a homogeneous dynamo is remote, but the theory of the disc dynamo does illustrate the complexity of behavior that may appear when the nonlinear terms $\mathbf{v} \times \mathbf{B}$ and $\mathbf{I} \times \mathbf{B}$ become important.

OTHER RELATED PHENOMENA

The dynamo theory was devised to account for the existence of the earth's magnetic field. In addition to the existence of the field it should explain the secular variation, the westward drift of the minor features, the slower motion of the dipole, the coincidence of the long term average of the dipole with the pole of rotation, and the occurrence and properties of the reversals demonstrated by paleomagnetism. Qualitatively one can see how most of these things might fit into the yet-to-be-developed theory, but the gap between this and a quantitative calculation is considerable.

In the nature of things the dynamo in the core of the earth is inaccessible, and it is important to look for other lines of evidence. One of great potential interest is the electromagnetic couple between the core and the mantle and the correlation that it can produce between changes in the field and changes in the rate of rotation of the mantle [*Ball et al.*, 1968]; the existence of this correlation now seems well established.

The field of the sun should be very instructive since there we can see the surface of the conducting body. Analogy with the earth may not be close since in the sun the kinetic energy greatly exceeds the magnetic energy, and the dynamics of the motion will be completely different from those in the earth's core, where the magnetic energy is many orders of magnitude greater than the kinetic energy. The two fields have been compared by *Bullard* [1966].

Clearly the dynamo theory has raised more questions than it has settled.

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FLUID MOTIONS IN THE EARTH'S CORE AND ORIGIN OF THE GEOMAGNETIC FIELD

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SURFACE MOTION OF THE EARTH'S CORE

Vestine, Kahle, and Ball [*Vestine*, 1965; *Vestine and Kahle*, 1966, 1968; *Kahle, Ball, and Vestine*, 1967; *Kahle, Vestine and Ball*, 1967; *Ball, Kahle, and Vestine*, 1968] estimated fluid motion near the surface of the earth's core on the basis of the magnetic field and its time-derivative observed at the earth's surface. They made use of the induction equation

$$\frac{\partial \mathbf{H}}{\partial t} = \frac{1}{4\pi\sigma} \nabla^2 \mathbf{H} + \text{curl}\,(\mathbf{v}_1 \times \mathbf{H}) \qquad (1)$$

where $\mathbf{H}$, $\mathbf{v}_1$, t, and σ denote the magnetic field intensity, velocity, time, and electrical conductivity in the core; $\mathbf{H}$ and $\partial\mathbf{H}/\partial t$ at the core's surface can be extrapolated from those observed at the earth's surface by applying potential theory. Most of their studies were made on the assumption that the diffusion term $(1/4\pi\sigma)\,(\nabla^2\mathbf{H})$ can be ignored. One of the outstanding features of their results is a marked downflow in the central Pacific Ocean and a marked upflow in Africa.

In a different approach, *Rikitake* [1967] derived core motions by assuming that the geomagnetic nondipole field is created by an interaction between a strong toroidal magnetic field and convective motions. In the derivation it is also assumed that a steady state has been attained. A marked pair of upflow and downflow is found, respectively, under Africa and the central Pacific Ocean (Fig. 1) with a maximum velocity amounting to 0.001 cm/sec or a little smaller. It is interesting to note that these results are similar to those derived by Vestine, Kahle, and Ball, though the two sets of studies have different bases.

In any case it seems likely that near-surface motions of the core should be closely correlated with the nondipole field.

PRELIMINARY STUDY OF A CUBIC FLUID DYNAMO

Existence of a geomagnetic dynamo is important not only for the explanation of the origin of geomagnetism, but also for inferring large-scale motions in the core. However, the theory of a geomagnetic dynamo is by no means complete.

Steady states of the Bullard-Gellman dynamo model [*Bullard and Gellman*, 1954], which has been one of the stronger supports of the dynamo theory, were obtained on the condition that magnetic fields expressed by spherical harmonics of higher degrees

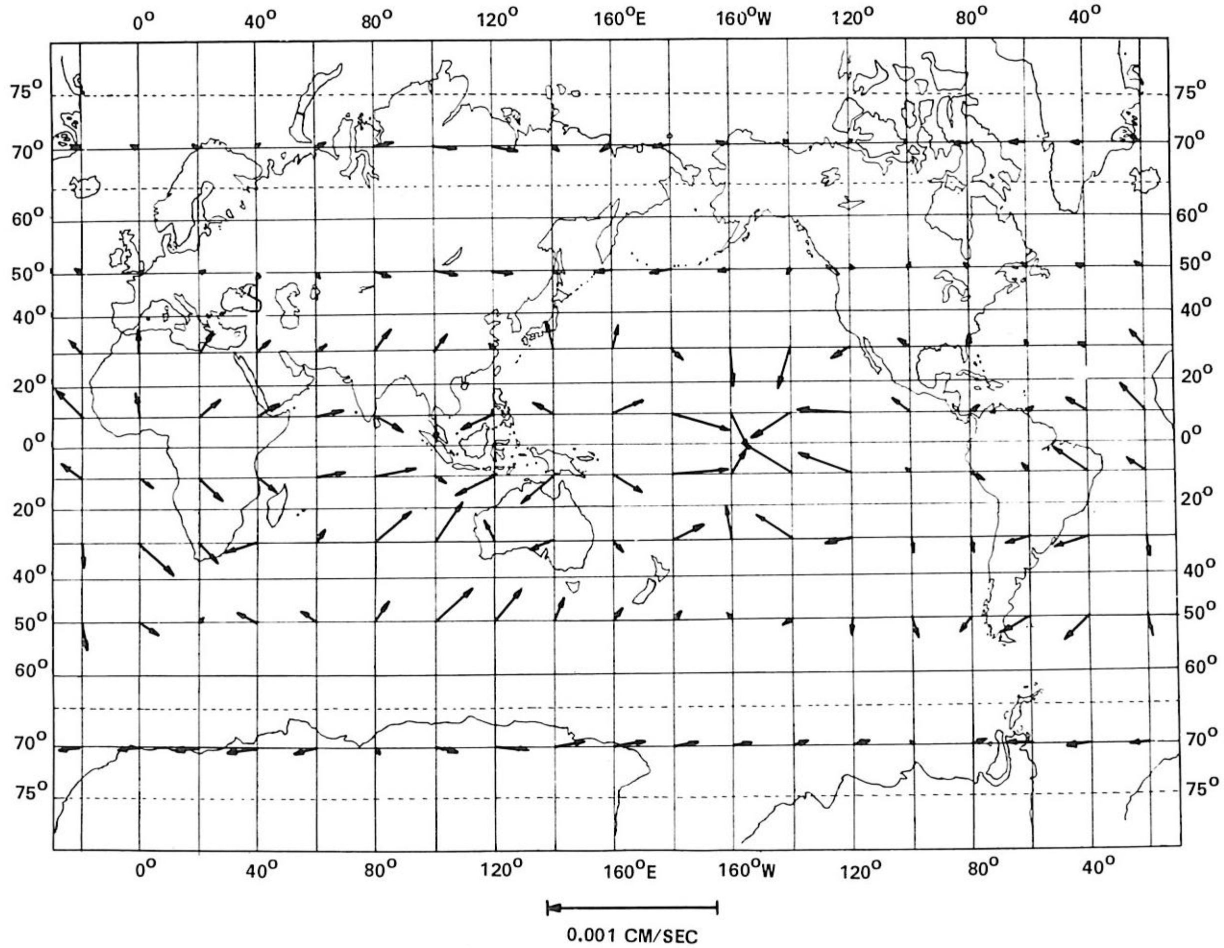

Fig. 1. The Horizontal Velocity at the Core's Surface for Epoch 1965.

can all be neglected. A recent study [*Gibson and Roberts*, 1967] of a similar model concluded, however, that no eigenvalue could be obtained if magnetic fields of higher order were taken into account. Theories [*Braginskii*, 1965; *Tough*, 1967] of dynamo action for a highly conducting fluid with motions slightly deviating from axisymmetry proved that the motion considered by *Bullard and Gellman* [1954] would not sustain a steady dynamo when the magnetic Reynolds number is large.

In the light of these recent findings, there is a renewed interest in finding dynamo models free from the above defects. The writer studied the problem of determining if all the analyses can be made in an entirely numerical way. One of the practicable ways would be to assume a fluid contained within cubic surface boundaries to avoid a singularity at the center. In practice, the space occupied by and surrounding the fluid is divided into numerous cubes, so that we may say that higher-order magnetic fields, of which the spatial extent is comparable with that of the unit cube, are taken into account. Although the cubic shape is not quite realistic for the earth's core, the writer hopes that essential points of the earth's dynamo would be represented by such a model.

For the fluid motion, velocity fields will be considered that do not violate Braginskii's criterion and that consist of two types of motion: axisymmetric flow and convective flow. Existence of such fluid motions in the earth's core would not be unreasonable to suppose. Growth of a magnetic field given to the zero-field state of the system will be studied, although no satisfactorily fine division can be made because of limited computer capacity. No attempt at obtaining an exact eigenvalue of steady state will be made because that problem would require spatial subdivisions much smaller than those presently used.

Equations to be Solved

The induction equation in a conducting fluid is given by Eq. (1) when the magnetic permeability is assumed as unity in electromagnetic units and the fluid is incompressible.

Following *Bullard and Gellman* [1954], the lengths, time, and velocities are measured in units of L, $4\pi\sigma L^2$ and $1/4\pi\sigma L$, respectively, where L denotes a typical length. In that case, Eq. (1) reduces to

$$\partial \mathbf{H}/\partial t = \nabla^2 \mathbf{H} + V \operatorname{curl}(\mathbf{v} \times \mathbf{H}), \tag{2}$$

in which t, V and $\mathbf{v}$ are dimensionless.

A relation

$$\mathbf{v}_1 = V\mathbf{v}/4\pi\sigma L \tag{3}$$

holds between $\mathbf{v}_1$, V, and $\mathbf{v}$.

Rewriting Eq. (2) in terms of components of the magnetic field and the velocity yields in rectangular coordinates x, y, and z,

$$\begin{aligned}
\frac{\partial H_x}{\partial t} &= \nabla^2 H_x + V\left(H_x \frac{\partial v_x}{\partial x} + H_y \frac{\partial v_x}{\partial y} + H_z \frac{\partial v_x}{\partial z} - v_x \frac{\partial H_x}{\partial x} - v_y \frac{\partial H_x}{\partial y} - v_z \frac{\partial H_x}{\partial z}\right),\\
\frac{\partial H_y}{\partial t} &= \nabla^2 H_y + V\left(H_x \frac{\partial v_y}{\partial x} + H_y \frac{\partial v_y}{\partial y} + H_z \frac{\partial v_y}{\partial z} - v_x \frac{\partial H_y}{\partial x} - v_y \frac{\partial H_y}{\partial y} - v_z \frac{\partial H_y}{\partial z}\right),\\
\frac{\partial H_z}{\partial t} &= \nabla^2 H_z + V\left(H_x \frac{\partial v_z}{\partial x} + H_y \frac{\partial v_z}{\partial y} + H_z \frac{\partial v_z}{\partial z} - v_x \frac{\partial H_z}{\partial x} - v_y \frac{\partial H_z}{\partial y} - v_z \frac{\partial H_z}{\partial z}\right).
\end{aligned} \tag{4}$$

It is obvious that the following equations hold outside the conductors:

$$\left.\begin{aligned} \nabla^2 H_x &= 0,\\ \nabla^2 H_y &= 0,\\ \nabla^2 H_z &= 0. \end{aligned}\right\} \tag{5}$$

Velocity field. Let us assume two types of fluid motion, their x, y, and z components being written as follows:

$$\text{T motion: } \mathbf{v}_T = \begin{cases} -\cos(\pi x/2)\sin(\pi y/2) \\ \sin(\pi x/2)\cos(\pi y/2) \\ 0 \end{cases} \tag{6}$$

$$\text{P motion: } \mathbf{v}_P = \begin{cases} \sin \pi x \cos \pi z \\ 0 \\ -\cos \pi x \sin \pi z. \end{cases} \tag{7}$$

The total velocity is then given by

$$\mathbf{v} = \epsilon \mathbf{v}_T + \mathbf{v}_P, \tag{8}$$

where ϵ is a constant which specifies the ratio of the T velocity to the P velocity. Equation (8) obviously

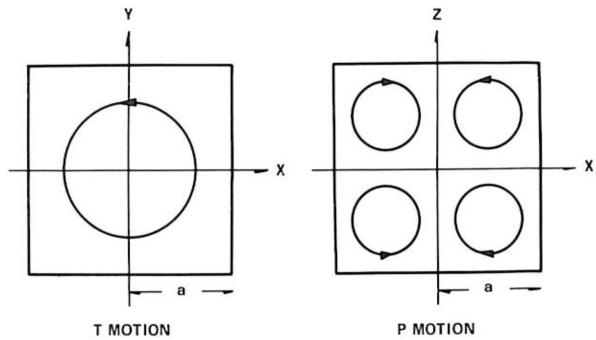

Fig. 2. Fluid Motions.

satisfies $\operatorname{div} \mathbf{v} = 0$. The two velocity fields are schematically shown in Fig. 2 in yx and zx planes. It is evident that the condition that the boundary is rigid is satisfied.

When we take cylindrical coordinates ρ, φ, and z of which ρ and φ are defined by

$$\left.\begin{aligned} \pi x &= \rho \cos \varphi,\\ \pi y &= \rho \sin \varphi, \end{aligned}\right\} \tag{9}$$

the radial component of velocity in a plane perpendicular to the z-direction can be written as

$$\begin{aligned} v_\rho = \frac{\epsilon}{\sqrt{2}}\Big[&\sin\left\{\frac{\rho}{\sqrt{2}}\cos\left(\varphi - \frac{\pi}{4}\right)\right\}\sin\left(\varphi - \frac{\pi}{4}\right) \\ &- \sin\left\{\frac{\rho}{\sqrt{2}}\sin\left(\varphi - \frac{\pi}{4}\right)\right\}\cos\left(\varphi - \frac{\pi}{4}\right)\Big] \\ &+ \cos z \sin(\rho\cos\varphi)\cos\varphi. \end{aligned} \tag{10}$$

Equation (10) can be rewritten in terms of Bessel functions, J_n's, as

$$\begin{aligned} v_\rho = \epsilon\sqrt{2}[&\{J_3(\rho/\sqrt{2}) + J_5(\rho/\sqrt{2})\}\sin 4\varphi \\ &- \{J_7(\rho/\sqrt{2}) + J_9(\rho/\sqrt{2})\}\sin 8\varphi \\ &+ \{J_{11}(\rho/\sqrt{2}) + J_{13}(\rho/\sqrt{2})\}\sin 12\varphi \\ &- \ldots\ldots\ldots\ldots\ldots] \\ &+ \cos z\,[J_1(\rho) \\ &+ \{J_1(\rho) - J_3(\rho)\}\cos 2\varphi \\ &- \{J_3(\rho) - J_5(\rho)\}\cos 4\varphi \\ &+ \ldots\ldots\ldots\ldots]. \end{aligned} \tag{11}$$

It is clear from Eq. (11) that the meridional velocity cannot be described only by cosine or sine terms with respect to φ. The velocity field considered does not therefore violate Braginskii's criterion for maintaining a steady magnetic field when

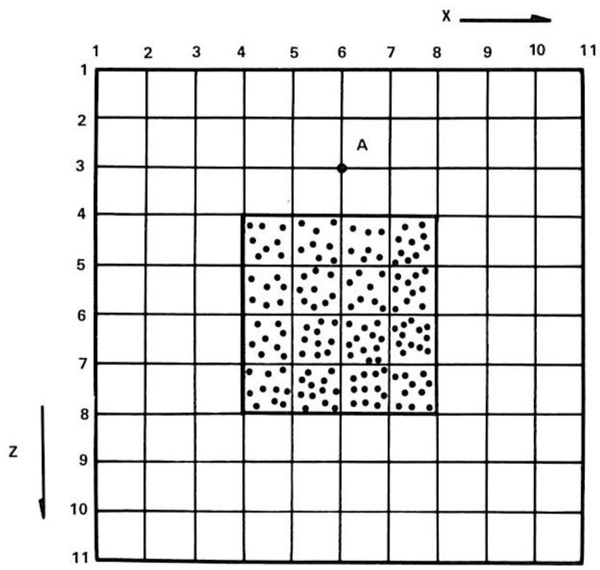

Fig. 3. Division of Space for Numerical Work. The Dotted Portion is Occupied by the Fluid.

the magnetic Reynolds number is large [*Braginskii*, 1965; *Tough*, 1967].

Boundary and initial conditions. The condition that should be satisfied at the fluid boundary is the continuity of the magnetic field components because the magnetic permeability is assumed as unity everywhere in electromagnetic units. The magnetic field must also vanish at infinity. In practice, the magnetic field components are fixed to be zero on planes parallel to the surfaces of the fluid cube at a finite distance.

It will be assumed in the numerical work that a uniform magnetic field of unit strength in a direction parallel to the z-direction is given to the system having no magnetic fields at $t = 0$. The time during which the field is applied to the system is so short that no external field is considered for $t > \Delta t$, Δt being the time interval of numerical integration of Eq. (4).

Numerical solutions. Let us start with the initial magnetic field components given at all the grid points in the fluid cube. It is then possible to estimate all the field components in the fluid cube and on the surface of a cube after a small time interval Δt by virtue of the difference form of Eq. (4) because the velocity components and their space derivatives are given. If we assume that all the field components are zero on the surfaces of the large cube, which represents the positions at infinity, it is possible to solve Eq. (5) numerically by making use of the relaxation method because the field components on the inner boundary are known. We thus determine the field components at all the grid points in the space bounded by the two boundaries. The same procedure can be repeated many times provided Δt is taken sufficiently small.

In the actual computation, the whole cubic region is divided into 10 by 10 by 10 small cubes. The fluid occupies the region of the inner 4 by 4 by 4 cubes. Figure 3 shows the cross section parallel to the xz-plane passing the center of the cube. Each grid point is specified by numerals indicated on the periphery. Point A, for instance, is designated by 6,6,3.

From Fig. 3, it is apparent that a much finer division of space should be made in order to reach an accurate solution. Equations (4) and (5) involve difference forms of the magnetic field components, so that it is desirable to divide the space as finely as possible for solving them accurately. However, the finest division possibly applicable for a HITAC 5020 computer now available at the University of Tokyo would be the one taken here. Even if we decrease the elements of the three-dimensional array from symmetry consideration, we still need 6 by 11 by 7 by 7 = 3234 storage locations for computing and storing the field components at all the grid points. Although more storage locations are required for definitive computations, the present division would be a practicable one for a preliminary study. Even though a computer having a drastically large capacity is required for getting at physically plausible solutions of a cubic dynamo, the writer hopes that some essential points of its time-dependent behavior would be brought to light by the present study.

In order to carry out successive integrations of differential equations of the heat-conduction type, it has been known that $\Delta t/(\Delta r)^2$ should not exceed a certain limit, Δr being the nondimensional length taken for the division of space. A limiting value cannot be easily obtained for equations as complicated as the present ones. But $\Delta t = 0.004$ combined with $\Delta r = 1$ seems to lead to satisfactory results.

If we assume that the inner cube simulates the earth's core, a in Fig. 2 may be taken as 3.5×10^8 cm. Since $a = 2L$ in the present calculation, the Δt amounts to 147 years provided we take a generally accepted value for the conductivity, $\sigma = 3 \times 10^{-6}$

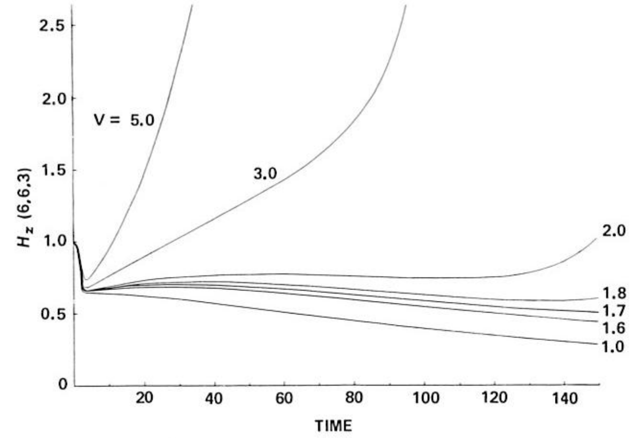

Fig. 4. *Changes in* H_z *at the Grid Point 6,6,3.*

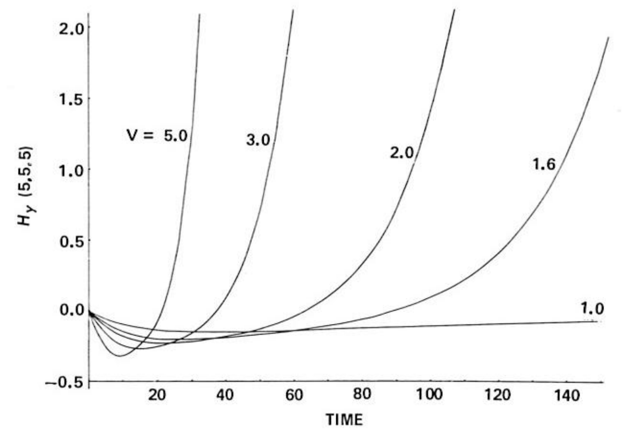

Fig. 5. *Changes in* H_y *at the Grid Point 5,5,5.*

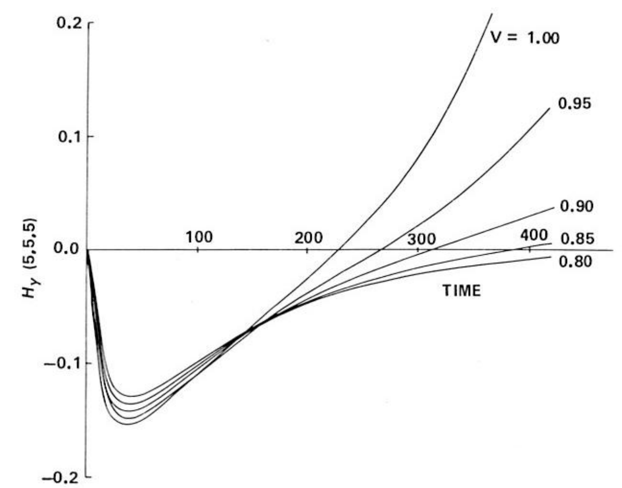

Fig. 6. *Changes in* H_y *at the Grid Point 5,5,5 for V Values around 0.9.*

emu, for example; $\epsilon = 10$ is also assumed throughout this paper.

Figure 4 shows how the z-component at a point (6,6,3) on the z-axis outside the fluid changes with time for a number of V values. When V is large, H_z, which indicates an initial decay for every case, tends to increase enormously. This means that dynamo action prevails for a large velocity. Conversely, H_z seems to decrease steadily for a V as small as 1.0 or thereabouts. It would not be possible, however, to continue the successive integrations indefinitely because of accumulation of computational errors. It does not seem practicable to continue the numerical integrations beyond $t = 150 \cdot \Delta t$ because of the time-consuming computer work.

For points inside the fluid, we can clearly observe growth of a toroidal magnetic field. Absolute values of H_X and H_y at a point (5,5,5), for instance, increase enormously for a large value of V as time goes on with frequent changes in sign. Such a field behavior can well be explained by a winding-up of the stretched magnetic lines of force about the z-axis. Figure 5 shows how $H_y(5,5,5)$ changes with time for a number of V's. Comparing Fig. 5 with Fig. 4, it is seen for V's around 1.0 or so that H_z outside the fluid continues to decrease even though H_y in the fluid tends to increase.

Discussion

Figure 4 indicates that the field of the system dissipates for small values of t but often tends to increase some time later because of the dynamo action. Although H_z (6,6,3) for $V = 1.0$ or so seems to be subjected to a simple decrease as can be seen in Fig. 4, it is apparent from Fig. 5 that $H_y(5,5,5)$ tends to increase after $t = 50 \cdot \Delta t$ or so.

To determine if the system reaches a steady state is of interest and importance for the dynamo theory. The numerical integrations are therefore extended to a t exceeding $400 \cdot \Delta t$ for the few values of V shown in Fig. 6, the interval of integration being taken as 0.01 in this case. The writer believes that no steady state has been attained in the present computation. If a steady state exists, however, the eigenvalue must be around $V = 0.90$, judging from the curves in Fig. 6. In the case of the Bullard-Gellman dynamo model [*Bullard and Gellman*, 1954], an eigenvalue amounting to 40–50 has been obtained for a similar fluid motion. It is not entirely clear why such a large difference exists between the Bullard-Gellman eigenvalue and that of the present model. Probably the reason could be understood if we take the following two points into account. A fairly large amount of energy seems to go out of the Bullard-Gellman model as higher mode fields, while in the present model some energy must be reflected back from the outer boundary, which is fairly close to the fluid mass because the field is assumed to vanish there.

It is interesting to note that for a V around 0.9, no field larger than the initial field can be maintained. The situation is much the same as that for nonsteady states of a Bullard-Gellman model [*Rikitake and Hagiwara*, 1968]. From the present model, it seems impossible to expect a magnetic field growing from a small stray field.

Although we cannot prove either the existence or nonexistence of a steady state of a cubic fluid dynamo, the point, that for certain values of V the system maintains a state for which changes in the magnetic field are extremely slow, seems to have an important bearing on geomagnetism. A computer program for determining eigenvalues and eigenfunctions when their approximate values are known is also formed although actual application will be postponed until a much finer spatial division becomes possible. The writer believes that a study on a cubic fluid dynamo similar to the present one but on a computer of larger capacity would certainly provide a better approach to either steady or nonsteady dynamo problems that are difficult to solve analytically.

SUMMARY

Surface motions of the earth's core have been estimated by Vestine, Kahle, and others on the basis of the knowledge of the magnetic field and its time-derivative observed at the earth's surface. It is assumed in the estimation that the magnetic lines of force move fixed to the highly conducting core material. Rikitake estimated the fluid motion in the core that may create the nondipole field on the assumption that a strong toroidal field in the core is distorted by the convective motions. The surface motions thus obtained roughly agreed with one another indicating an outstanding upflow in Africa and a downflow in the Pacific Ocean.

More regular motions of large scale in the core may be the ones that sustain the earth's dynamo for the dipole field. In recent years serious doubts have been cast on the fluid motion suggested for the Bullard-Gellman dynamo because of the influence of higher order magnetic fields worked out by Roberts, Gibson, Braginskii, and Tough.

A preliminary search for a fluid motion that resembles that of the Bullard-Gellman model was made by Rikitake and Hagiwara by assuming cubic boundaries. All the calculations were made in a numerical manner. Although it was not possible to prove or disprove a steady state of the dynamo, a quasi-steady state that lasts over a period much longer than the time of free decay of the magnetic field was found.

The writer is thankful to Dr. Y. Hagiwara who undertook most of the computer work in this paper.

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DYNAMO THEORY OF GEOMAGNETISM

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This paper gives a review of recent results in the theory of dynamos in homogeneous masses of fluid and presents a new discussion of Rikitake's self-reversing dynamo.

Dynamo theory is not only of obvious importance to geomagnetism but is also undergoing an explosive development at the present time.

The basic task of dynamo theory is to provide persistent source-free solutions of the induction equations

$$\frac{1}{R}\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{1}{R}\nabla^2 \mathbf{B} \qquad (1)$$

$$\nabla \cdot \mathbf{B} = 0 \qquad (2)$$

where **u** is the fluid velocity, **B** is the magnetic field, and R is the magnetic Reynolds number

$$R = \frac{UL}{\eta}, \left(\eta = \frac{1}{\mu\sigma}\right). \qquad (3)$$

Here σ is the electrical conductivity (mks units) of the fluid, μ is its permeability, η is its "magnetic diffusivity," U is a typical velocity of flow, and L is a typical length scale. To cast Eq. (1) in the dimensionless form shown, L has been chosen to be the unit of length, and L^2/η to be the unit of time, t.

By "source-free" we mean that the field is not maintained by currents "at infinity." In the case in which the fluid is confined to a fixed volume, V, this condition is met by insisting that on the surface of V, the field **B** is continuous in all components with a potential field $\nabla\Phi$ in the exterior of V, where $\Phi = 0(r^{-2})$ at great distances, r, from V. By "persistent" we mean that the magnetic field energy does not tend to zero as $t \to \infty$. The usual cases considered are those in which **u** is specified. The resulting fields **B** are called kinematic dynamos (described in the following section), in contrast to the hydromagnetic dynamos to be discussed later. In an effort to gain more understanding of the phenomenon of reversals an account will be given in the last section of integrations of the simple two-disk dynamo model proposed by *Rikitake* [1958].

This paper will exclude as far as possible material already included in another review by the author [*Roberts*, 1967a] and that contained in the proceedings of the NATO conference held in Newcastle upon Tyne, March 29 - April 4, 1967. These have been published only very recently by John Wiley and Sons in a book entitled, *The Application of Modern Physics to the Earth and Planetary Interiors.* This volume is simply referenced as NATO in the bibliography.

RECENT RESULTS ON THE KINEMATICAL DYNAMO PROBLEM

Cowling's Theorem: The Dynamo of Lortz

One of the most natural ways of trying to find a dynamo is [*Cowling*, 1933] to reverse the procedure: i.e., to assume the **B** to be maintained and then to seek a source-free singularity-free **u** that will satisfy the induction equations. Using this approach, Cowling proved his theorem that a dynamo cannot maintain an axially symmetric **B**, i.e., a field whose cylindrical polar (ω, φ, z) components are all independent of φ. Specializing to large ω, the result also shows that a dynamo cannot maintain a two-dimensional **B**, i.e., a field whose cartesian (x, y, z) components are all independent of one coordinate x, for example. Although axisymmetric and two-dimensional **B** are in this way excluded, *Lortz* [1968a] has recently shown how a curious compromise may be struck between the axisymmetric and the two-dimensional **B** to give a "helical" dynamo. This provides the simplest example of a dynamo so far constructed, the only one, in fact, for which a solution may be written in closed analytic form. Although the field has infinite magnetic energy, it does not appear to be maintained at infinity.

The Periodic Dynamos of Roberts

This subsection contains a brief report on the work of my colleague G. O. Roberts. Like Lortz, *G. O. Roberts* [1967, 1970, 1971] considered an unbounded conductor and thereby avoided the inconvenience of having to apply boundary conditions. The demand that there be no sources "at infinity" was met by requiring the magnetic field energy to be finite at all times, t (although, in the case of dynamo action, it may grow indefinitely). The motions considered were periodic in space (or in space-time, though this is not considered here). By periodic in space, we mean that three noncoplanar constant vectors, $\mathbf{l}_i$, exist such that

$$\mathbf{u}(\mathbf{x} + \mathbf{l}_i) \equiv \mathbf{u}(\mathbf{x}) \qquad (i = 1, 2, 3).$$

It was shown that any **B** of finite energy is a linear combination of fields of the form

$$\mathbf{B}(\mathbf{x},t) = \mathbf{H}(\mathbf{x})e^{pt+i\mathbf{k}\cdot\mathbf{x}}$$

where p and **k** are constant, and **H** is complex and of the same periodicity as **u**.

The mathematical advantages of considering periodic flows are twofold. First, the powerful tool of Fourier analysis becomes available. Second, by making k small, i.e., by making the primary length scale $(2\pi/k)$ of **B** large compared with the scale of **u**, the effect of ohmic dissipation can be rendered almost harmless.

Roberts has proven that "nearly all" such periodic motions give dynamo action at "nearly all" values of the magnetic Reynolds number, R. More precisely, using the norm

$$\|\mathbf{u}_1 - \mathbf{u}_2\|^2 = \int_V |\mathbf{u}_1 - \mathbf{u}_2|^2 \, dV,$$

where V is the unit cell of periodicity, he has shown that the motions for which dynamo action occurs form an open set with respect to this norm, with closure the set of all motions of the given spatial periodicity. Furthermore, if the dynamo functions for one value of R, then it does so for all R except, perhaps, for a set of discrete values, possibly countable, but with no finite point of accumulation.

A specific example of a working Roberts dynamo is the Beltrami motion ($\mathbf{u} \times \text{curl}\, \mathbf{u} = 0$)

$$\mathbf{u} = (\cos y - \cos z, \sin z, \sin y).$$

The Axisymmetric Dynamo of Roberts

It may be observed that the Beltrami motion is two-dimensional, although the field it will maintain is not two-dimensional. This raises the interesting possibility that, by analogy, dynamos may exist in which the motions are axisymmetric although the fields they maintain are not axisymmetric. To avoid confusion here, we should emphasize that many alternative demonstrations of Cowling's theorem [*Backus and Chandrasekhar*, 1956; *Cowling*, 1957; *Braginskii*, 1964a; *Lortz*, 1968] assume both **B** and **u** are axisymmetric. (The most recent of these amends the earliest and extends it to inhomogeneous $\eta = \eta\ (\omega, z)$.) Although these investigations do, perhaps, enhance the mathematical rigor of Cowling's result in this special case of axisymmetric **u**, they increase the danger of believing that Cowling's theorem excludes axisymmetric **u**, even for asymmetric **B**. *G. O. Roberts* [1972] disproves this by a very convincing example. The flow chosen was essentially the Beltrami motion wrapped into toroids and compressed into a unit sphere; more precisely

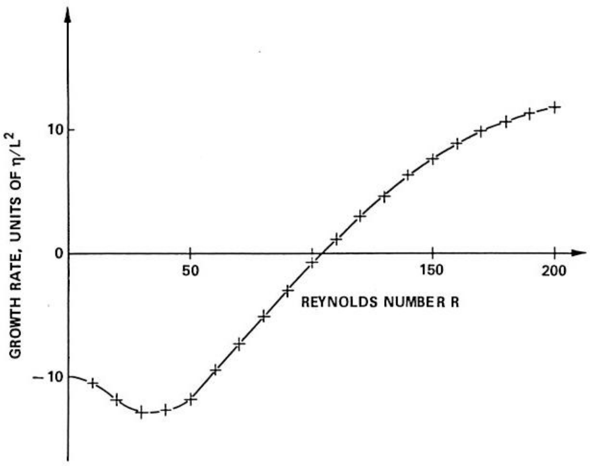

Fig. 1. Growth Rate of Dynamo Field for Various Reynolds Numbers.

$$\mathbf{u} = \left(-\frac{1}{\omega}\frac{\partial f}{\partial z}, \omega g, \frac{1}{\omega}\frac{\partial f}{\partial \omega}\right)$$

where

$$f = Pk^{-2}\,\omega \sin k\omega \sin kz \tanh k\,(1\text{-}r)$$

$$g = \frac{\sin kz}{\tanh kz} \sin k\omega \tanh k\,(1\text{-}r)$$

and k and P are constants $[r = \sqrt{(\omega^2 + z^2)}]$. In Fig. 1, a graph of the rate versus Reynolds number, R, is given for $k = 8$ and $P = 2$, where the rate is measured in units of η/L^2 where L is the radius of the sphere in physical units. It is clear that for $R \gtrsim 105$ the growth rate is positive, i.e., the field grows without limit. It may also be noted that for $R = 0$, the decay rate agrees to an 8-figure accuracy with the classical value of π^2 for a solid conducting sphere. For $P = 2$ and $k \lesssim 6$, the dynamo does not, apparently, function for any R.

The numerical technique of solving the induction equation in a sphere has hitherto been through the formalism of *Bullard and Gellman* [1954] in which **u** and **B** are divided into toroidal and poloidal parts that are then further subdivided into spherical harmonic components (see, for example, the following section). G. O. Roberts developed an alternative grid-point method of some independent interest.

The results of G. O. Roberts are easily the most compelling demonstration of dynamo action in a sphere that has been given to date.

The Dynamo of Lilley

The formulation of the steady dynamo problem by *Bullard and Gellman* [1954] has been touched on in the above section. The flow **u** is assumed to be a finite linear combination of toroidal (**T**) and poloidal (**S**) harmonics, and **B** can then be represented as an infinite series of similar harmonics. The defining scalars (T(r) and S(r)) for these field harmonics satisfy an infinite set of ordinary differential equations. In practice the series is truncated by discarding all harmonics whose degree, n, exceeds some value (N, for example). Moreover, the differential equations in r are represented by difference equations over , for example, K equally spaced grid points in (0, 1). The magnetic Reynolds number, R, appears as an eigenvalue, $V_{N,K}$, of the corresponding set of linear equations. The hope is that the numerical values of $V_{N,K}$ will give convincing evidence of convergence as $N \rightarrow \infty$ and $K \rightarrow \infty$.

Although the formulation of Bullard and Gellman was quite general their computational effort was confined to one example that they felt was a good candidate for dynamo action, viz.,

$$\mathbf{u} = \mathbf{T}_1 + \mathbf{S}_2^{2c}, \tag{3a}$$

where

$$T_1(r) = \epsilon r^2(1\text{-}r), \quad S_2^{2c}(r) = r^3(1\text{-}r)^2. \tag{3b}$$

(Here the suffix denotes harmonic degree, n, and the superfix, m, gives its φ-dependence and whether that dependence involves a cosine (c) or a sine (s) of $m\varphi$.) *Gibson and Roberts* [1967] examined this example in more detail. For $\epsilon = 5$, their best estimates of V were 66.5, 83.1, 76.0, and 143 for N = 2, 3, 4, and 5, respectively. *Lilley* [1970] has recently confirmed this trend for $\epsilon = 10$. For the same values of N he obtained values of $V_{N,14}$ of 50.4, 70.2, 75.0, and 102.3. Clearly there is no evidence of convergence.

Following Braginskii's lead (see the following section), *Lilley* [1970] also examined the flow

$$\mathbf{u} = \mathbf{T}_1 + \mathbf{S}_2^{2c} + \mathbf{S}_2^{2s}, \tag{4a}$$

where

$$T_1 = 10r^2(1\text{-}r^2), \; S_2^{2c} = r^3(1\text{-}r^2)^2,$$

$$S_2^{2s} = \begin{cases} 1.6r^3(1\text{-}4r^2)^2, & r \leq 0.5 \\ 0, & r \geq 0.5 \end{cases}. \tag{4b}$$

For the smallest eigenvalue, $V_{N,16}$, he obtained 24.92, 22.28, 17.76, 21.28, and 20.73 for N = 2, 3, 4, 5, and 6, respectively. Clearly there is evidence of convergence.

Braginskii's Dynamo Theory

It was already clear in the work of *Bullard and Gellman* [1954, see particularly p. 248] that, if unfavorable motions were chosen, the corresponding eigenvalues would be large and the eigenfunctions would have the structure of "main stream and boundary layer" familiar in hydrodynamic flows at large Reynolds numbers, and for which the well-developed techniques of singular perturbation methods are available. *Braginskii* [1964,a,b,c] capitalized on this idea by introducing the "almost" axisymmetric dynamo. Completely axisymmetric **B** requires infinite Reynolds numbers, and nearly axisymmetric **B** will require large magnetic Reynolds numbers. As the degree of asymmetry tends to zero and R tends to infinity, the Braginskii dynamo is set up. One could object that such large values of R are not relevant to the earth or, indeed, any cosmical situation, but it is not less true to say that infinite Reynolds numbers never occur in fluid mechanics, and yet the notions of boundary layers and matched asymptotic expansions are fundamental to that subject. Moreover, the basic flow and field visualized by Braginskii are in accord with general geophysical belief, viz., they are predominantly toroidal and axisymmetric. More precisely, the 0(1) parts of **u** and **B** are axisymmetric and in the φ-direction, their asymmetric components (**u**′ and **B**′) are $0(R^{-1/2})$, while their meridional axisymmetric parts, if present, are $0(R^{-1})$.

It is not the purpose of this review to repeat the details of Braginskii's analysis. The interested reader can refer to the original papers, or to expanded accounts [*Roberts*, 1967a; *Tough and Gibson* 1967]. In brief, Braginskii showed that if certain "effective" fields were introduced to replace the poloidal axisymmetric components of **B** and **u** these fields satisfied the modified induction equation

$$\frac{1}{R}\frac{\partial \mathbf{B}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{B} = \frac{1}{R}\nabla^2 \mathbf{B} + \nabla \times (\Gamma B_\phi \mathbf{1}_\phi), \tag{5}$$

$$\Gamma = \Gamma(u_\varphi, \mathbf{u}'),$$

an equation that had been anticipated in qualitative terms by *Parker* [1955]. The last (Γ) term represents the "source" of axisymmetric **B** created by the asymmetric flow **u′** and is $0(R^{-1})$. It would not serve any useful purpose to give its functional dependence on **u′** here, but we may observe that it may vanish identically for some flows and, if so, those flows will not give dynamo action in the Braginskii limit. Such, in fact, is the case for the flow (Eq. 3) chosen by Bullard and Gellman. Lilley carefully selected his flow (Eq. 4) so that $\Gamma \not\equiv 0$.

The analysis given by Braginskii to obtain the modified induction equation above is valid only to order R^{-1} in the expansion of **B**. *Tough* [1967] has shown that, however, with some suitable modifications to the effective fields, it is correct also to order $R^{-3/2}$. At first this suggested it might be true to all orders in the expansion in $R^{-1/2}$, but *S. Childress* (unpublished, 1968) has recently proposed a simple counter-example that shows that it does not hold to order R^{-2}.

THE HYDROMAGNETIC DYNAMO PROBLEM

Basic Equations

The formulation of the kinematic dynamo problem has the advantage of involving linear homogeneous equations and boundary conditions for **B**, a type of situation for which a considerable mathematical apparatus exists. In this linearity, however, the model contains the seeds of its own destruction, for it implies that, if a situation exists for which **B** persists without source as $t \to \infty$, then in fact $|\mathbf{B}| \to \infty$ (the case of constant amplitude is only possible by careful, and therefore artificial, arrangement). In practice, of course, this growth of field energy would be limited by nonlinear effects, particularly the feedback of the Lorentz force, which is quadratic in **B**, upon the fluid motion (Lenz's law). It is, then, necessary to discard the idea of specifying **u** and to suppose instead that **F**, a nonconservative body force per unit mass acting on the fluid, is given. Then an effort should be made to solve not only the induction equations governing **B** but also simultaneously, the Navier-Stokes equations governing **u**. As before, one would be interested only in cases in which **B** is source-free and persistent. This model, representing the next level of difficulty in the subject, is termed "the hydromagnetic dynamo problem."

Ultimately, still more complex models will arise in which a theory for **F** is also included. (So far, however, no one except Gilman has attempted this; see *Gilman* [1968], where earlier references may be found.)

In the case of the earth, the dominant terms in the equations of motion are the Coriolis and Lorentz forces (and a concomitant pressure gradient); it is easily shown that the inertial term $\mathbf{u} \cdot \nabla\mathbf{u}$ and (except in boundary layers) the viscous term $\nu \nabla^2\mathbf{u}$ are negligible (cf., e.g., *Hide*, 1956). The term $\partial\mathbf{u}/\partial t$ is also apparently small but it is convenient to retain it for the moment. In dimensionless units, we now have

$$R_d \frac{\partial \mathbf{u}}{\partial t} + \mathbf{l}_z \times \mathbf{u} = -\nabla p + (\nabla \times \mathbf{B}) \times \mathbf{B} + R^{-\frac{1}{2}}\mathbf{F}, \quad (6)$$

$$\nabla \cdot \mathbf{u} = 0. \quad (7)$$

Here p is pressure, $\mathbf{l}_z$ is a unit vector along the geographical axis, R_d is a Rossby number based on the velocity of diffusion, η/L, of lines of force (cf., e.g., *Roberts*, 1967c, Section 2.4d), and **B** has been measured in units of $\mathcal{B} = L\mathcal{F}(\mu\rho/2\Omega\eta)^{1/2}$, where $\mathcal{F}$ is a typical magnitude of **F** and Ω is the angular velocity. The typical value U of Section 1 is $L\mathcal{F}^2/4\Omega^2\eta$, and $R = (L\mathcal{F}/2\Omega\eta)^2$.

Nearly Symmetric Dynamos

Tough and Roberts [1968] have used Braginskii's technique on the hydromagnetic dynamo problem. With the scaling defined in the above section the same expansion scheme applies (u_φ and $B_\varphi = 0(1)$ and axisymmetric, $\mathbf{u}' = 0(R^{-1/2})$, etc.) and the treatment of the induction equation outlined in the section on Braginskii's dynamo theory may be taken over unmodified. Concerning the equations of fluid motion, it is found that, in the leading order in which **u** and **B** are axisymmetric and in the φ-direction, $2\Omega \times \mathbf{u}$ and $\mathbf{j} \times \mathbf{B}$ lie in meridian planes and are balanced by a gradient of (axisymmetric) pressure. None of these forces do work to this order since each is perpendicular to **u** everywhere. It is also easily shown that, in toto, there is no work done to $0(R^{-1/2})$ either. There is, nevertheless, an energy loss of order R^{-1} via the dissipation $(\nabla \times \mathbf{B})^2/R$ of the $0(1)$ field. This is made good by the working of an assumed asymmetric body force ($\mathbf{F} = \mathbf{F}'$) against the asymmetric components, **u′**, of flow.

A remarkable simplification occurs. It is found that the same effective axisymmetric fields as those introduced by Braginskii arise naturally from the hydrodynamical equation (Eq. 5) also, leading to the following equation governing the axisymmetric $\mathbf{u}$ and $\mathbf{B}$:

$$R_d \frac{\partial \mathbf{u}}{\partial t} + \mathbf{l}_z \times \mathbf{u} = -\nabla p + (\nabla \times \mathbf{B}) \times \mathbf{B} + \Lambda \mathbf{1}_\varphi, \qquad \Lambda = \Lambda(u_\varphi, \mathbf{u}', \mathbf{F}'). \quad (8)$$

The last (Λ) term represents the "source" of axisymmetric $\mathbf{u}$ created by $\mathbf{F}'$ and the asymmetric flow $\mathbf{u}'$ and is $0(R^{-1})$. It would not serve any useful purpose to give its functional dependence on these variables here, but we may observe that it may vanish identically for some flows (if $\mathbf{u}' \cdot \mathbf{F}'$produces a zero average over φ) and, if so, there is no energy source to maintain the axisymmetric components of $\mathbf{u}$ and $\mathbf{B}$; the dynamo will therefore not function. It is interesting to note that if $\mathbf{F}$ is supplied by buoyancy, it is likely to be asymmetric since, in a highly rotating sphere (such as the core) containing heat sources, the most unstable modes are asymmetric and give rise to a motion for which $\Lambda \not\equiv 0$ [*Roberts*, 1967b, 1968].

The theory of this nearly symmetric hydromagnetic dynamo is described fully elsewhere [*Tough and Roberts*, 1968] where it is displayed as a closed problem and where a procedure is outlined for its solution. The main difficulties are numerical and have not been overcome to date. They concern the derivation of $\mathbf{u}'$ from $\mathbf{F}'$ via the asymmetric parts of Eqs. (1) and (6). This problem is summarized in Eqs. (39) to (42) of the paper by Tough and Roberts already referenced. We should recall here that *Taylor* [1963] has laid down a general criterion that $\mathbf{B}$ should obey when Eq. (6) is satisfied in the case $R_d = 0$, and has further given a procedure whereby, when this criterion is obeyed, Eq. (6) may be solved for $\mathbf{u}$. In our case, Taylor's condition is not always applicable since the (Ekman) boundary layer on the core surface may create a suction which Taylor's theory does not admit. Nevertheless, a similar condition can be deduced and, when satisfied, we may similarly solve for $\mathbf{u}$ formally in terms of $\mathbf{B}$. This does not, however, help us to derive $\mathbf{u}'$ from $\mathbf{F}'$ since the expression obtained for $\mathbf{u}'$ involves an integral over $\mathbf{B}'$ that can itself, by use of the induction equation, be written as an integral over $\mathbf{u}'$. The Taylor type solution is then revealed as an integral equation, equivalent to the basic demand (Eq. 42) of the Tough-Roberts theory and equally intractable. Numerical procedures for solving this equation are still under investigation.

Application of the Bullard-Gellman Technique

If one writes Eq. (6) in the form

$$R_d \frac{\partial \omega}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{l}_z) + \nabla \times (\mathbf{j} \times \mathbf{B}) + R^{-\frac{1}{2}} \nabla \times \mathbf{F}' \quad (9)$$

where $\omega = \nabla \times \mathbf{u}$, and $\mathbf{j} = \nabla \times \mathbf{B}$, he sees that the Bullard-Gellman expansion method can be applied without change to the expansion of the first two terms on the right of Eq. (9) into poloidal and toroidal harmonics. One may now solve Eqs. (1) and (9) by time integration using, for preference, the well-known leap-frog method. At each time step the equation $\omega = \nabla \times \mathbf{u}$ must be integrated to extract $\mathbf{u}$ from the new ω predicted by Eq. (9). This involves solving a set of second-order equations for the poloidal harmonics of $\mathbf{u}$, a rapid process where the familiar algorithm for tridiagonal matrices is employed.

The total labor may be reduced by half by parity arguments. Define a scalar, S, to be even when $S(r, \theta, \varphi) = S(r, \pi - \theta, \varphi)$, and odd when $S(r, \theta, \varphi) = -S(r, \pi-\theta, \varphi)$. Define a vector to be even when its r and φ components are even scalars, and odd when these components are odd. It is easily seen that Eqs. (1) and (6) preserve the parity of a solution in which $\mathbf{B}$ and ω are odd, and $\mathbf{u}$, $\mathbf{j}$, $\mathbf{F}$, and p are even.

The disadvantage of time-stepping is its slowness. Its advantage is in storage, it being practical on our IBM 360/67 at Newcastle, for example, to store all seventy ω and $\mathbf{B}$ harmonics up to $n = 5$ for 50 grid points at two time steps. A program for this purpose is currently being tested.

It may be noted that, with the parity scheme given above, reversals (if they occur) will be accompanied by a reversal in toroidal field though not necessarily at the same moment in time.

REVERSALS: RIKITAKE'S MODEL AND GENERALIZATION

Rikitake's Model

In its simplest form, the model proposed by *Rikitake* [1958] consists of two identical frictionless disk dynamos, the current from each of which is used to

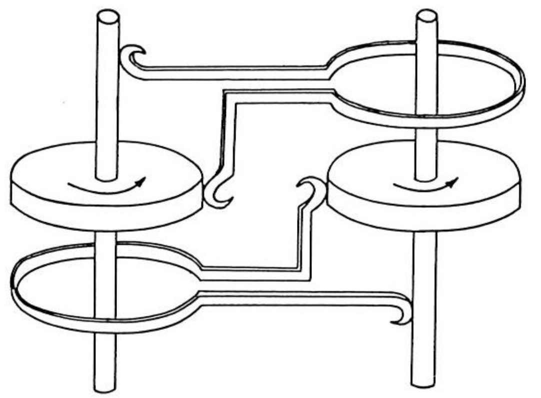

Fig. 2. A Dynamo Model, from Rikitake [1958].

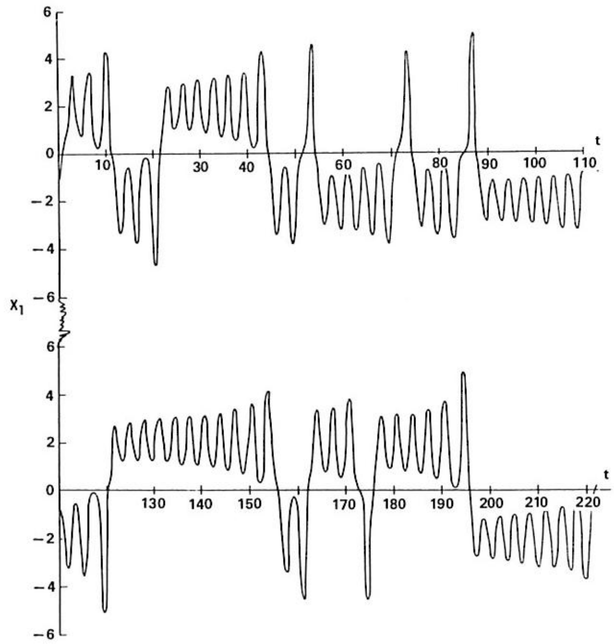

Fig. 3. Example of Field Oscillations ($\mu = 1$, $K = 2$).

provide the inducing field for the other (see Fig. 2). The dynamos are driven by identical torques that maintain the motion of the disks in the face of ohmic losses. The disks may be taken to resemble two large eddies in the core, each exciting the other after the manner of Herzenberg's dynamo [*Herzenberg,* 1958; *Gibson* 1967]. The torques may be likened to, for example, buoyancy forces turning the eddies. The neglect of frictional forces and the retention of resistive dissipation may be partially justified by the (probable) dominance of ohmic diffusion over viscous diffusion in the earth's core. Although these features of Rikitake's model duplicate the earth faithfully, the model is, of course, crude in several other respects, notably the neglect of anything to represent the dominance of Coriolis forces in the core. It is therefore not expected that the model will imitate the core in anything but the crudest qualitative way.

On measuring the currents, X_1 and X_2, in the coils, and the angular velocities, Y_1 and Y_2, of the disks in suitably scaled variables, the equations governing the motion may be reduced to the form

$$\left[\frac{d}{dt} + \mu\right] X_1(t) = Y_1(t)X_2(t), \quad (10)$$

$$\left[\frac{d}{dt} + \mu\right] X_2(t) = Y_2(t)X_1(t), \quad (11)$$

$$\frac{d\,Y_1(t)}{dt} = 1 - X_1(t)X_2(t), \quad (12)$$

$$\frac{d\,Y_2(t)}{dt} = 1 - X_2(t)X_1(t). \quad (13)$$

Here μ^2, the only dimensionless parameter remaining, is the ratio of a mechanical time scale of the system to its electrical time constant. Equations (12) and (13) show immediately that

$$Y_1 - Y_2 = A = \text{constant}. \quad (14)$$

Equations (10) to (13) admit two steady solutions

$$X_1 = \pm K,\ X_2 = \pm K^{-1},\ Y_1 = \mu K^2,\ Y_2 = \mu K^{-2}, \quad (15)$$

where $A = \mu(K^2 - K^{-2})$. Without loss of generality we may take $A > 0$ (i.e., $K > 1$) since otherwise the roles of the dynamos are merely reversed. We refer to the upper sign in Eq. (15) as "the normal state" and the lower sign as "the reversed state."

Integrations of Eqs. (10) to (12) and (14) have been performed by *Allan* [1962], *Lowes* (unpublished), by *Somerville* [1967], and by *Cook and Roberts* [1970]. I will concentrate on the work of the latter. This shows clearly that, unless the dynamo is set off precisely in one of the steady states (Eq. 15), it will oscillate irregularly about each of them forever. Figure 3 shows a particular example of this ($\mu = 1$, $K = 2$). A linear stability analysis of motion in the neighborhood of a state (Eq. 15) suggests that the system will indefinitely execute sinusoidal oscillations about it of frequency $\sqrt{(K^2 + K^{-2})}$. When nonlinearity is allowed for, however, it is found that the solution will systematically depart from that state through oscillations of ever-increasing amplitude until reversal occurs.

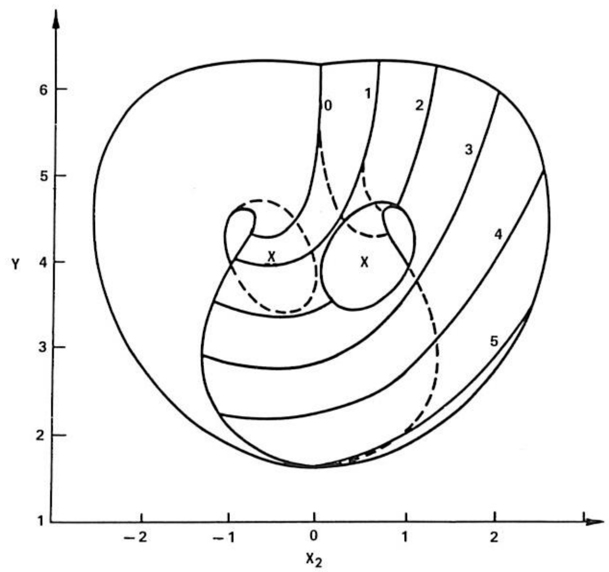

Fig. 4. Dynamo Trajectory for $K = 2$ and $\mu = 1$.

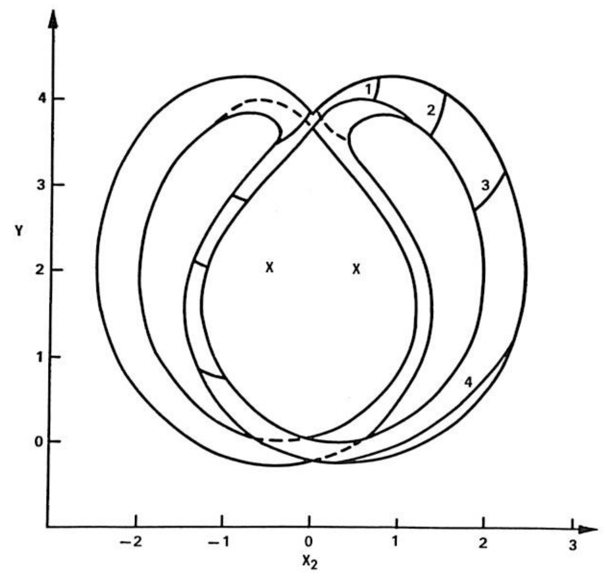

Fig. 5. Dynamo Trajectory for $K = 2$ and $\mu = 0.1$.

Although a diagram such as Fig. 3 is informative, a more revealing description of the dynamo is obtained by plotting its trajectory in (X_1, X_2, Y)-space, where $Y = Y_1$. It may be shown [*Allan*, 1962] that, as $t \rightarrow \infty$, nearly all orbits approach arbitrarily close to a two-dimensional limit surface in this phase space (see also *Lorenz*, 1963). This has been confirmed by Cook and Roberts using both digital and (with the assistance of J. Dobson) analog computers. The surfaces they obtain depend on μ and K, but are always double-connected. In Figs. 4 and 5 they are shown in (X_2, Y) projection for $K = 2$, $\mu = 1$, and for $K = 2$, $\mu = 0.1$, respectively. Some contours of constant X_1 are given and labeled when $X_1 > 0$. The corresponding negative X_1 contours can be imagined to be placed symmetrically to the left. The surface consists of two sheets, an upper right-hand sheet and a lower left-hand sheet. The boundaries of the latter are shown dotted when they lie below the former. Each lobe contains an "inner" loop that surrounds one of the states (Eq. 15); i.e., these states do not lie on the limit surface, implying that ultimately, as the orbit traverses the limit surface, oscillations about states (Eq. 15) will be of finite amplitude. The trajectory describes a path clockwise about the right-hand loop and counterclockwise round the left-hand loop. The nearer it is initially to either of these loops, the longer it will remain in its vicinity, i.e., the greater will be the number of (finite amplitude) oscillations about the corresponding state (Eq. 15). It will, however, systematically depart from the loop and ultimately pass to the other sheet via their join, the existence of which is indicated in Figs. 4 and 5 in the area $Y > \mu K^2$ of the limit surface. Sometimes the orbit will reverse, only to revert to its original polarity at once ("polarity event"); at other times it will oscillate many times about a loop before reversing ("polarity epoch"). In fact, the behavior is strikingly similar to that revealed by the geological record over the last four million years (cf., e.g., *Cox*, 1968).

A search was made for precisely reversing solutions of Eqs. (10) to (12) and (14), using a modified Davidon method [*Davidon*, 1959; *Fletcher and Powell*, 1963], the function minimized being

$$F(X_1(0),X_2(0),Y(0),\tau) = [X_1(\tau) + X_1(0)]^2 + [X_2(\tau) + X_2(0)]^2 + [Y(\tau) - Y(0)]^2, \quad (16)$$

and the minimization being performed over the initial values, $X_1(0)$, $X_2(0)$, and $Y(0)$, of X_1, X_2, and Y and over τ, the period between normal and reversed states. The presence of a zero F solution would imply a dynamo periodic in perpetuity. In fact, no evidence was found that such solutions existed. Local minima were found, however, corresponding to "almost periodic" solutions of a greater (small F) or lesser (large F) degree of permanence.

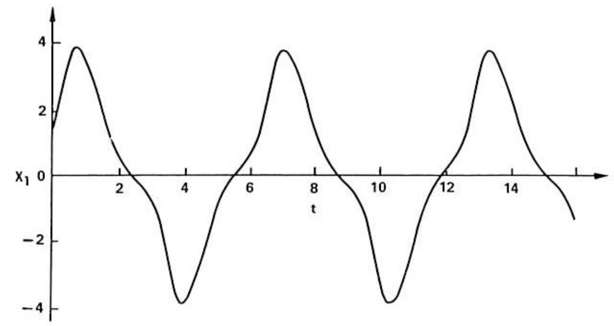

Fig. 6. Nearly Periodic Solution for $K = 2$, $\mu = 0.6$.

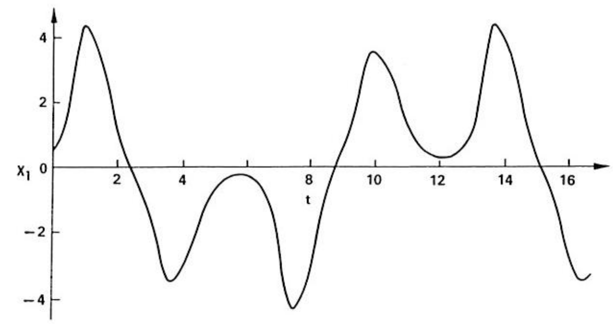

Fig. 7. Nearly Periodic Solution for $K = 2$, $\mu = 0.6$.

For small μ only one such minimum was found. For larger μ, two minima were observed. Those shown in Figs. 6 and 7 are for the case $K = 2$ and $\mu = 0.6$. They show, respectively, a fairly stable single oscillation and a rather permanent double oscillation. It was observed that, even when an integration was started far from an almost periodic solution, the orbit, when describing the limit surface ergodically, would tend to linger longest in the vicinity of the almost periodic solution(s).

Generalizations of Rikitake's Model

Two generalizations of Rikitake's model have been investigated by *A. E. Cook* (unpublished). One includes the effects of time delays by replacing the right-hand sides of Eqs. (10) to (13) by, respectively, $Y_1(t)X_2(t\text{-}\tau)$, $Y_2(t)X_1(t\text{-}\tau)$, $1\text{-}X_1(t)X_2(t\text{-}\tau)$, and $1 - X_2(t)X_1(t\text{-}\tau)$, where τ is the (constant) time delay. In its geophysical context, this modification is intended to allow qualitatively for the diffusive and/or Alfvénic transmission times between the two interacting eddies.

For small τ, the solutions (after the decay of transients) tend to equality ($X_1 = X_2$, $Y_1 = Y_2$), therefore behaving like a *Bullard* [1955] single-disk dynamo with time-delay. As τ approaches twice a reversing period of the almost periodic solutions described in the section on Cowling's theorem, however, the orbit behaves quite irregularly, neither revealing any tendency to behave as a single Bullard dynamo nor holding any promise of falling onto a limit surface.

The second generalization, referred to above, concerns two disk dynamos of different properties driven by different couples. This, besides being more realistic, is preferred by those who (instead of the two eddy picture) liken, in qualitative terms, the field produced by one disk to the poloidal field of the earth, and that produced by the other to its toroidal field. Nevertheless, the general unsymmetric case involves too many dimensionless parameters for any degree of comfort, or completeness, and attention has been restricted to the case of identical dynamos driven by different couples. It is easily shown that Eq. (14) does not then hold. Indeed $Y_1 - Y_2$ grows linearly in time. To prevent this unrealistic feature and also to restore the effect of viscosity hitherto omitted, the frictional torques λY_1 and λY_2 are added to the left of Eqs. (12) and (13), respectively. It is then easily shown that, as $t \rightarrow \infty$, an integral of the form displayed in Eq. (14) is asymptotically attained and that it is then again possible to work with the variables X_1, X_2 and $Y(= Y_1)$ alone. As before, a limit surface exists in this space. For small λ there are three steady-state solutions: one pair (normal and reversed) being close to those given in Eq. (15), and one being a nonmagnetic solution ($X_1 = X_2 = 0$). For small λ, the structure of the limit surface is much the same, though there is a noticeable tendency for the orbit to remain longer in the vicinity of an inner loop before reversing.

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MAGNETIC ANOMALIES

TYPES OF MAGNETIC ANOMALIES MEASURED ON LAND AND GENERAL ASPECTS OF THEIR GEOLOGICAL MEANING

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PREFACE

In this paper magnetic anomalies shall be considered as they appear on charts with a scale between 1:50,000 and 1:10,000,000. The anomalies can be obtained by airborne measurements in profile grids with a spacing between 500 m and 10 km or by equivalent ground surveys. A standard field comprising the dipole field and its anomalies of continental dimensions is subtracted.

REMARKS ON THE MAGNETIZATION OF GEOLOGICAL BODIES

Such a chart shows anomalies that are the proper magnetic fields of geological bodies. These bodies are, generally speaking, volume parts of the earth's crust, the magnetization of which is different from that of the surrounding crust in at least one of two properties: mean magnetization and magnetic fluctuation. From experience, the following can be stated: the amplitude of fluctuation is in most cases in the same order of magnitude as the mean magnetization; a fracture smaller than 1/10 can hardly be found in a geological body. The magnetic fluctuations are produced by inhomogeneities in the distribution of magnetic minerals, in their magnetization, and in the lack of petrological uniformity in the composition of the whole body. The "wavelength spectrum" of the magnetic fluctuations ranges from cm to km or more; the upper end of the spectrum depends on the extension of the volume part, which is considered as a "body."

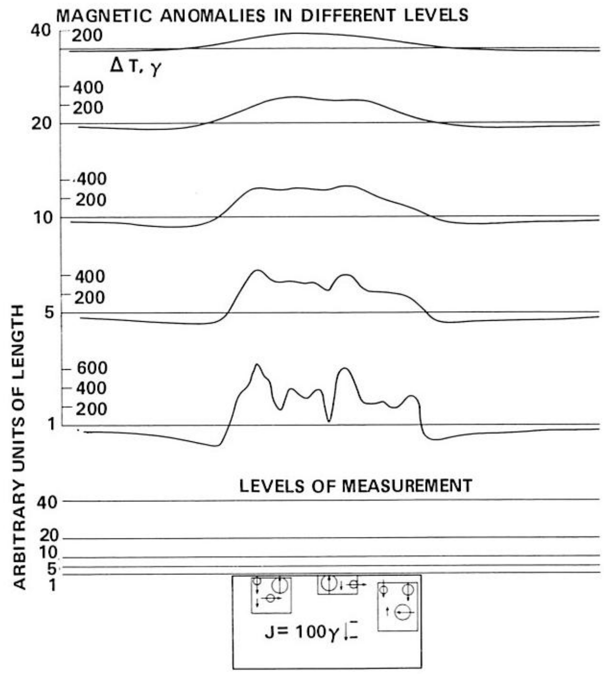


Fig. 1. Two-Dimensional Model for an Inhomogeneously Magnetized Body and ΔT Profiles in Different Levels (Inclination $i = 90°$). The Magnetizations of the Large Rectangular Body and of its Subvolumes are Indicated by Arrows in a Uniform Scale. The Magnetizations of the Subvolumes are Superimposed on the Magnetization of the Bigger Units.

An inhomogeneously magnetized volume can be considered as a superposition of a volume with a homogeneous magnetization and subvolumes with different (but homogeneous) magnetizations that on their part involve smaller subvolumes with different magnetizations, etc. The anomaly produced by this assembly is, of course, a very complex one. If the distance to the measuring point is increasing, however, the anomalies of the small volumes decrease much quicker than those of the big volumes, and, hence, the anomaly becomes smoother. This is demonstrated schematically in Fig. 1. As can be seen, the "wavelength" of the smallest detectable fluctuations of the anomaly is of the same magnitude as the distance from the measuring level to the body's surface. Hence, volume parts with diameters equal to this distance may be considered as homogeneously magnetized.

The proportions shown in Fig. 1 allow a very simple estimation of the depth to the upper surface of the magnetized bodies by simply taking the distance maximum-minimum or the half-width values of the fluctuations of its anomaly as a measure for this depth. On the other hand, in an aeromagnetic map these characteristic lengths are equal to or larger than the ground clearance of the survey. Therefore, in order to comprehend all details of the field in a certain level the profile spacing should not exceed the twofold vertical distance to the top of the magnetized bodies. Such a dense measurement, however, is in most cases considered to be too expensive. The maps resulting from profiles that are spaced larger than indicated above show in critical areas a more or less random assemblage of "anomalies" directed preferably perpendicular to the direction of the measuring profiles. The direction of anomalies of this type naturally does not have any geological meaning. Figure 2 shows two examples of measurements above outcropping igneous rocks, the ground clearance amounting to 350 m and 1100 m, respectively, and the profile spacing 2.2 km. In the second case, the field is represented rather well but possibly not completely.

This should be borne in mind when drawing conclusions from the shape of small anomalies.

THE GEOLOGICAL MEANING OF THE MAGNETIZED BODIES

The amount of magnetization of different groups of rocks that depends mainly on the rocks' content of titaniferous magnetite can be characterized as follows:

	Magnetization (γ)		
Magnetite iron ore	100,000	3000	1000
Basic igneous rocks	3000	300	1
Basic metamorphic rocks	1000	100	0
Acid igneous and metamorphic rocks	300	10	0
Sedimentary rocks	100	0	0

The numbers shown in the left column represent the order of magnitude that only in rare cases is exceeded; the center column represents the order of magnitude as it is usually found. The numbers in the right column show that, except for the iron ore, all groups of rocks contain single rock types that have so weak a magnetization as to be practically nonmagnetic.

As a consequence of this distribution of magnetization in areas with thick sedimentary layers, the depth of the underlying metamorphic or igneous basic rocks can be estimated from the shape of their magnetic anomalies because the anomalies produced by the sediments are so small that they cannot essentially disturb the basement anomalies. Only the anomalies of basic intrusive or extrusive rocks may be apt to do so. Another consequence is that in areas of outcropping metamorphic or igneous rocks the outcrops of acid and basic rocks can often be distinguished by the different amplitude of the corresponding anomalies. A coordination of this type, however, is usually restricted to a limited area of 100 - 1000 km in diameter.

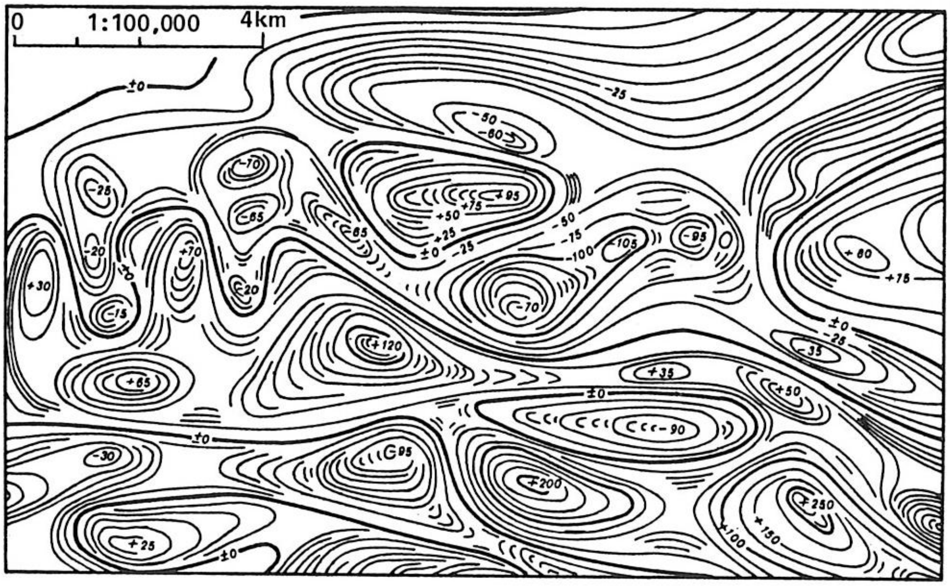
Some examples of magnetic anomalies above areas of different geological type are given in the following section.

EXAMPLES OF ANOMALY TYPES

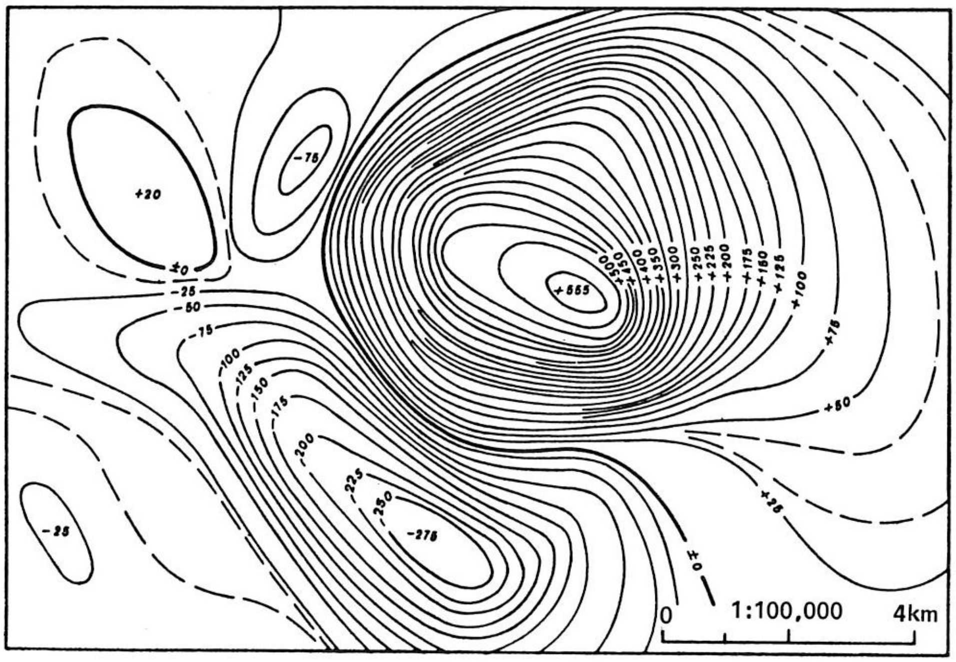
Old Shield Area

In areas of this type, the largest part of the surface is formed by outcropping metamorphic rocks, in some places intercalated by igneous rocks. The metamorphic rocks usually consist of folded layers that show displacements by tectonic faults and flexures with radii of different lengths. The entire arrangement is cut by the present surface. Since the amount of magnetization is changing from one layer to the next, the magnetic anomalies usually give a good representation of the tectonic structure of such an area. The near-surface structures are represented most clearly; for deeper-lying structures only the big trends can be detected. Figures 3 and 4 give examples of an aeromagnetic survey in northwestern Canada. The strong anomalies in Fig. 3 are "believed to be caused by tuffaceous iron formation in

ANOMALY VALUES ARE IN UNITS OF GAMMAS.



EFFECT OF RATIO PROFILE SPACING/GROUND CLEARANCE = 2.2/0.3



EFFECT OF RATIO PROFILE SPACING/GROUND CLEARANCE = 2.2/1.1

Fig. 2. Example of the Effect of the Ratio "Profile Spacing"/"Ground Clearance". The Profile Spacing is 2.2 km, the Ground Clearance (a) 350 m, (b) 1100 m. Details of the Aeromagnetic Survey of Germany (a) Westerwald, 60 km North of Frankfurt (b) Kaiserstuhl, Rhine Rift Valley.

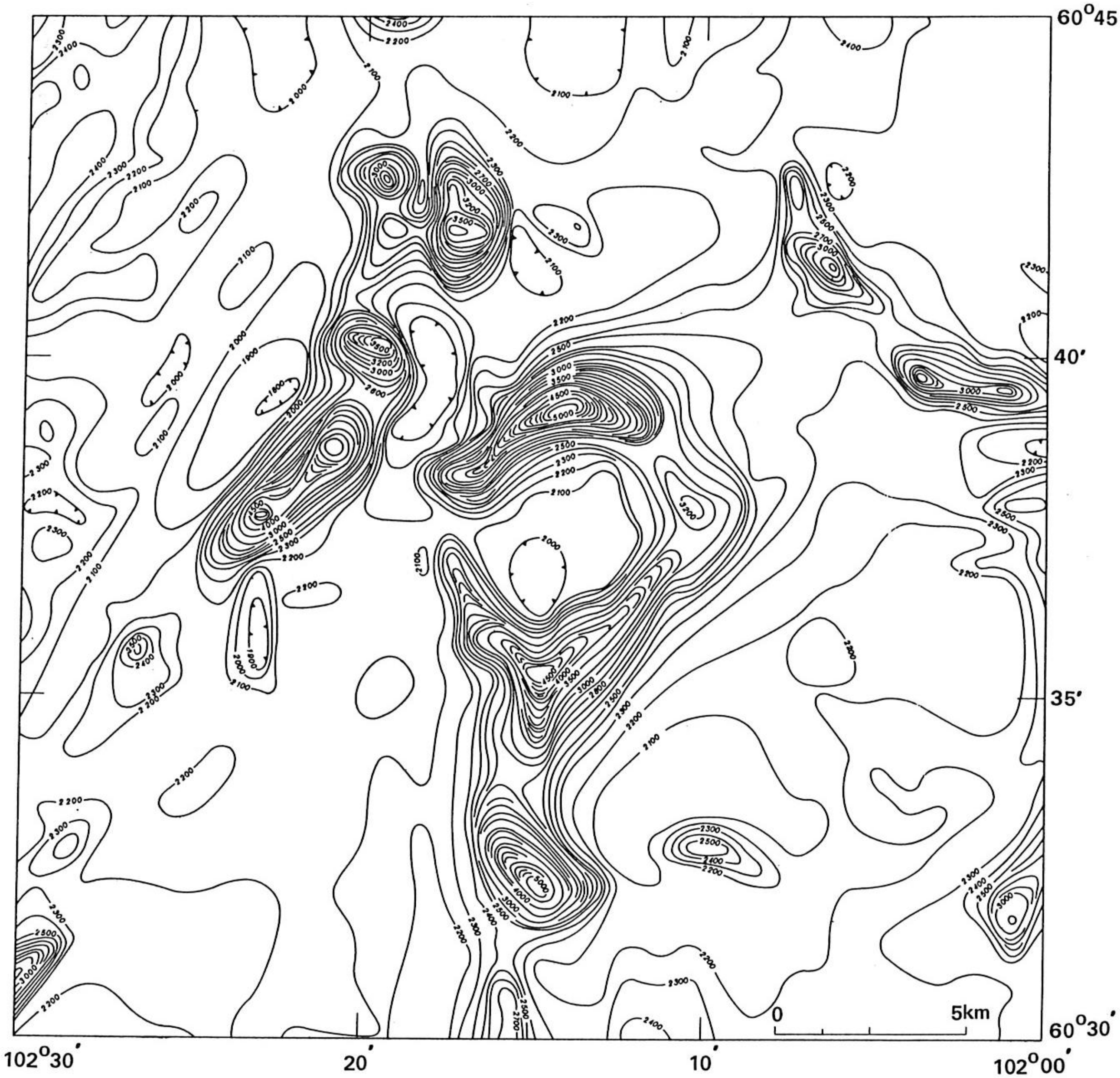


Fig. 3. Anomalies in Gammas of Outcropping Metamorphic and Igneous Rocks—Canadian Shield, Northwestern Canada. After Geological Survey of Canada, Aeromagnetic Series, Sheet 65 D/9.

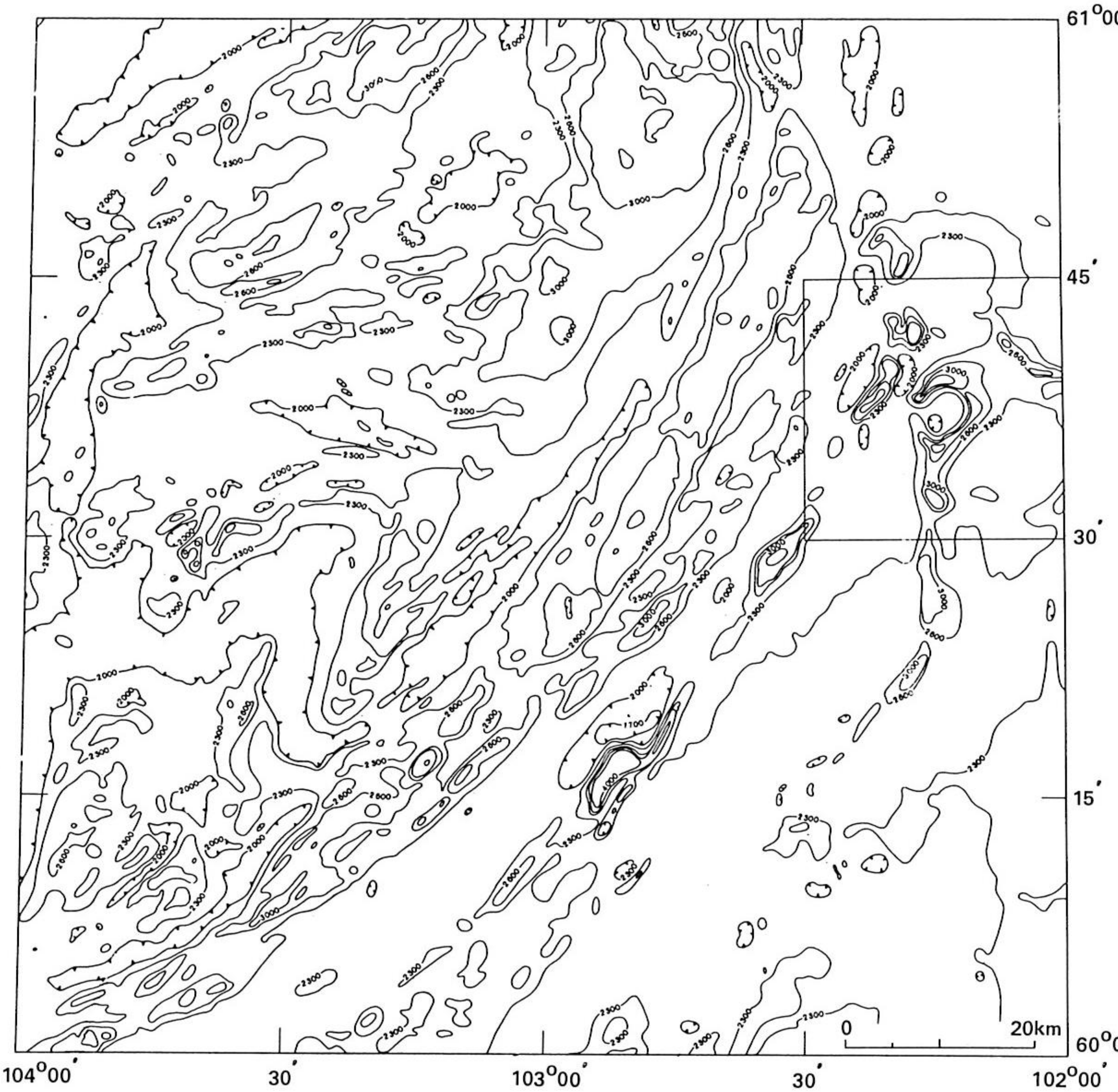


Fig. 4. Anomalies in Gammas of Outcropping Metamorphic and Igneous Rocks. Compilation of Section Shown in Figure 3 and Sections Shown on Adjacent Sheets—Canadian Shield, Northwestern Canada. After Geological Survey of Canada, Aeromagnetic Series, Sheet 65 D.

country rocks composed of meta-sediments, granite and granodioritic intrusions, and weakly ferromagnetic gneisses" [*MacLaren*, 1959].

Sedimentary Basin

Figure 5 represents a section of the regional aeromagnetic survey of the United Kingdom. The section is situated on the southern coast of England. Here metamorphic and igneous rocks are buried below a cover of sedimentary rocks, the thickness of which is estimated to be more than 6000 m in the area north of Southampton [*Terris and Bullerwell*, 1965]. The difference from the survey above the old shield is obvious. The anomalies are smooth and large due to the large distance between the measuring level and the magnetized bodies, the sediments being practically nonmagnetic.

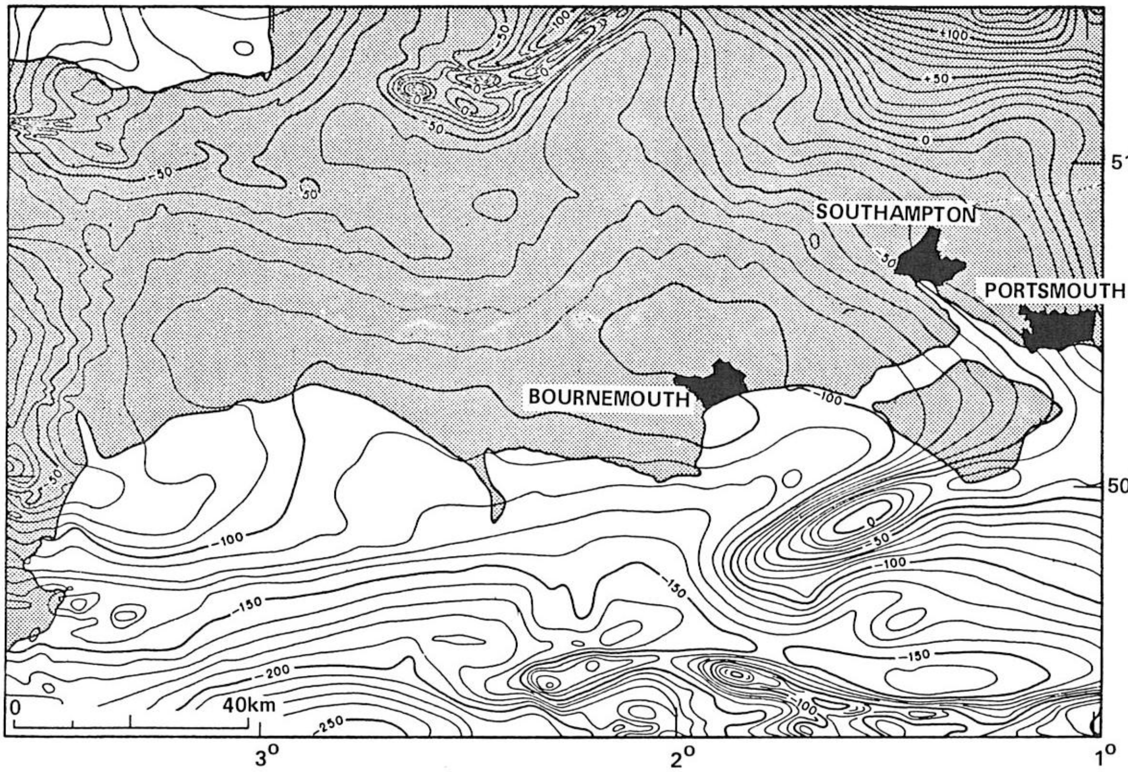


Fig. 5. Anomalies in Gammas of a Sedimentary Trough on the Southern Coast of England. After Aeromagnetic Map of Great Britain, Sheet 2, Compiled by the British Geological Survey, 1965.

Intrusive and Extrusive Igneous Rocks

Bodies of basic igneous rocks in an environment of sediments are characterized by an assemblage of anomalies that can easily be separated. This can be seen in Fig. 6, which represents a section of a regional aeromagnetic survey of Germany situated in the Eifel mountains 100 km northwest of Frankfurt. The large circular anomaly evidently is produced by a basic pluton. The numerous anomalies of high amplitude and small extension belong to outcropping basalt pipes.

Iron Ore Deposits

An example of the anomaly of an iron ore deposit is shown in Fig. 7. It is a deposit of strongly folded quartz-magnetite that forms the central hard buttress of a hill elongated in an east-west direction. The deposit lies below the geomagnetic equator in Africa. Hence the ΔT-anomaly of the horizontally magnetized ore body shows a minimum in a line vertical above the body. The amplitude of the anomaly reaches 1600γ deviating from the average value of the surrounding field. In other cases, the amplitude above magnetite ore deposits reaches 10,000 to 50,000γ or even more, always depending on mass, shape, depth, and magnetization.

Magnetized Sedimentary Layers

In areas with thick sedimentary covers, anomalies sometimes occur with small amplitudes and small extensions. These anomalies are evidently caused by magnetized sedimentary layers partaking in folds, vertical faults, or outcropping sequences of strata, etc. Figure 8 shows an example of such an anomaly measured in northwestern Germany. The magnetized

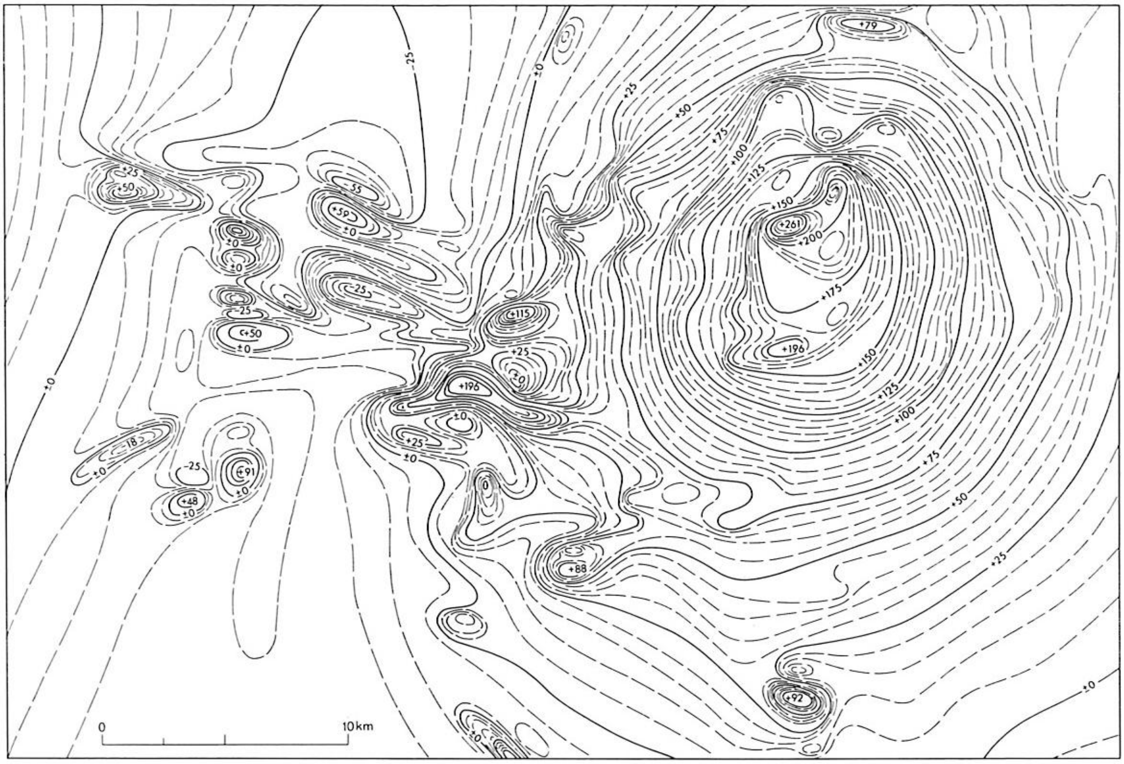


Fig. 6. *Anomalies in Gammas Measured above a Basic Pluton (Large Circular Structure) and Basalt Pipes (Anomalies of High Amplitude and Small Extension). Section of the Aeromagnetic Survey of Germany—Eifel Mountains.*

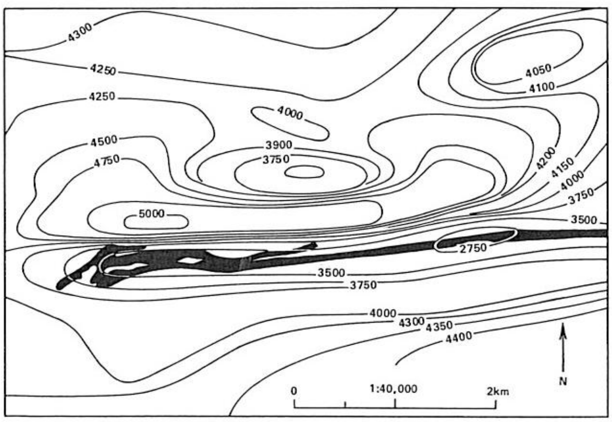


Fig. 7. *Anomaly in Gammas of a Magnetic Iron Ore Deposit, Liberia, West Africa (Courtesy of Gew. Exploration, Düsseldorf).*

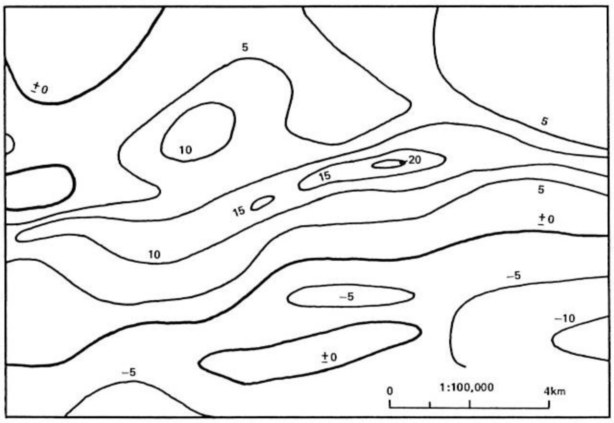


Fig. 8. *Anomaly in Gammas Caused by a Magnetized Sedimentary Layer in the Middle Albian, Northwestern Germany. After Bundesanstalt Für Bodenforschung, Research Program A 254.*

layer is a horizon in the middle Albian of approximately 30 m thickness with an average magnetization of 20γ. This horizon crops out beneath a nonmagnetic overburden of a few meters thickness. This outcrop corresponds to the east-west striking maximum line of 10 - 20γ in the center of the figure.

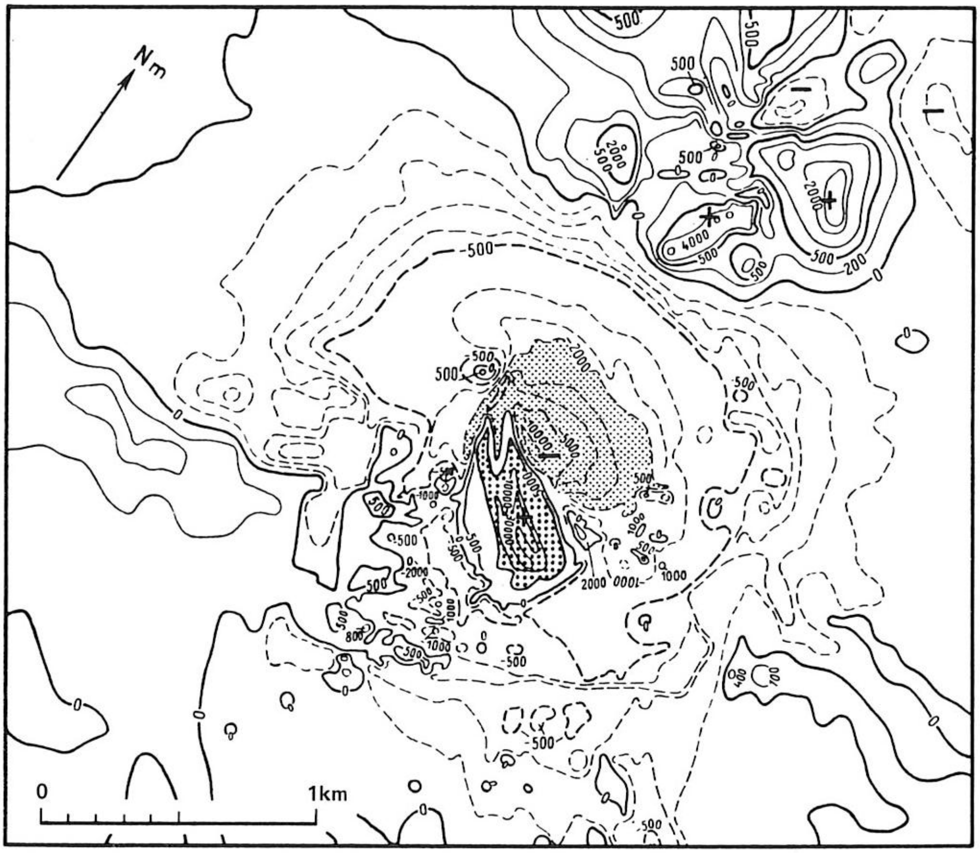


Fig. 9(a). Anomaly in Gammas of Magnetite Ore Deposit Tschogart, Northeastern Iran—Ground Survey, ΔZ.

INTERPRETATION

The interpretation of magnetic anomalies depends on the problems to be solved by the investigation. The problems can be characterized by four items:

1. Surface distribution of rock types with different magnetization,
2. Near-surface tectonic structures involving magnetic layers,
3. Depth of magnetic basement, and
4. Shape of isolated magnetic bodies (magnetite ore, basic igneous rocks).

METHOD OF SOLUTION

For Item 1. An attempt to derive the surface distribution of different rock types from a magnetic chart can only be made in an area where a high percentage of the surface is occupied by crystalline rocks. Furthermore, in a sufficient number of representative points the outcropping rock should be known. If these conditions are satisfied, in many cases a good coordination of the character of the anomalies to the outcropping rocks becomes possible by a mere visual comparison at those representative points. The result may be given in the form of a preliminary geological map that can serve as a valuable basis for a detailed mapping.

For Item 2. If the tectonic structure of an area is to be estimated, a magnetic survey is suitably applied provided that not less than 10 - 20% of all the horizons are magnetized, these layers being near the surface more or less equally distributed. In this case, apart from a visual evaluation, a quantitative interpretation can be applied by comparing the measured anomalies with model bodies of the "dyke" type. The results of these comparisons are the following: the ascertainment of the position of the upper edges of those dykes; and the determination of the lines where these edges are displaced, the displacement being connected in some cases to a change in strike and dip of the dyke.

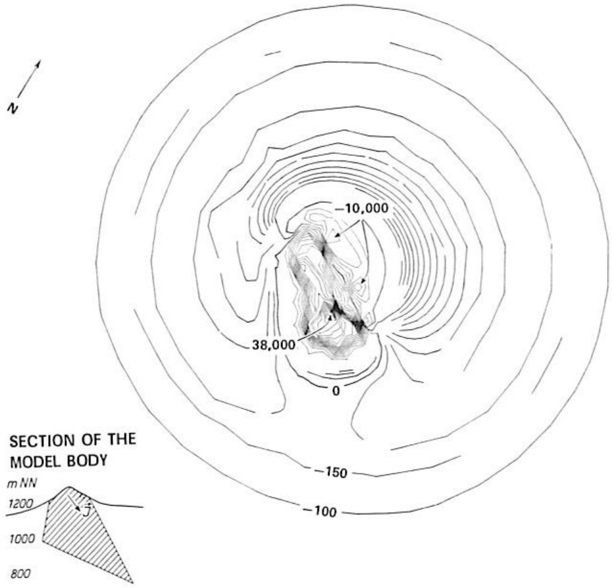


Fig. 9(b). Interpretation by Assuming a Model Body with a Section as Indicated. After Bosum [1965].

For Item 3. Geophysical companies are frequently asked by petroleum geologists to investigate the magnetic basement below a cover of sediments by an aeromagnetic survey. Here a knowledge of the depth to the top of the basement rocks and hints on the most important tectonic structures are needed. Since time and money play an important role in these operations, many methods have been developed for solving this problem quickly and cheaply. Most of these methods assume that the bodies producing the anomalies can be represented by vertical prisms with rectangular cross sections or by a vertical step in the surface of the magnetic matter. A set of standard anomalies of model bodies of this shape is calculated and compared to the measured ones. Two disadvantages, however, arise: (1) The shapes of these anomalies depend, in addition to other parameters, on the inclination of the magnetic field and on the magnetization of the body, which is assumed to be homogeneous and parallel to the field. This yields necessarily a great number of standard anomalies. (2) Neighboring anomalies are superimposed one on another and prevent a clear comparison with the standard anomalies calculated for isolated bodies.

To meet these difficulties reduction to the pole of the field is often made, meaning a transformation of the measured field to the form it would have at the magnetic pole. It is then merely necessary to calculate standard anomalies with the inclination of 90°. Furthermore, in this case, the maximum of the anomalies of a compact body is situated vertically above its center of gravity, which, for geologists, facilitates reading the chart. This is additionally supported by the fact that at the pole the mutual superposition of anomalies is smallest. In the case of an area with an inclination of $<15°$, however, the method yields results of very little probability [*Baranov*, 1957].

Another way of suppressing the mutual superposition of neighboring anomalies is the calculation of the first or second vertical derivative of the measured field. A comprehensive review of these methods is given in articles in special issues of *Geophysics*, edited by *J. Affleck* [1964, 1965].

A direct interpretation of a survey measured in an area with a thick sedimentary cover can be given under the following assumptions: The anomalies in question are produced by the interface relief of a homogeneously magnetized layer situated beneath a nonmagnetic cover. The magnetization contrast at that interface and the mean depth of the interface are provided by other considerations [*Hahn*, 1965]. By separating the long waves of the field, the lower limit of vertical prisms may be estimated [*Bhattacharyya*, 1967].

For Item 4. Isolated magnetic bodies, whose vertical extension is greater than the distance measuring level-top of the body, are best interpreted by comparing their anomalies with those of a model body. For a good approximation the model body should have a great degree of flexibility, which demands so complicated a calculation of the theoretical field that it requires an adequate computer and a well-adapted program. Interpretations involving so many details should be applied only to objects of high interest in research or economy, e.g., to an iron ore deposit, the volume and vertical extension of which are to be investigated.

An example is given in Fig. 9 which shows the magnetic anomalies measured at Tschogart, Iran (a) and calculated for the model body, a section of which is shown in (b). This interpretation led to a rough estimate of the entire volume of this iron ore deposit [*Bosum*, 1965].

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COMMENT ON THE SEAFLOOR SPREADING HYPOTHESIS

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Oceanographic ships engaged in geophysical work at sea have been gathering total field magnetic measurements for more than ten years. Since 1956 these observations have been made with towed proton magnetometers; prior to that date a few ships used fluxgate magnetometers. Perhaps half of all available measurements have been collected by the ships of the Lamont-Doherty Geological Observatory of Columbia University, U.S.A. The volume of the data available must be considerable. I am engaged in collecting all data gathered during the International Indian Ocean Expedition, 1961 - 1966, and have at present collected data for ~100,000 nmi of track in the Indian Ocean alone. With the exception of the southwestern Pacific, I believe the track density in the Indian Ocean to be fairly typical of the world's oceans. Most observations have been reduced to anomalies by the subtraction of a variety of regional fields, and much of this has been published, but the oceanographic laboratories have been relatively slow to produce the information in a form that is easily read by computer. With the establishment of the International Geomagnetic Reference Field (IGRF), it is hoped that this problem will be quickly solved before the mass of data becomes impossible to handle.

Perhaps the most important single contribution made from the study of these anomaly profiles has been to the seafloor spreading hypothesis. At the International Oceanographic Congress in 1959 *Ewing, Hirshman, and Heezen* [1959] noted the existence of a characteristic magnetic anomaly associated with the median rift valley of the midocean ridge, and they pointed out that it must be due to a subsurface body of high magnetic susceptibility. About this time a survey by *Mason and Raff* [1961] revealed an extensive linear pattern of north-south magnetic anomalies off the coast of California that *Menard* [1960] subsequently showed to be parallel with the trend of the East Pacific Rise. The idea that new oceanic crust is formed at the crest of the midocean ridges and is carried away on a conveyer belt, riding on a mantle convection cell, was first proposed in this context by Hess in 1960 [*Hess*, 1962; *Meyerhoff*, 1968]. *Vine and Matthews* [1963] extended the idea to explain the formation of linear magnetic anomalies observed over the ridge crests. Their hypothesis was based on a study of a 1° square on the crest of the Carlsberg Ridge in the northwest Indian Ocean, which was surveyed in detail by the HMS *Owen* in 1962. Here Vine had used a vector fitting technique to show that a seamount adjacent to the median valley was reversely magnetized and that a seamount farther from the axis was normally magnetized; the magnetic pattern in the area could be simulated by a block magnetized in the direction of the earth's field under the median valley, flanked by alternately reversed and normally magnetized blocks [*Cann and Vine*, 1966]. *Vine and Matthews* [1963] suggested that these blocks were formed of feeder dykes and their associated lava flows, which were injected near the crest of the ridge and shouldered their predecessors aside. As they cooled they would become magnetized permanently in the direction of the ambient field; if the earth's magnetic field reversed periodically, the result of the continuing process would be a series of blocks elongated parallel with the ridge and alternately normally and reversely magnetized. This would account for the linear anomaly pattern over the ridge crests.

In 1965 Wilson realized that the hypothesis also demanded symmetry of the anomaly pattern about the ridge crest. *Wilson* [1965] and *Vine and Wilson* [1965] demonstrated this symmetry in part of the anomaly pattern off Vancouver Island and showed that the observed pattern could be simulated with a model combining *Cox, Doell, and Dalrymple's* [1964] newly published timescale of the reversals of the earth's magnetic field during the past 3.5 million years with a spreading rate of 1.5 cm/yr per limb of the ridge. At this time, Wilson also proposed his concept of transform faulting as a consequence of seafloor spreading from the crest of the midocean ridge, and this concept subsequently received independent confirmation from the earthquake mechanism studies of *Sykes* [1967].

At this time the majority of oceanographers disagreed with the seafloor spreading hypothesis. The publication of magnetic surveys of the Reykjanes Ridge south of Iceland in 1966 and of *Gakkel et al.* [1966] Russian survey of the Arctic Ocean at the Second International Oceanographic Congress in Moscow, both of which showed a strong lineation parallel with the crest of the midocean ridge, did much to dispel their opposition. *Pitman and Heirtzler* [1966], now converted, demonstrated the magnificent symmetry of some of the profiles across the Pacific-Antarctic ridge and showed that a block model derived from the fast spreading ridge in the Pacific would also serve to explain the anomaly pattern observed across the Reykjanes Ridge where the spreading rate is low. *Vine* [1966], in a classic paper, extended the time scale and used it to date the ocean floor. *Heirtzler et al.* [1968] at Lamont-Doherty sub-

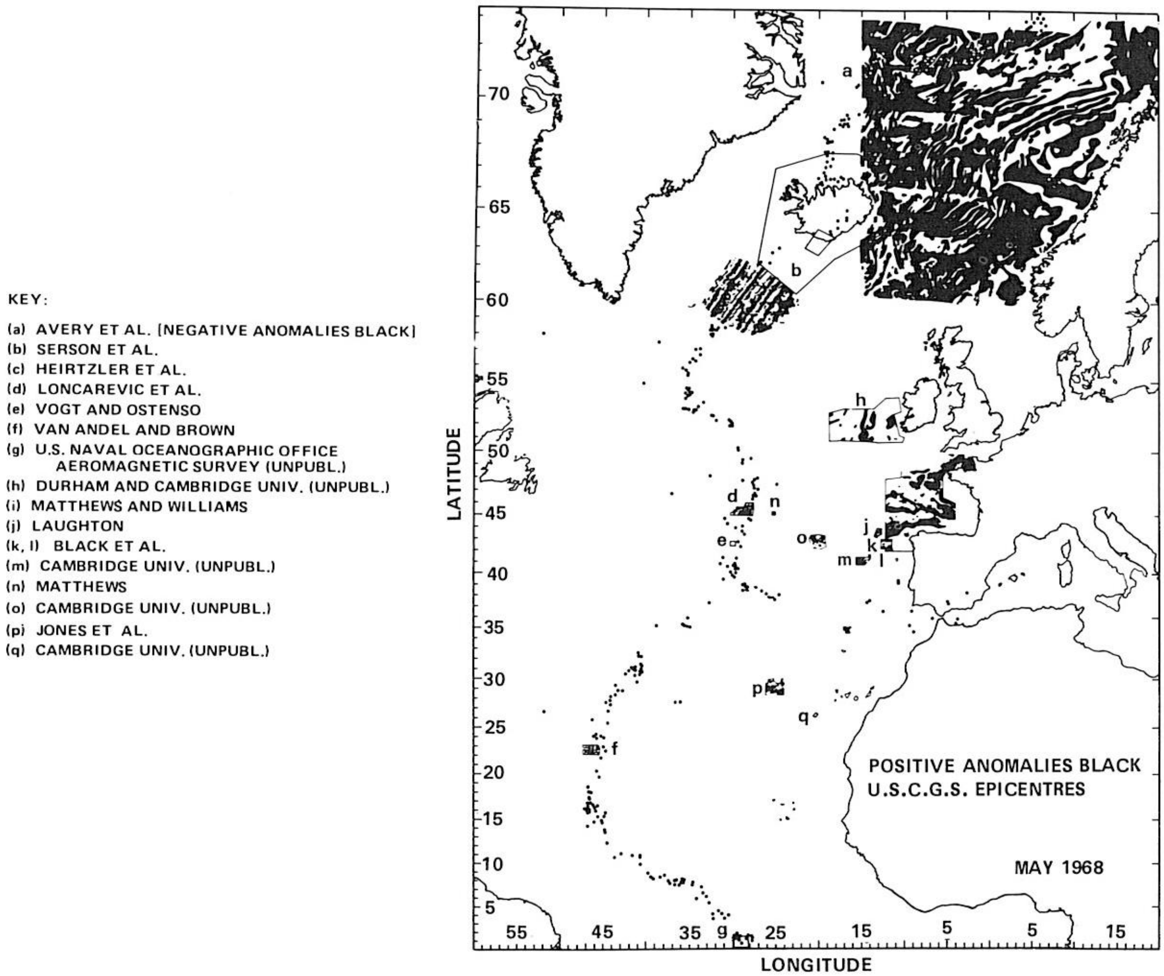

Fig. 1. Contoured Magnetic Anomaly Surveys in the Northeast Atlantic.

sequently produced a provisional reversal time scale extending backwards 80,000,000 years and used it to outline the history of the seafloor in the South Atlantic, Pacific, and Indian Oceans. Since then a considerable number of papers on seafloor spreading, originating largely in North America, have been published. An excellent nontechnical review has recently been published by *Heirtzler* [1968].

A major advance, originating with *Morgan* [1968] at Princeton, was the concept that the motions of the earth's crust can be interpreted in terms of relatively few plates bounded by growing midocean ridges, transform faults, and active mountain chains and ocean trenches where the crust sinks down into the mantle again. This idea, called the new global tectonics, has proved a fruitful link between seismology and seafloor studies [*Isacks, Oliver, and Sykes,* 1968]; this paper includes the best presently available technical review of seafloor spreading.

The *Vine and Matthews* [1963] hypothesis has provided a clue to the formation of the anomaly pattern of the fast spreading, nonrifted ridges like the Pacific-Antarctic ridge. It has worked less well in detailed prediction of the anomaly patterns on the rifted ridge, where the anomalies are much less perfectly symmetric and the spreading rates appear to be slow (about 1 cm/yr). Scatter of dyke injections about the centerline of the ridge and subsequent faulting, exposing the metamorphic greenstones from beneath their basalt cover, are explanations that seem to account for this disruption of the pattern.

So far, visual correlations between widely spaced profiles have been used in applications of the theory; while these correlations are fairly clear in the areas of the nonrifted ridges, they become less clear nearer to the rifted ridges. We need an objective correlation technique. We also need more detailed, contourable, magnetic surveys on the flanks of such ridges before we can be certain that the anomalies are really sufficiently linear for simple correlations to be valid at all. Figure 1 shows all such surveys that were available in the summer of 1968 in the northeastern Atlantic. The lineation pattern is obvious in the larger surveyed areas near the crest of the mid-atlantic Ridge; it is less obvious in the small patches of survey on the lower flanks. It is worthwhile to remember that the hypothesis originally evolved from a study of a really detailed survey, in which the lines were spaced 1 mile apart so as to define the anomalies with certainty. Further advances may yet come from such detailed surveys, though they are very time-consuming. There are 17 surveys shown in Fig. 1; the ten Cambridge surveys have all been reduced using the same regional field, but the seven other surveys have each used different fields, as have all the national aeromagnetic surveys of the adjacent land areas. The establishment of an IGRF will do much to reduce this unhappy confusion and to ensure that in the next few years we are able to compile a single magnetic anomaly survey of the North Atlantic and the surrounding countries. Such a map promises to have considerable bearing on the geological history of the area.

ACKNOWLEDGMENT

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THE INTERNATIONAL GEOMAGNETIC REFERENCE FIELD 1965.0

INTRODUCTION

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The choice of an International Geomagnetic Reference Field (IGRF) for the field of internal origin and its secular variation is primarily the concern of two groups with overlapping objectives and personnel: (1) The International Association of Geomagnetism and Aeronomy (IAGA) World Magnetic Survey (WMS) Board and (2) The IAGA Working Group on Analysis of the Geomagnetic Field; this unit was Group No. 8 in Commission 3 (Magnetism of the Earth's Interior) from August 1963 through September 1967 and subsequently became Working Group No. 4 in Commission 2 (Representation of the Main Field). There was general recognition of the need for a reference field to form an agreed basis for main-field calculations and to unify results in studies on, for example, removal of trend to yield surface anomalies, field residuals potentially applicable to the calculation of ionospheric and magnetospheric currents, the shape of a field line, locations of conjugate points, and field values used in the B-L space of trapped particles.

An agreed reference field answering a wide spectrum of such needs was seen as attainable and desirable. There was less prospect of concurrence in higher terms such as might be needed for meeting the critical requirements of surface and air navigation. Regarding secular change, the benefits of adopting a definite model would include not only standardization in adjusting the main-field model to epoch but also convenience in, for example, testing models of dynamo action in the earth's core.

The following is a chronological development of the major discussions and studies on an IGRF. At the XII General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Helsinki, Finland, July 25 to August 6, 1960, the IAGA Committee No. 5 on World Magnetic Survey and Magnetic Charts, with Chairman E. H. Vestine, made a recommendation that was subsequently adopted by the Assembly that as part of the World Magnetic Survey a potential analysis be made providing spherical harmonic terms up to and including a degree and order useful for adequate representation of the data [*Vestine*, 1961]. In a Working Group memorandum of May 1, 1964, the Group's Reporter, A. J. Zmuda, made a proposal, later accepted, that the Group undertake the evaluation of harmonic coefficients. At an informal open meeting of the WMS Board in Pittsburgh on November 18, 1964, the IGRF was discussed by L. R. Alldredge, J. C. Cain, P. F. Fougere, E. H. Vestine, and A. J. Zmuda [*WMS Notes No. 3,* 1966]. At the Herstmonceux Colloquium of October 4 - 6, 1966, *Leaton* [1967] stressed the need for the international adoption of a geomagnetic reference field.

In a major step, *B. R. Leaton and S. R. C. Malin* [1966] and *B. R. Leaton* [1967] examined relatively recent sets, extracted five [*Adam et al.*, 1962, 1963; *Nagata and Oguti*, 1962; *Leaton et al.*, 1965; *Hurwitz et al.*, 1966; *Cain et al.*, 1967], and then consolidated for 1965.0 a set with 48 terms ($n = m = 6$) for the main as well as secular change field as one case and a set with an additional 32 terms in the main field ($n = m = 8$) as another. These seven sets formed the initial group to be evaluated for an IGRF. In a Working Group communication dated July 7, 1967, J. C. Cain noted that the GSFC 12/66-1 field [*Cain et al.*, 1967] gave a better fit to the observations than either of the consolidated sets and suggested a truncation of this GSFC field for the IGRF.

The subsequent deliberations included the following considerations.

Form. The possibilities treated were a single series of spherical harmonics for all points, those on the earth's surface as well as those above and below the surface but external to sources of magnetization; one harmonic series for the earth's surface and one for the other points; and for the surface data, a group of values of the field components at specified grid points. In the spherical harmonic series, whose coefficients should be used? Is there one set clearly superior, or are there several good ones sufficiently close to warrant consolidating into a single group?

Number of terms. Harmonic coefficients contain errors stemming from the uneven distribution of, and errors in, the raw data; from the difficulty of removing transient fluctuations; from the influence of local anomalies that cannot be depicted by any practicable method of analytic representation; and from the mutual dependency of the coefficients [*Chapman and Bartels*, 1940a; *Zmuda and Neuman*, 1961]. With these fundamental limitations, what coefficients are reliable, and, relatedly, how many are to be used in the series for the main field and in the series for the secular variation? *Nagata* [1965] discusses the convergence of the harmonic series, and *Roberts and Scott* [1963] discuss the truncation errors.

Scalar Intensity. Satellite observations of the scalar intensity are numerous and made with a high precision. However, incorporating this element into calculations for the harmonic coefficients is not as direct as that with any of the vector components. *Cain et al.* [1967] and *Tyurmina and Cherevko* [1967] showed ways of using this scalar quantity in harmonic analysis.

Epoch and Duration. The epoch is 1965.0, but what should be the total period of applicability? The period must be long enough to preserve the utility of a reference field, but any reference chosen will undoubtedly contain imperfections that must be ultimately removed.

Coordinate System. Part of the problem concerning an IGRF is to specify the coordinate system to be used and to specify the reference shape of the earth. The question of how to use the reference field, particularly with respect to surface data, cannot be avoided, and a recommendation for a set of coefficients has limited value if its usage is not prescribed. The earth's surface and the geoid resemble an oblate spheroid more closely than they do a sphere, and surface component measurements are made with respect to the local vertical due to gravity and to directions in a plane normal to this vertical. As an expedient procedure compatible with the precision of the available data, some of the pioneer analyses treated the earth as a sphere, and the measured components are along the unit vectors of spherical polar coordinates relative to a spherical earth. The observational data were then analyzed with spherical harmonics to yield the coefficients. From the work of *Kahle et al.* [1964, 1966], *Cain* [1966], and *Cain et al.* [1967], to better the values of the coefficients and to take advantage of the improved observations, it is necessary to take into account the oblateness of the earth and the difference between the measured surface vector components and those referenced to a true sphere, and to make the harmonic analysis with respect to a true sphere.

The following analyses relate to at least one phase of the IGRF: wavelengths of field patterns and the marked decrease after the sixth order of the size of the distinguishing parameters [*Alldredge et al.*, 1963; *Alldredge*, 1965]; removal of trend in magnetic surveys [*Bullard*, 1967]; the separation of anomalies from the main field [*Heirtzler*, 1965]; statistical analysis of magnetic profiles [*Serson and Hannaford*, 1957] and of the main field [*Kautzleben*, 1965a, b]; evaluations and limitations of harmonic series [*Heuring*, 1964; *Cain et al.*, 1965; *Heuring*, 1965; *Cain*, 1966; *Adam et al.*, 1967; *Cain et al.*, 1967; *Heuring et al.*, 1968; *Malin and Pocock*, 1969; *Yukutake*, 1968]; magnetic data for trapped particle evaluations [*Hendricks and Cain*, 1966] and for locating conjugate points [*Leonard*, 1963; *Cain* 1968a]; and spheroidal harmonic functions [*Winch*, 1967].

At the XIV General Assembly of IUGG at St. Gall, Switzerland, September 25 to October 7, 1967, evaluations of harmonic descriptions were given at Assembly sessions and Working Group meetings. With some dissension, the consensus at St. Gall was for truncating the main-field series at the 80th term, $n = m = 8$, and for a secular change series with first derivatives only and containing at most 80 terms, up to $n = m = 8$, and possibly terminating at $n = m = 6$ with 48 terms. Arguments for this arrangement were the following: the predominant part of the geomagnetic field is accounted for; core and crustal features are approximately separated since nearly all the effects of currents in the core are included in the IGRF and the effects of the magnetization of crustal rocks are excluded by the smoothing produced by truncation of series; and additional terms do not contribute significantly to the field description for the purpose of the IGRF. Those opposed to this view believed that more terms were needed to describe the field adequately. No IGRF agreement was reached [*Transactions*, 1967], and it was then decided to allow submission of new harmonic sets until March 15, 1968, to continue the assessments, and to try choosing an IGRF at the IAGA Symposium on the Description of the Earth's Magnetic Field, in Washington, D. C., October 22 - 25, 1968.

In the post-St. Gall period, the Working Group considered eight harmonic sets for the main field and eight for the secular change. Table 1 shows some general characteristics of the sets. The coefficients are available on request to the editor or the individual contributors. Some of these coefficients were also considered in the pre-St. Gall evaluation: the main and secular variation fields of *Cain et al.* [1967] and *Leaton et al.* [1965], the latter resubmitted only as a potential surface reference if the Working Group were to recommend two IGRF's; and the main-field coefficients of *Hurwitz et al.* [1966]. The remaining candidates were new harmonic sets: *Cain* [1968b]; *Fougere* [1967, 1968a]; *Hurwitz* [1968]; *IZMIRAN* [1967a, b]; and *Malin* [1968].

TABLE 1

HARMONIC DESCRIPTIONS SUGGESTED FOR IGRF 1965.0

Authors	*Number of Coefficients* Main Field	Secular Variation
Cain, Hendricks, Langel, and Hudson [1967]—GSFC 12/66 - 1 field	120, n = m = 10	120 in first and 120 in second derivative
Cain, Hendricks, and Langel [1968b]—POGO	99, n = m = 9	99, n = m = 9
Fougere [1967]	120, n = m = 10	120 in first and 120 in second derivative
Fougere [1968]	120, n = m = 10	120 in first and 120 in second derivative
Hurwitz, Knapp, Nelson, and Watson [1966] for main field and *Hurwitz* [1968] for secular change field	168, n = m = 12 for field of internal origin 168, n = m = 12 for field of external origin	80, n = m = 8
IZMIRAN [1967a] for main field and *IZMIRAN* [1967b] for secular change field	99, n = m = 9	48, n = m = 6
Leaton, Malin, and Evans [1965]	80, n = m = 8	48, n = m = 6
Malin [1968]	80, n = m = 8	48, n = m = 6

The following are some characteristics related to the individual models:

Cain et al. [1967]: The GSFC 12/66-1 model is derived from a sample of all magnetic data available from the interval 1900 - 1964 plus preliminary total field observations from the OGO 2 (1965-81A) spacecraft for epoch 1965.8.

Cain et al. [1968b]: Based on a fit to a selection of scalar intensity values observed by the near-earth POGO spacecraft OGO 2 (1965-81A) and OGO 4 (1967-73A). The root mean square (rms) deviation between observed and computed satellite values equals 11γ.

Fougere [1967]: Derived using 1000 observations from the following sources: OGO 2 [1965-81A] and Vanguard [1959 η] satellites, the Project MAGNET (airplane) data, and surface observatory data.

Fougere [1968]: Here 3000 observations were applied using the sources cited in the earlier model augmented by additional survey data supplied by the U.S. Coast and Geodetic Survey. The method of analysis here and in the earlier model was a variation of one applied by *Jensen and Cain* [1962] but guaranteeing convergence

Hurwitz et al. [1966] and *Hurwitz* [1968a]: The main-field model was derived from approximately 425,000 airborne and surface measurements made since 1900 and reduced to 1965. Secular variation coefficients are for the interval 1960 - 1965 and are based on observatory annual means of X, Y, and Z since 1960.

IZMIRAN: COSMOS-49 [1964-69A] data for altitudes 200-500 km are used to correct a preexisting set of main-field coefficients. Secular coefficients are derived from charts of secular variation.

Leaton et al. [1965]: If two reference fields are considered, this model is submitted for the surface field. All available surface and airborne observations of magnetic declination from 1955.0 and of vector force components from 1945.0 up to mid-June 1964 are brought up to epoch 1965.0 and subjected to harmonic analysis.

Malin [1968]: Input data for the main field are those used by *Leaton et al.* [1965] and those from satellites OGO 2 (1965-81A) and 1964-83C. The secular variation coefficients are based on the observatory annual means published in the Royal Observatory Bulletin No. 134.

The differences in the raw data and methods used in the analyses are reflected in differences of values of the harmonic coefficients of the main field as well as of the secular variation. Figure 1 shows the range of values for each of 80 main-field coefficients from the eight harmonic sets, a range which extends from 7 to 115γ. The following are some examples obtained with the aid of the numbers on the graph and the associated algebraic signs preceding and following the numbers: the g_1^0 coefficient ranges from -30282 to -30388γ, a spread of 106γ; and the h_1^1 coefficient, from 5707 to 5782γ, a spread of 75γ. Figure 2 shows the range of values for each of 80 secular-variation first-derivative terms. Here the coefficients have small values but the spread about a mean is relatively large. For a specific coefficient the range of values lies within 2 to 21γ. There are some coefficients in specific harmonic sets considerably outside the range of values for the comparable coefficients in the remaining sets. For example, the $\dot{g}_1^0$ coefficient in the POGO series has the value 26γ/year while the values for the other sets lie within the range 12 to 17γ/year.

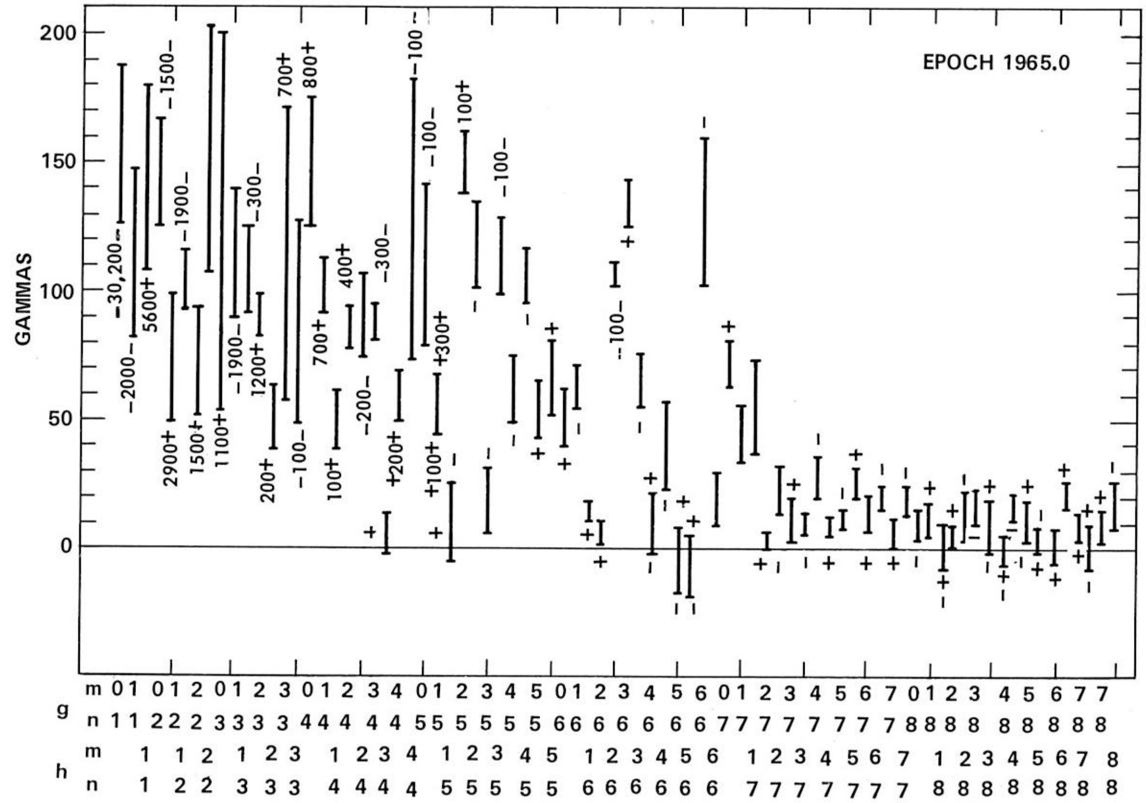

Fig. 1. Range in Harmonic Coefficients Submitted for the Main Field of IGRF.

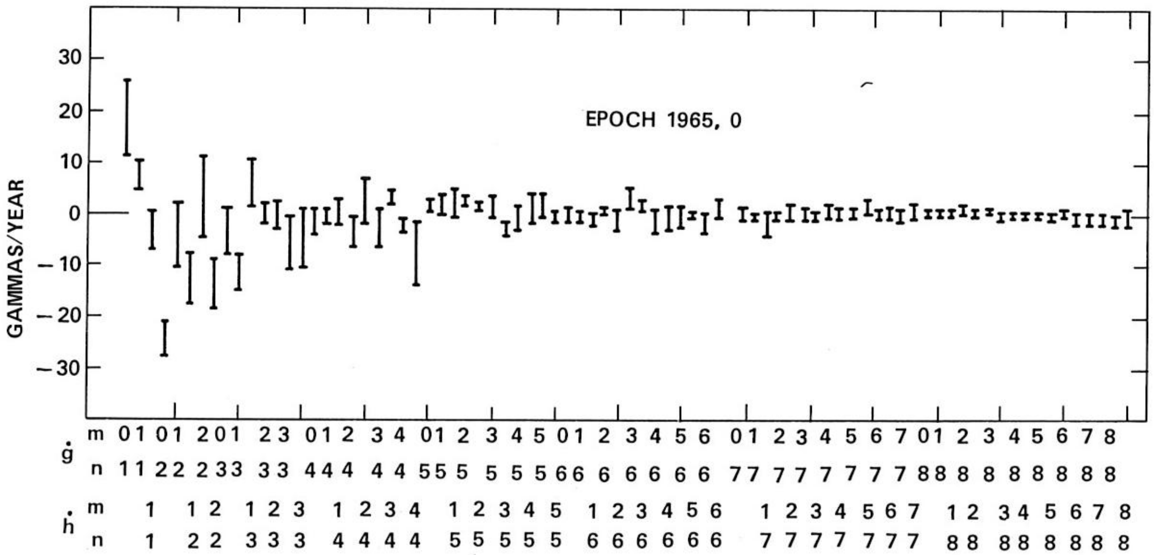

Fig. 2. Range in Harmonic Coefficients Submitted for Secular Change of IGRF.

The following persons served at some time on the Working Group:

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References included in this and the other papers on the IGRF are listed at the end of the IGRF section.

EVALUATIONS BY VARIOUS AUTHORS

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The use of an analytic model as a reference for the main geomagnetic field has applicability to at least three problems associated with the main field: the secular variation, the outward extrapolation, and the analytic representation. In this connection we investigated seven of the models proposed for an IGRF. Representations, which are discussed in a preceding article by Zmuda, are often labeled as follows: F_1 for *Fougere* [1967], G for GSFC 12/66-1 from *Cain et al.* [1967], H for *Hurwitz et al.*, [1966], I for IZMIRAN, L for *Leaton et al.*, [1965] and M for a median field with $n = m = 8$, and contained in the letter from B. R. Leaton dated March 3, 1967, P or POGO for the field from *Cain et al.* [1968b].

It is reasonable to divide the results of this work into three categories: comparisons between the computed intensities and those measured with the COSMOS-49 satellite; comparisons between the world magnetic charts and computed fields; and comparisons between models derived using satellite data and the observations used in their derivations—the COSMOS-49 data and the IZMIRAN model, the POGO data (from the OGO 2 and OGO 4 satellites) and the POGO model.

COMPARISON WITH COSMOS-49 MEASUREMENTS

As a basis for comparison, the measured values of the scalar intensity F were taken. Due to the comparatively low altitudes (260-490 km) and the near-circular orbit of inclination 50° as well as the quality of the measurements on magnetically quiet days, these data are very suitable to verify which of the analytical models offers the better outward extrapolation. Undoubtedly, such a comparison will be correct only within the latitudinal band ±50°. The scalar values were computed using all the coefficients in each model; the COSMOS-49 data used totaled 4000 values. The magnitudes and distribution of $\Delta F = F(\text{COSMOS}) - F(\text{model})$ are shown in Fig. 1 in a series of histograms; root mean square (rms) and arithmetical means are also given for each of the models. Bearing in mind the accuracy of the measurements (positional errors being included) to be about $\pm 30\gamma$, one could initially consider deviations higher than 100γ as a result of some random errors or, if they are of a gross character, as a result of a low accuracy of the given model. But it was revealed that a rejection of all values with $|\Delta F| \geq 100\gamma$ would lead to a rejection of a great amount of ΔF's for the models derived using mainly surface data. Therefore, the width of ΔF filter was increased up to 225γ. That had but little effect on the IZMIRAN, GSFC, and POGO models, since their ΔF's rarely exceeded $\pm 100\gamma$. As illustrated in the figure, the satellite models (or models with a great percentage of satellite data) give a much better fit to the measured values than the models based on surface or near-surface data. The IZMIRAN model gives

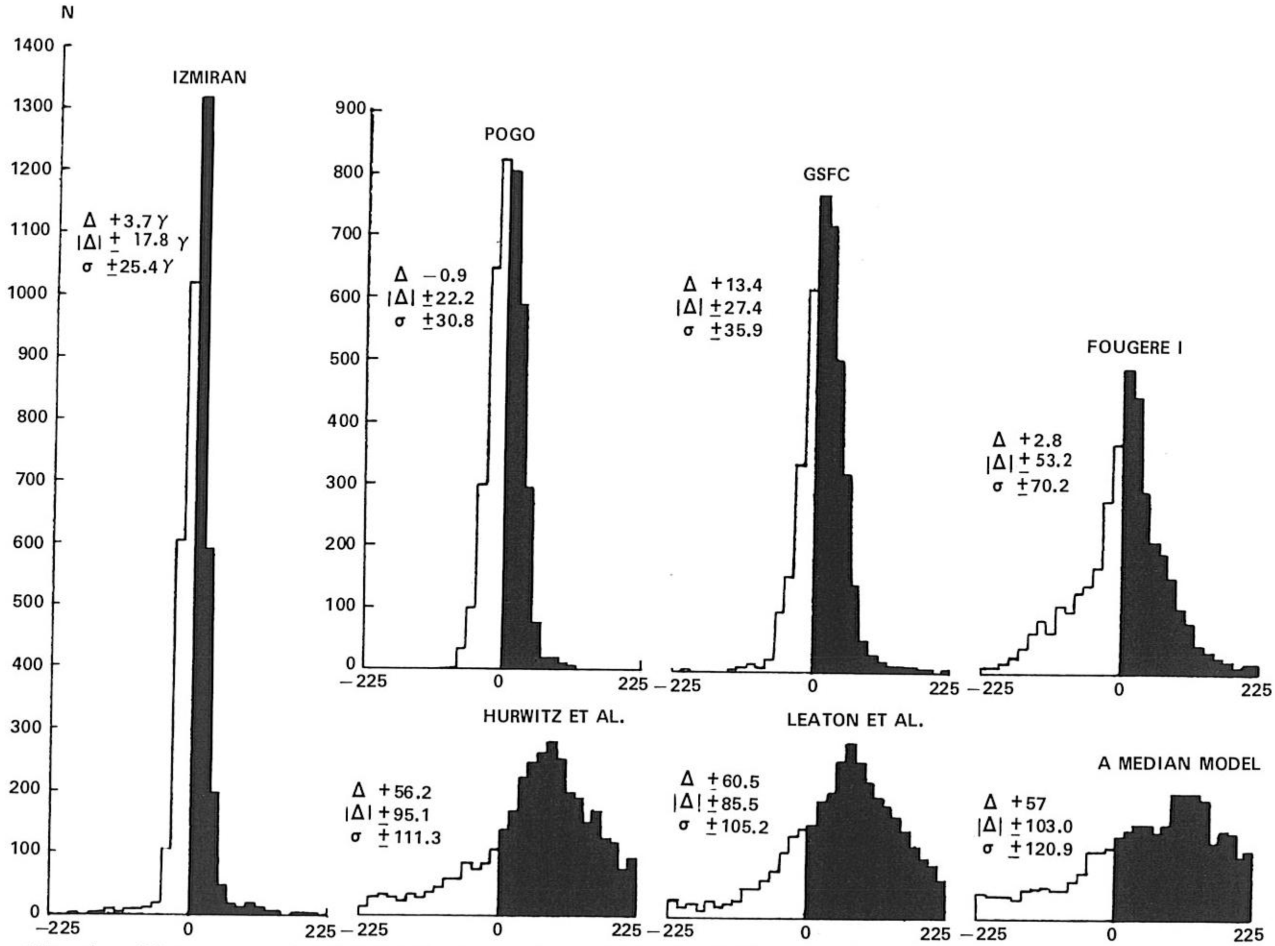

Fig. 1. Histograms of ΔF Distributions where ΔF is the Difference in Gammas between a Value Observed by COSMOS-49 and a Value Computed by the Model Designated on the Graph. The Arithmetic Mean of the Difference (Δ), the Arithmetic Mean of the Absolute Value of the Difference (|Δ|) and the RMS of the Difference (σ) are Also Shown.

the best fit to the COSMOS-49 data, an expected agreement since the model was derived using COSMOS-49 data to improve a preexisting set of coefficients.

Figure 2 shows the distribution of ΔF's along an orbit of COSMOS-49; the corresponding changes in latitude ϕ, longitude λ, and altitude h are shown at the bottom of the figure. The similar pattern for the IZMIRAN and GSFC models is given at the top of the figure. Similar comparisons for the IZMIRAN and POGO models are shown in Fig. 3. With respect to the data in both figures, isolated sharp peaks in ΔF's are simultaneous for all the models and are evidently connected with some computational errors. The comparatively small ΔF's of the IZMIRAN model, indicating good agreement between observed and computed models along some revolutions of COSMOS-49, were expanded into a Fourier series with terms up to $m = 18$. The amplitudes of the Fourier terms were revealed to be about 2γ on the average, which means that the spherical harmonic coefficients used to obtain the ΔF's were defined with an accuracy of 2γ. The term $m = 10$ is somewhat larger (6γ); terms with $m > 10$ decreased gradually to 1γ. Considering the fact that the coefficients were fitted by the least squares method and the spherical harmonic series

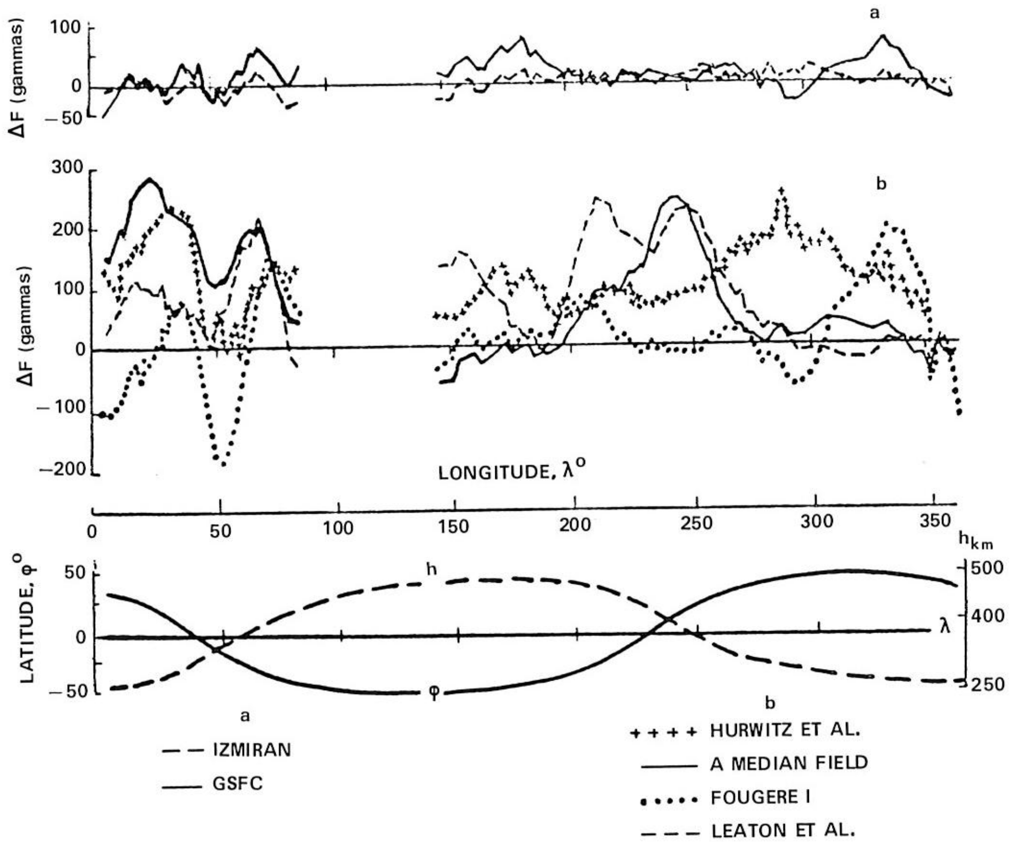

Fig. 2. The Difference between Observed and Computed Values of Scalar Intensity for Different Models and for an Orbit of COSMOS-49. The Latitude, φ, Longitude, λ, and Height, h, of the Satellite are Also Shown.

truncated at n = m = 9, the tenth harmonic could have a certain "leap", but it is possible that a prolongation of a spherical harmonic series could improve the measurement approximation. Examining the "surface" models one may see that ΔF's are of an order higher (see Fig. 2) and have a distribution similar to that of large-scale anomalies; this may significantly distort the field distribution at altitudes.

The Fougere 1 model gives a rather peculiar distribution: for a certain part of the COSMOS-49 paths it yields small ΔF's and is very similar to the IZMIRAN, GSFC, and POGO models; however, there are numerous cases where the ΔF's are large in magnitude and widely spread. As a result (see Fig. 1) the Fougere 1 model has a much smaller rms error compared to the "surface" models, but the arithmetical mean is almost the same. Perhaps it is a result of the scantiness of the raw data used in deriving the model: only 1000 values were used, with 500 values from the POGO satellites. The median model was the worst of all. It was obtained as a median of five different analytical representations. The objections against such a formal averaging of different analyses have been offered elsewhere and are not repeated here.

The estimates of the outward extrapolation suggested above are similar to those obtained by other authors. The rms residuals from some of our comparisons and those obtained by other authors are given in Table 1. The order of σ's is the same; the difference may be connected with some differences in computing.

TABLE 1

THE RMS DIFFERENCE σ BETWEEN OBSERVED AND COMPUTED VALUES OF SCALAR INTENSITY

Satellite	*Height (km)*	*Model*	*Rms (gammas)*	*Investigators*
COSMOS-49	260–490	Leaton et al.	±105	L. O. Tyurmina and T. N. Cherevko
OGO 2	500–1500	Leaton et al.	±83	J. C. Cain et al.
1964-83C	1100	Leaton et al.	±109	A. Zmuda and F. T. Heuring
COSMOS-49	260–490	Hurwitz et al.	±111	L. O. Tyurmina and T. N. Cherevko
1964-83C	1100	Hurwitz et al.	±117	A. Zmuda and F. T. Heuring
COSMOS-49	260–490	Median	±121	L. O. Tyurmina and T. N. Cherevko
1964-83C	1100	Median	±105	A. Zmuda and F. T. Heuring

REPRESENTATIONS OF THE MAIN GEOMAGNETIC FIELD AT THE EARTH'S SURFACE

The application of an analytical model to surface values inevitably leads to the following difficulties:

1. An analytical field is a very smoothed field pattern. It must not (and cannot) contain the anomalies whose origins are in the earth's crust. But contribution of such anomalies to the observed field, according to the statistical estimation, is of an order of 100-200γ.
2. Information on the surveys at the earth's surface has been stored for many decades; naturally, this information has suffered from a poor knowledge of the secular variation. The estimations of rms errors of the magnetic elements at the earth's surface (after J. C. Cain and colleagues) are given in Table 2.

TABLE 2

RMS ERROR IN SURFACE VALUES OF MAGNETIC ELEMENTS

Magnetic Element	*Rms Error*
D	1°
I	0.3°
H	300γ
Z	280γ
F	200γ

These estimates seem to be real for every element but F. The use of proton and rubidium magnetometers has resulted, in our opinion, in a sufficient decrease of errors in F measurements. Naturally, a comparison between any analytical and surface fields will be limited by the surface-field errors. This comparison may be carried out more reliably when only an F chart is involved because of the better coverage and higher accuracy of F measurements, but we have tried to obtain some estimates for the field components as well. For this the U.S.S.R. World Charts for the epoch 1960 reduced to 1965 were used. These charts were graphically compiled and had not been used in any of the model compilations. The rms differences "chart-model" for the field components are nearly equivalent for all the models: ΔX is ± 300 to $\pm 350\gamma$; ΔY is ± 300 to $\pm 370\gamma$; ΔZ is ± 380 to $\pm 430\gamma$.

The comparison with computed F values was made with the U.S.S.R. World F Chart for the epoch 1965. This chart was compiled using the recent results of *Zarya*, MAGNET, the U.S.S.R. aeromagnetic survey, etc. The interval between isolines was normally 500γ but was 1000γ for some limited regions. The chart's accuracy, according to the author's estimate, is 200 to 300γ in the northern hemisphere and increases up to 500 and even 1000γ in the southern hemisphere. The residuals "chart-model" are given in Table 3. The residuals are computed for a totality of 972 points; the filter for rejection of erroneous ΔF's was determined as 1500γ.

The residuals in Table 3 are larger than those obtained with COSMOS-49 measurements, and there is no striking difference between "satellite" models and "surface" models. The increase of ΔF's may be easily explained by the chart errors and by amplifying the analytical field uncertainties when extrapolated downward. Some additional increase of the IZMIRAN model residuals (compared with the GSFC

TABLE 3

DIFFERENCE BETWEEN CHART AND MODEL VALUE

Difference (γ)	*IZMIRAN*	*GSFC*	*Fougere 1*	*Leaton et al.*	*Hurwitz et al.*	*Median*
Δ	−52	−03	−16	+34	+07	−17
$\lvert\Delta\rvert$	±159	±131	±153	±180	±183	±245
σ	±238	±188	±213	±247	±239	±304

model) is due to the latitudinal restriction of the survey (±50° of latitude). If the same comparisons were done within the latitude band ±50°, the residuals would be similar to those of POGO. The illustration of the geographical distribution of the residuals is given in the form of schematic charts (Figs. 4 and 5).

For compiling these charts two field models were used: IZMIRAN for latitudes within ±50° and GSFC for the remaining latitudes. The basic isoline of the ΔF chart is the isoline ±200γ. In the high southern latitudes ΔF's are increasing up to 400 and even 1000γ. This is in quite good agreement with the accuracy of the World F Chart itself. No correlation with the main-field intensity or any latitudinal dependence is revealed. We believe it is possible to conclude that the smoothed scalar field is presented by the satellite surveys rather well, and the problem of the main-field scalar representation is practically solved.

The results with the horizontal component H are not as good; the ΔH's rise up to 400γ frequently and at all the latitudes. The better agreement exists at the northern latitudes; in the southern hemisphere the ΔH's are increasing, but not as prominently as the ΔF's in the preceding figure. Of course, due to the small H-values the relative errors in the neighborhood of the polar caps will be rather great.

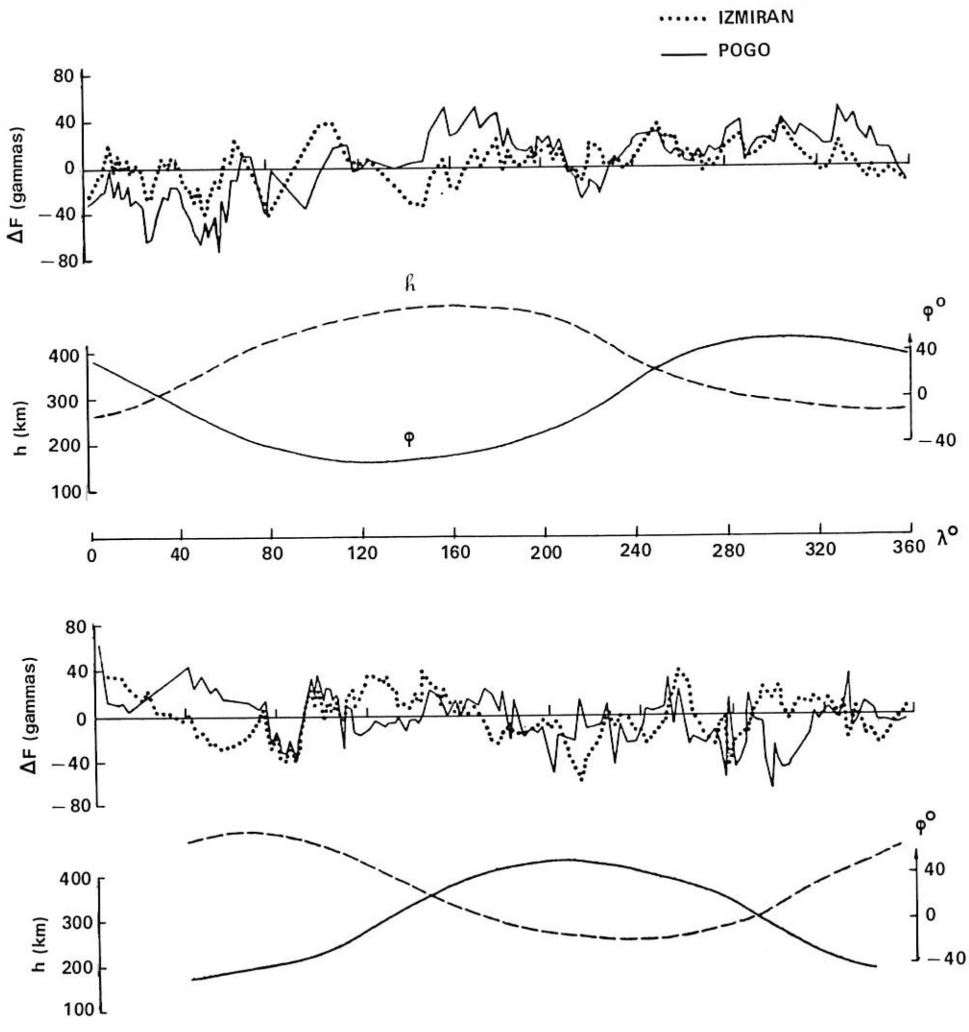

Fig. 3. The Difference between Observed and Computed Values of the Scalar Intensity; the Observed Values are from the COSMOS-49 Data. The Latitude, φ, Longitude, λ, and Altitude, h, of the Satellite for Each of Two Orbits are Also Shown.

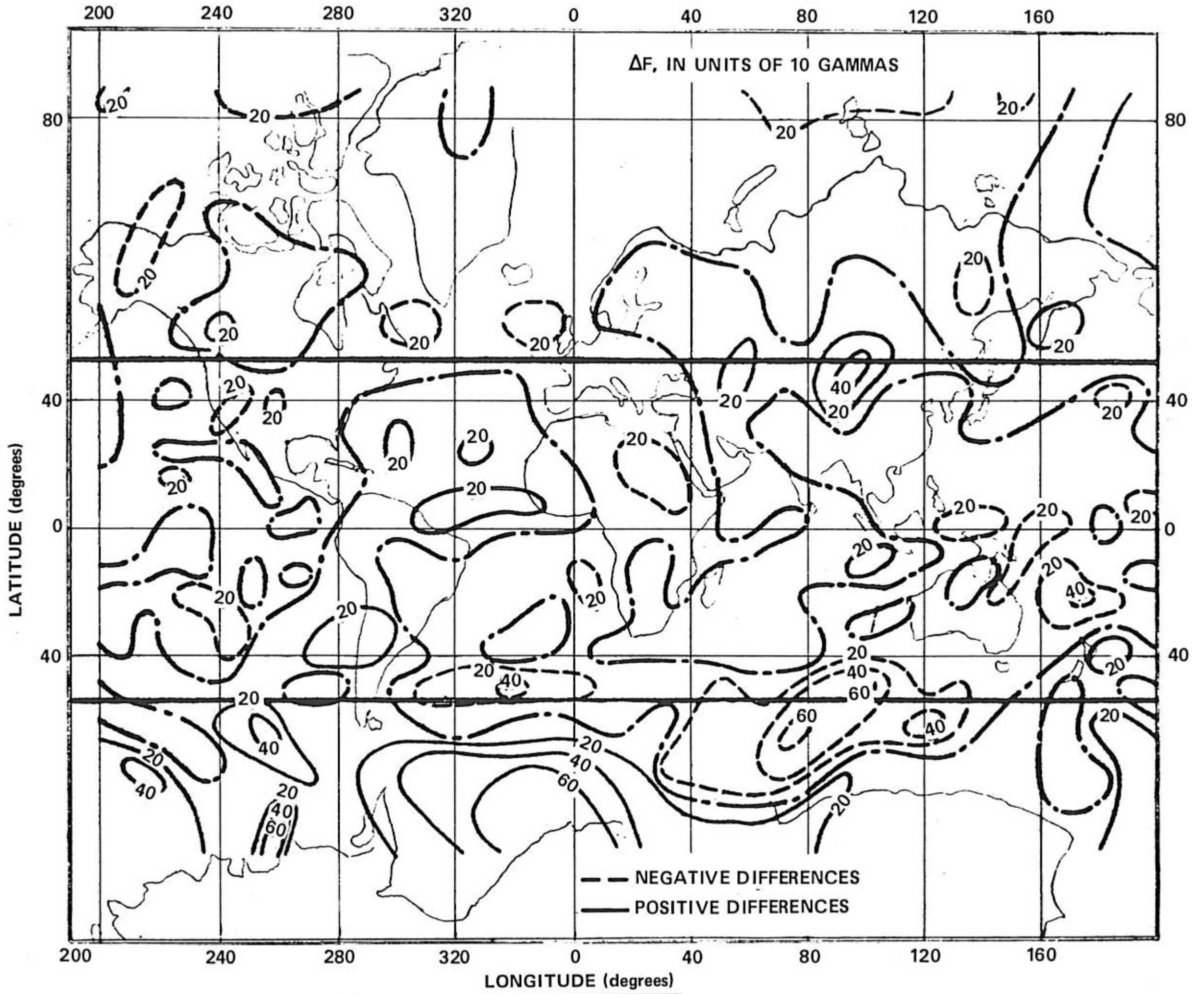

Fig. 4. The Difference between the Chart and Computed Values of Scalar Intensity. See Text for Further Discussion.

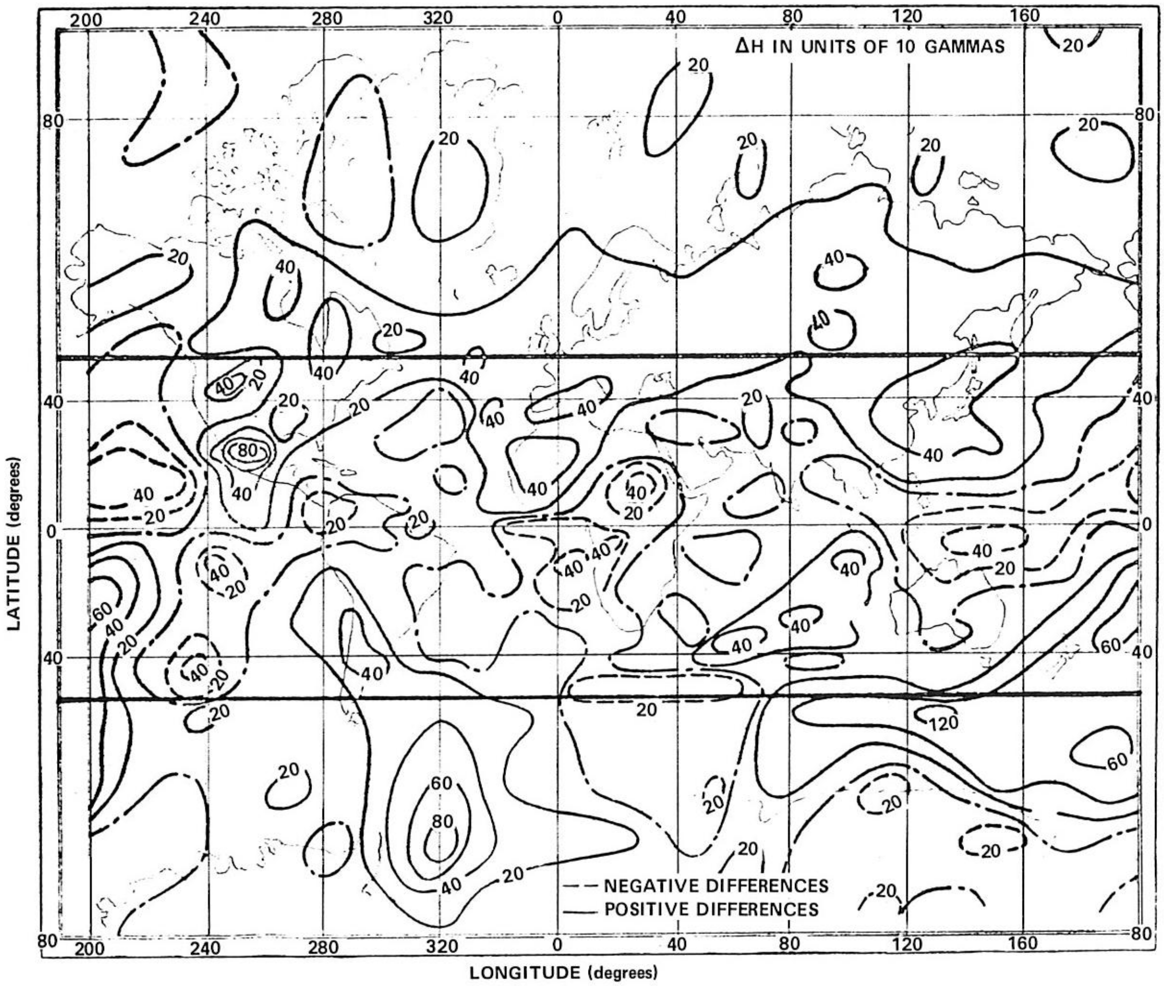

Fig. 5. The Difference Between the Chart and Computed Values of the Horizontal Intensity. See Text for Further Discussion.

COMPARISON BETWEEN THE TWO SATELLITE MODELS, IZMIRAN AND POGO

The availability of the two satellite field models has afforded a way of estimating the reliability of determining the vector magnetic field using only scalar measurements. As was mentioned earlier, both analyses have been carried out by the same "iteration method," and the spherical harmonic series was truncated at $n = m = 9$. These facts are advantageous for this comparison, but there are some serious differences that are to be emphasized: (a) the difference in the survey coverage, (b) the difference in the altitudes of flight, and (c) the difference in the survey duration and time. These distinctions might have prominent influence on the coefficients determined in the analysis and the computed fields themselves.

It is undoubtedly of great interest to compare these two satellite models. In Fig. 6 the vertical columns show the spreads in some coefficients of various models given separately with the I (or IZMIRAN) model and with POGO. The differences in the tesseral ($n > m > 0$) harmonics are shown (at the bottom of the figure) between the IZMIRAN and POGO models only. It is evident that the largest and the most systematic deviations between the IZMIRAN

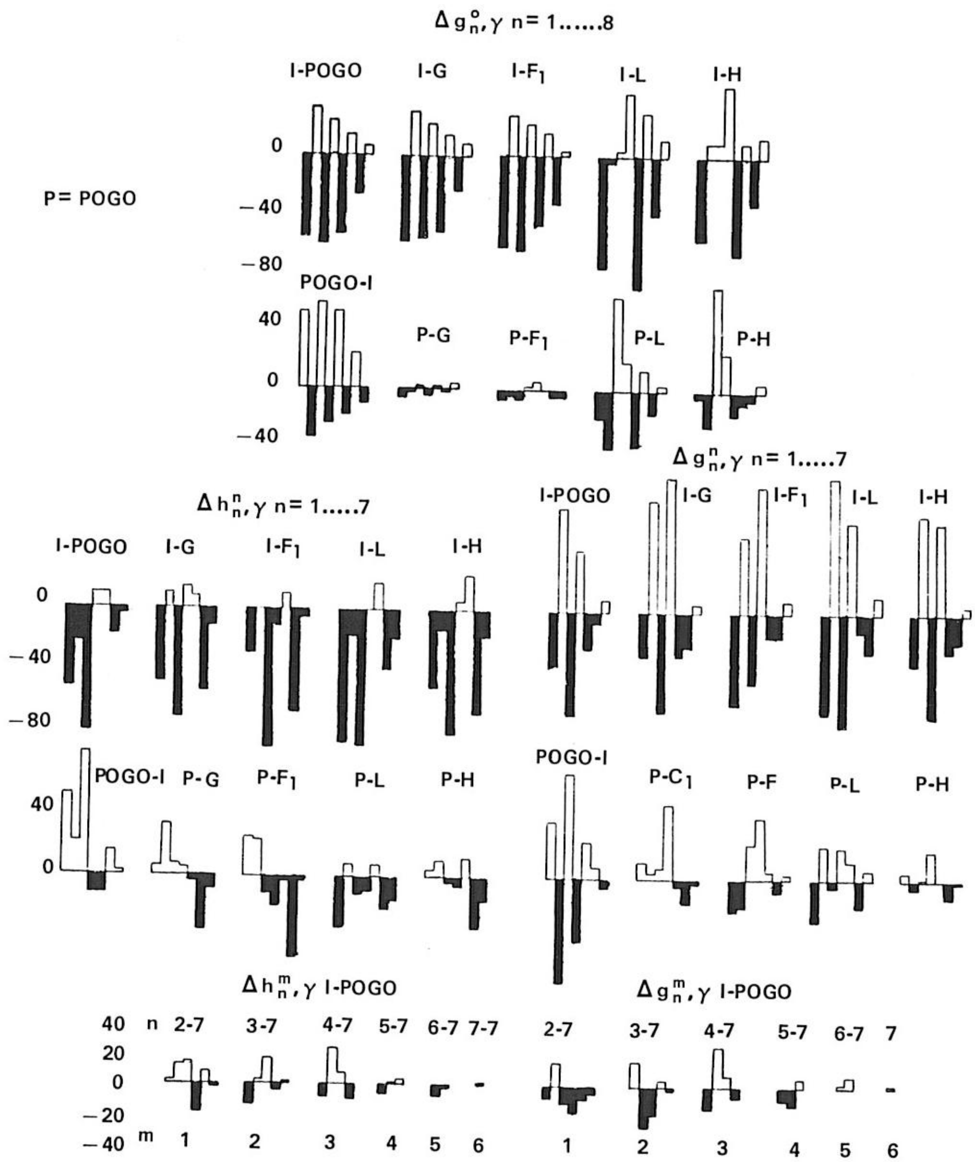

Fig. 6. The Spread in Some Harmonic Coefficients from Various Models.

and POGO models are associated with the zonal ($m = 0$) and the sectorial ($m = n$) coefficients. The divergencies in tesseral harmonics are random and rather small.

Some considerations concerning these types of harmonics have been offered by some authors of the various analyses. L. O. Tyurmina draws attention to the fact that, when comparing the zonal coefficients of four quite identical analyses based on the COSMOS-49 measurements on the different days, she found rather marked differences in the computed odd zonal harmonics and found a good correlation between the changes of the odd zonal harmonics and the changes in the external field. As to the sectorial harmonics, J. Cain connects their possible errors with the positional errors: OGO 2 and 4 orbits were oriented along the meridians. The sectorial and zonal coefficients of the I-model could be essentially influenced by the latitudinal restriction of the survey. The result of the test of the I-model against four others confirms the large differences in the zonal and sectorial harmonics. The remarkable feature of the differences of the I-model zonal coefficients with those of the POGO, F_1, and G models is the sign alternation between the odd and the even coefficients. The agreement of the zonal coefficients of POGO, F_1, and G models is appreciably better. One may suggest that it is a result of the input data: F_1 and G models have incorporated a great amount of OGO 2 measurements. Perhaps a certain bias on the coefficients of the POGO and I models could have been the choice of the set of coefficients used as a "zero approximation." This question has not been properly investigated, as far as we know.

One of the most serious factors still to be considered is the latitudinal scantiness of the COSMOS-49 survey. Though this survey covered about ¾ of the earth's surface, it did not embrace the high latitudes. Therefore, the coefficients associated with the functions P_n^0 (cos θ) and P_n^n (cos θ) could receive wrong weights compared to those they would have in analyses using data for the whole earth. In consideration of the above, it is rather hazardous to accept the IZMIRAN model as a model of the IGRF, but we believe it quite necessary to incorporate these extremely valuable data in the proposed IGRF.

A comparison of the fields computed by the IZMIRAN and POGO models was made for points at the earth's surface as well as for points at a number of altitudes. Results are shown in Figs. 7, 8, and 9 and in Table 4. In most cases, the difference is the value computed by the IZMIRAN model minus the value calculated with the POGO model. The isolines on the ΔF chart with $\Delta F \geqq 50\gamma$ are situated rather randomly and no latitudinal or longitudinal dependence is observed. On the average, the IZMIRAN values exceed those for POGO. Probably it is because the secular variation inserted in POGO was calculated for the period of 1.8 years and stresses the somewhat high coefficient $\dot{g}_1^0$ (26γ/year instead of 17 or 20γ/year). The result of F-value comparison shows that the satellite models provide a more accurate field presentation than the "ground" models. Unfortunately, the component comparison revealed essentially worse results. In addition to ΔX, ΔY ΔZ being great, their extrema are very regularly arranged. The distribution and magnitude of the extrema appeared rather unexpected. Proceeding from the formula

$$\Delta F = (X/F)\Delta X + (Y/F)\Delta Y + (Z/F)\Delta F,$$

it was supposed that the least error for X, Y, Z will be where X, Y, or Z are close to F. As shown in the upper part of Fig. 9, the differences in X, Y, Z are distributed depending on the greatest one and form a certain "false" anomaly. The decrease of the differences with altitude (Fig. 7) is rather slow, and for altitudes of about 2000 km the divergencies are still kept within $100\text{-}200\gamma$.

It seems reasonable to attribute the large differences in X, Y, and Z to differences between the g_n^0, g_n^n, and h_n^n coefficients, since they are the most sensitive to the sources of the uncertainties of the satellite surveys. An attempt was made to eliminate the effect of these coefficient differences. For that the g_n^0, h_n^n, and g_n^n terms were taken to be zero, and the divergencies between the two models were calculated once more (Fig. 9, bottom). Inspection of the two parts of Fig. 9 shows a sharp decrease of the divergencies in both the intensity and spreading (see also Table 4). Naturally, the mutual relation between the components has remained, but it is not as clearly traced now.

The rms difference of the components at the ground level, after Cain et al., is of an order of $200\text{-}300\gamma$. As can be seen in Table 4 both models agree within $150\text{-}300\gamma$. So, in spite of some differences in the initial data and other restrictions mentioned above, the rms errors of the field components by the satellite models are comparable with those we have estimated for the earth's surface.

TABLE 4

DIFFERENCES BETWEEN VALUES OF MAGNETIC INTENSITY COMPUTED BY THE IZMIRAN AND POGO MODELS, FOR POINTS ON THE EARTH'S SURFACE

	Difference (γ)	ΔF	ΔZ	ΔX	ΔY
	Δ	−17	+22.8	0	+21.4
	$\lvert\Delta\rvert$	31.4	116.6	142.6	177.6
	σ	±38.4	±148.4	±193.6	±277.1
Range of difference, gammas	All terms used	+80 −139	+826 −1207	+480 −460	+632 −645
	g_n^0, g_n^n h_n^n terms eliminated		+318 −442	+322 −336	+222 −170

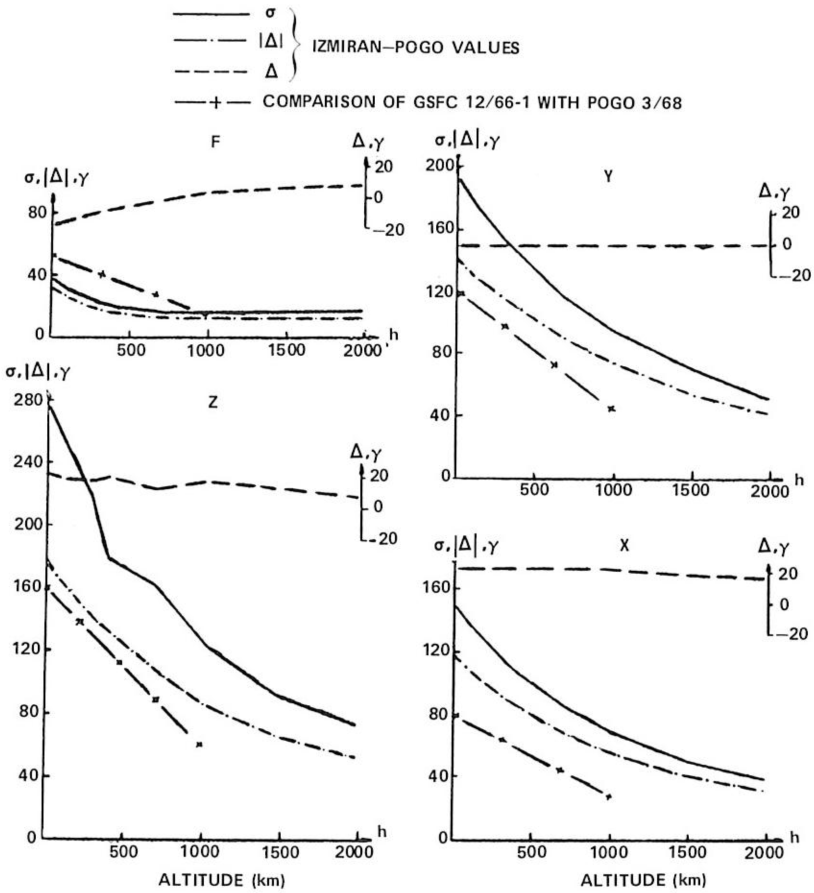

Fig. 7. Differences between Values of Magnetic Elements Computed by the IZMIRAN and POGO Models and by GSFC 12/66 and POGO Models.

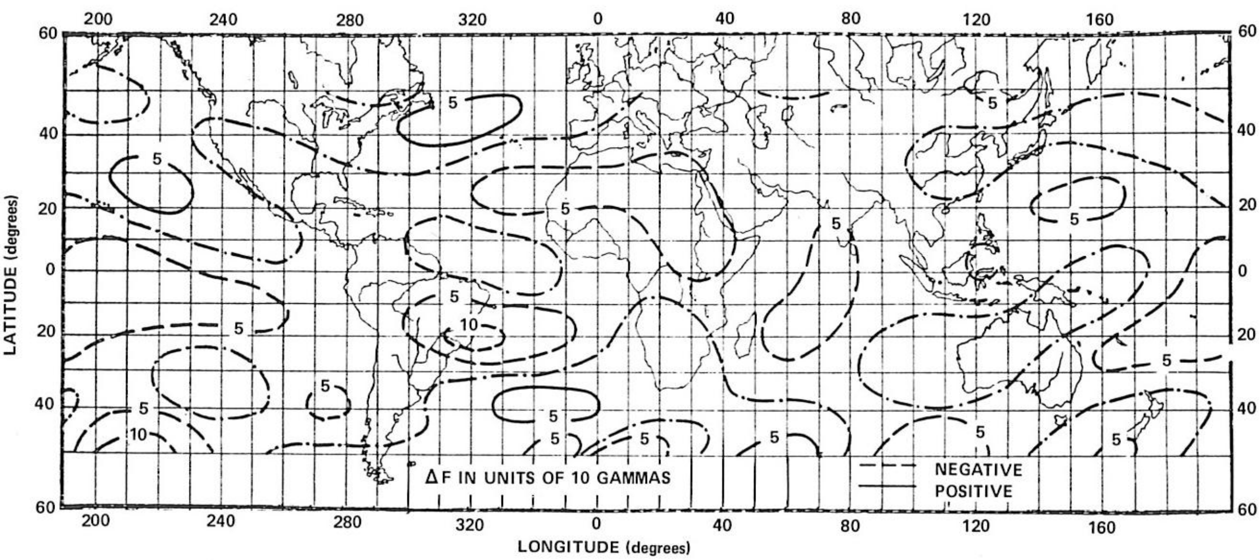

Fig. 8. The Differences between Values of Intensity Computed by the IZMIRAN Model and Those Computed by the POGO Model.

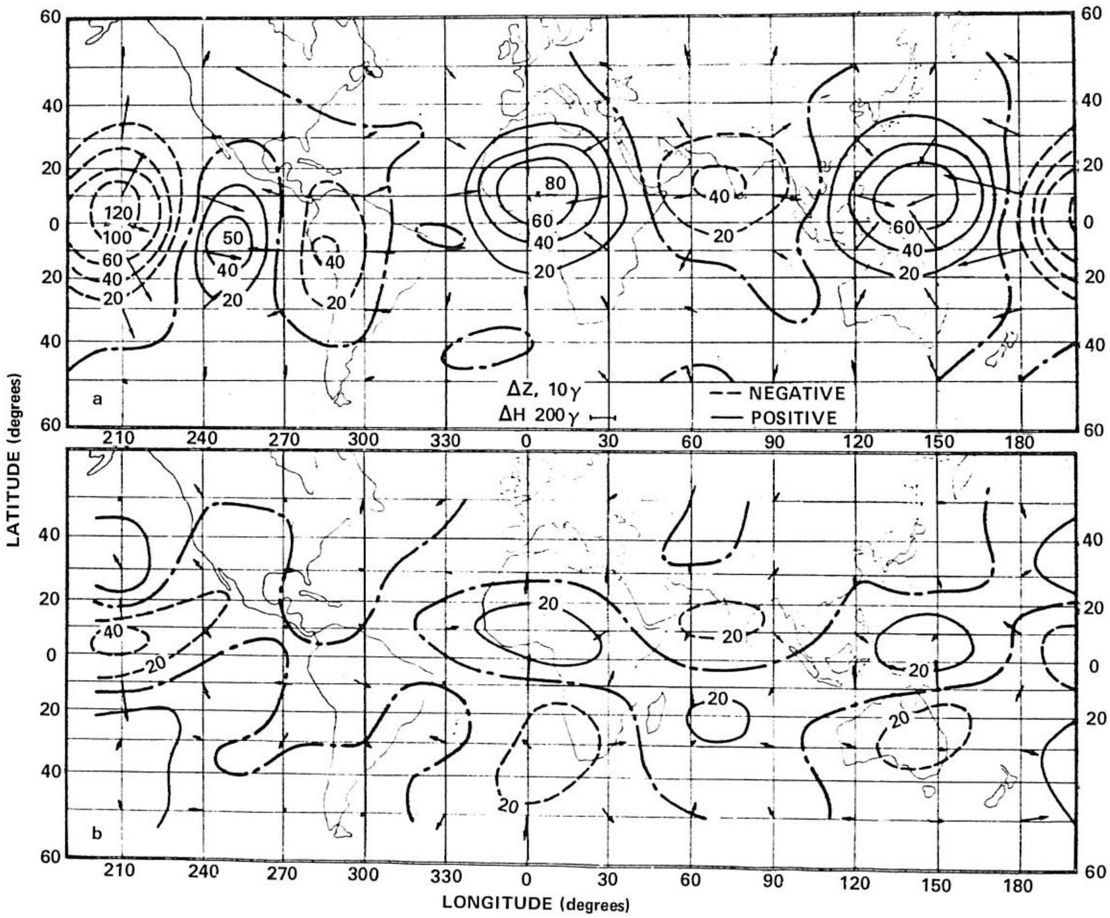

Fig. 9. The Difference of IZMIRAN-POGO Values at the Earth's Surface. In Both Figures the Contours Refer to ΔZ Values; the Vector to ΔH. In the Top Figure All Terms in Each Series are Included; in the Bottom Figure, the Part Due to Δg_n^o, Δg_n^n and Δh_n^n is subtracted.

CONCLUSIONS

In summary, we conclude that at present the best initial data for the IGRF determination are presented by the satellite survey. For the scalar fields these data can solve the main IGRF problems: the computation of the summary secular variation, the outward extrapolation of the field, and the representation of the main field.

The field components are obtained with an accuracy comparable with the one determined for the ground component data. The regularity observed in the distribution of differences of the two satellite models is apparently connected with some restrictions of the initial data and, possibly, with a certain deficiency of the analysis method.

The greatest difficulty arises while investigating the vector-field secular variation using only scalar measurements. It should be desirable to compile a model using the observational data of both satellites (COSMOS and OGO), but selecting only the observations close in time, perhaps, obtained in October and November 1964 and November and December 1965. We believe it would provide for the present time as accurately as possible a model of the geomagnetic field, both at ground level and in space. This model would be, in our opinion, free of some of the restrictions of the IZMIRAN and the POGO models.

To obtain the best approximation for the field components we recommend the definition by the satellite of not only the magnitude of the field but also its direction. The inclusion of the satellite data together with the surface and airborne data would not appreciably improve the analytical presentation of the vector components.

The theoretical estimation of the validity of the method of analysis when the scalar data alone are included is highly desirable.

It is quite necessary while performing the analysis on the satellite data to make allowance for the following sources internal and external to the satellite orbit: S_q variations, ring current, and trapped radiation for the quiet and disturbed magnetosphere.

Since we consider the secular variation of the main geomagnetic field to be one of the most important problems of the earth's magnetic field investigation, we would like to emphasize the importance of improving the experimental data. Accurate oceanic, airborne, and land surveys are necessary if the restrictions of the satellite surveys are to be conquered.

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This report summarizes tests of the various magnetic field models against the available World Magnetic Survey data and includes details of some of the International Geomagnetic Reference Field (IGRF) computations made at the International Association of Geomagnetism and Aeronomy (IAGA) Symposium on "Description of the Earth's Magnetic Field," held in Washington, D. C., October 22 - 25, 1968. The material in this report is discussed in greater detail by *Cain and Cain* [1968].

TEST DATA

Although no explicit formula was agreed upon prior to the meeting for the derivation of an IGRF, there was an understanding that the considerations would need to be somehow based on the correspondence between the field values predicted by the proposed models and the available survey data.

Since the epoch of this IGRF was to be 1965.0, an arbitrary data cutoff time of 1961 was chosen so the results would not be too heavily weighted by observations prior to 1965. Testing was done on all data available since that date. These were divided into the following major categories:

1. Surface magnetic observatory annual means (1961 - 1967).
2. Surface magnetic surveys. This category includes land surveys, repeat stations, and shipboard and ship-towed observations.
3. Aeromagnetic survey of Japan (1965) [*Nagata,* 1966].
4. Aeromagnetic survey of Canada (1961 - 1963).
5. Aeromagnetic survey of Scandinavia (1965).

   (4 and 5:) See paper by P. H. Serson "Airborne Magnetic Surveys of Canada and Scandinavia," in this volume.
6. Project MAGNET worldwide (principally oceanic) airborne survey (1961 - 1966) [*U.S. Navy Oceanographic Office,* 1965].
7. OGO 2 data as available during magnetically quiet intervals (October 1965 - September 1967).
8. OGO 4 data during magnetically quiet intervals (July - December 1967).
9. 1964-83C observations (1964 - 1965) [*Zmuda et al.,* 1968].
10. COSMOS-49 observations (1964.8) [IZMIRAN, 1967].
11. Other airborne (towed proton magnetometer) data.

All the nonsatellite data were obtained from the file prepared by the Geomagnetic Division of the U.S. Coast and Geodetic Survey and discussed elsewhere in this volume by E. Fabiano and S. Cain. The file contains the contributions from many separate organizations and survey groups and is constantly updated as new observations are submitted. It was edited by rejecting those observations deviating by more than 1000γ from the GSFC (12/66-1) model using $n^* = 10$ where n^* is the highest degree of the harmonic in the model applied in the procedure used to eliminate the highly anomalous data beyond about five times the root mean square (rms) deviation. Since all models were ultimately truncated to $n^* = 8$ for testing, it gave no particular advantage to GSFC (12/66-1). This model was used since it fitted the data set best, hence eliminating the smallest fraction of data. The amount rejected is seen to be small as shown in Table 1.

TABLE 1
NONSATELLITE DATA CONSIDERED

Data Type	No. of Observa-tions*	Observations Rejected No.	Observations Rejected % of Total
1. Observatory	1,984	34	1.7
2. Surface	22,425	204	0.9
3. Japanese Aeromagnetic	1,461	6	0.4
4. Canadian Aeromagnetic	9,470	27	0.3
5. Scandinavian Aeromagnetic	6,973	1	0.01
6. Project MAGNET	104,228	401	0.4
7. Other Aeromagnetic	1,763	9	0.5

* In this and in the ensuing discussion a value of D, I, H, Z, or F is counted as one observation even though other values may have been measured at the same time and location.

The scalar magnetic intensity values from the OGO 2 and OGO 4 satellites (data sampled every 30 seconds or at a spacing of approximately 200 km) were initially selected from periods of time for which Kp = 0. They were then used to derive the POGO (10/68) model employing 143 internal coefficients and their first time derivatives. The distribution of the absolute values of the differences between observed intensities and those computed with the model was as follows:

Range in $\lvert \Delta F \rvert$, γ	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–100	100–200	200–600
No. of Obs.	27,646	4218	589	141	23	26	6	2	9	4

32,664 Total

where, for example, there were 27,646 observations with $\lvert \Delta F \rvert$ between 0 and 10γ and 4218 with $\lvert \Delta F \rvert$ between 10 and 20γ.

Since the distribution indicated that the 15 observations over 70γ were likely anomalous, they were rejected and the resulting rms deviation computed to be 7γ. The remaining 32,649 observations were included in the testing.

The COSMOS-49 data were similarly treated by fitting with a special function and eliminating those data that deviated significantly from the rest. The data were prepared by the U.S. Coast and Geodetic Survey from the catalog published by IZMIRAN [1967]. These were sorted into time order, and each fourth observation fit with a series of 99 spherical harmonic coefficients. Data exceeding 100γ from the fitting surface were rejected in the coefficient determination. The distribution of residuals from this model, labeled COSMOS 9/68, is as follows:

Range in $\lvert \Delta F \rvert$, γ	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100	>100
No. of Obs.	1853	1243	648	271	93	41	23	18	19	15	138

4362 Total

The use of every fourth observation in the fit is adequate for these purposes, since each orbit then contains about 10 observations for the shortest wavelength used of the fitting function ($n^* = 9$ corresponds to $360/9 = 40°$). Since the rms deviation of these data from the COSMOS 9/68 field was 21γ, the selections used for model testing were those deviating less than 60γ, a total of 16,554 from approximately 18,000 originally available.

The 1964-83C observations entered the testing unedited except for the rejection of one spurious point that gave a $\lvert \Delta F \rvert > 1000\gamma$.

TEST RESULTS

The various models were tested against the data sets both with the limitation of 80 coefficients and also using all coefficients if more were available. Table 2 illustrates for the GSFC 12/66 model the distribution of residuals using the first 80 coefficients, up to n = m = 8 as well as the full number of 120, up to n = m = 10. Since the survey data were edited with this model using a 1000γ criteria, there can be no residuals above this figure with 120 coefficients. The effect of the truncation is seen to increase the rms residuals by 10-20γ regardless of their magnitude. Using 80 terms has only a small percentage effect on the surface data, since magnetic anomalies account for a great deal of the scatter. The consequence on the satellite data is more obvious as seen in the OGO 2 results. Here the effect is to increase the observations in the 50-100γ range from 5 to 10% of the total data and to push the number over 100γ from 1 to 3%.

These distributions were also calculated for each of the other test models, and the rms values were compiled in Table 3. Here the relative match of each data set to each model can be readily compared.

Although for each model there is an improvement with an increase in coefficients, the differences are generally smaller for those with higher average residuals. Characteristics of the models are discussed in a preceding paper by Zmuda.

TABLE 2

DISTRIBUTION OF RESIDUALS FROM GSFC 12/66-1

Data Type	*Number of Coeffi- cients in Model*	*Data Points in Various Residual Ranges (γ)* 0–50	50–100	100–250	250–500	500–1000	1000–	*Number of Observations Used*	*Rms (γ)*
Observatory	120	740	414	532	205	59	0	1950	187
	80	490	499	653	227	81	0		198
Land/Sea	120	7089	5418	7071	2081	562	0	22221	180
	80	5202	4686	8778	2876	660	19		202
Japanese	120	362	301	491	252	49	0	1455	211
Aeromagnetic	80	331	274	504	294	51	1		226
Canadian	120	2112	1935	3633	1516	247	0	9443	202
Aeromagnetic	80	1865	1683	3593	1974	328	0		225
Scandinavian	120	2113	1718	2573	537	31	0	6972	145
Aeromagnetic	80	1715	1560	2889	776	32	0		163
Project MAGNET	120	28130	23357	37245	13003	2101	0	103827	186
Aeromagnetic	80	23967	21834	39609	15987	2397	33		200
COSMOS-49	120	15446	1095	13	0	0	0	16554	27
Satellite	80	11557	4463	534	0	0	0		48
1964-83C Satellite	120	1242	75	13	0	0	0	1330	28
	80	1206	112	12	0	0	0		32
OGO 2 Satellite	120	18296	948	249	0	0	0	19493	27
	80	16878	2022	592	1	0	0		39
OGO 4 Satellite	120	9300	3037	819	0	0	0	13156	51
	80	8448	3363	1341	2	0	0		61

TABLE 3

ROOT MEAN SQUARE DEVIATIONS OF TEST DATA FROM VARIOUS MODELS USING 80 COEFFICIENTS, UP TO $n = m = 8$ IN EACH MODEL

Data Type	*No. of Data Points*	*GSFC 12/66-1*	*POGO 3/68*	*POGO 10/68*	*Fougere [1967]*	*Fougere [1968]*	*LME*	*Malin*	*IZMIRAN*	*Hurwitz et al.*	*IGRF 1965.0*
Observatory	1950	198	211	203	208	208	223	202	272	245	196
Land/Sea	22221	202	203	207	214	204	290	253	258	331	201
Japanese Aeromagnetic	1455	226	234	239	223	243	249	255	259	276	227
Canadian Aeromagnetic	9443	225	227	226	240	238	230	223	234	249	223
Scandinavian Aeromagnetic	6972	162	159	159	163	178	185	162	255	197	167
Project MAGNET Aeromagnetic	103827	200	232	215	216	209	234	216	330	244	201
COSMOS-49 Satellite	16554	48	49	51	80	67	149	99	47	146	50
1964-83C Satellite	1330	32	34	33	68	47	85	58	33	96	32
OGO 2 Satellite	19493	39	28	30	52	57	98	66	94	110	39
OGO 4 Satellite	13156	61	39	40	85	89	126	89	114	144	57

RECOMMENDATIONS

A few recommendations can be made as to the way an international reference field might be used. As can be seen in this report and others published [*Cain et al.*, 1965; *Cain et al.*, 1967; *Cain and Hendricks*, 1968], ambient values of the earth's field are dependent on contributions from the core, crust, subsurface, and ionospheric electric currents, and the effects of trapped plasma, magnetospheric boundary, and tail effects. The exact secular variation is subject to shifts that make a linear fit with time increasingly uncertain beyond a few years. Further, even for the decade of validity of the IGRF, 1955 - 1971, we already know that there are more accurate models available.

The IGRF was developed to meet a broad spectrum of needs including the requirement for a standard field model where the permanence of a standard over a period of years outweighs the advantages of a high accuracy for a specific set of data such as, for example, satellite observations. Thus, the ultimate use of this model and further requests for revisions must be left to the users.

The way to test whether the IGRF is suitable to any particular need is to periodically test newer or more accurate models and to decide on the basis of the differences whether the continued use is adequate. As the core field deviates more and more from the IGRF estimate, the accuracy will continuously decrease.

We have already made this test in regard to analysis of the time variations of the COSMOS-49, OGO 2, and OGO 4 data. For such studies the IGRF is not useful; even the GSFC 12/66-1 model is insufficient, and fits based on the data themselves are being used. For higher accuracy studies, we would suggest using the GSFC 12/66 model over the range 1900 - 1965 and the POGO 10/68 model from 1965 through 1968. Beyond 1968, POGO 10/68 could be used until it is updated by more recent data and planned improvements in the analysis.

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One of the criteria suggested for the selection of an IGRF is the reduction of systematic residuals in the world's well-surveyed areas. This implies that an accurate representation of the geomagnetic field depends directly on the number of coefficients used in the analysis; the greater the number of coefficients, the more faithfully will the model represent the field. Unfortunately the solution is not quite this simple, since the model should represent the core field and not the field observed at the earth's surface, consisting of contributions from both core and crustal sources. If the models are tested against data that have been reasonably cleaned of crustal noise, then the residuals should reflect mainly a combination of the following: errors in the data (ours and the models), secular variation discrepancies, errors in individual coefficients, and differences arising due to dissimilar methods in developing the models.

This paper describes two tests of the eight models proposed for the IGRF. For the first test, smoothed values of declination D, horizontal intensity H, and vertical intensity Z were used: 558 D-values, 549 H-values, and 548 Z-values from the series of magnetic charts of Canada for 1965.0 [*Dawson and Dalgetty*, 1966]. They were derived from approximately 18,000 three-component observations distributed as shown in Fig. 1 and ranging in time from 1945 to 1963. Approximately 75% of these are airborne data. All were updated to 1965.0 by graphical methods. A modified equal-area grid, equivalent to a 2° quadrangle at the equator, was used to derive the mean values. Rejection levels, based on the dispersion and number of measurements within a unit grid, were used to ensure that the derived average value was representative of the area. The degree of smoothing is roughly equivalent to that of a spherical harmonic representation of degree 50 [*Bullard*, 1967]. The root mean square (rms) deviation of the observations from average value is 0.8° in D, 160γ in H, and 119γ in Z. Figure 2 shows the distribution of the H-mean values, which number about 550.

For the second test, graphs of X, Y, Z observations at 131 repeat stations and 15 observatories were drawn and extrapolated to year 1970. In most cases, the terminal year for the observed data was 1966, with data for a few months in 1967 and provisionally 1968. Graphical values were at five-year intervals from 1940 to 1970 and used in the model comparisons. Figure 3 shows the distribution of these stations.

The uncertainty in the secular variation data is due to instrumental errors and, more importantly in the case of repeat stations, to the difficulty of correcting for transient variations at locations far from permanent magnetic observatories. A recent estimate of the probable error from these sources is $\pm 6'$ in D, $\pm 36\gamma$ in H, and $\pm 62\gamma$ in Z, roughly double the estimate published by *Dawson and Dalgetty* [1966].

The results for the first test are shown in Table 1; 90 to 96% of the smoothed values fit all models to within 3° in D and 300γ in H and Z, except the IZMIRAN model, which was ~83% in H and Z.

For all components, the GSFC 12/66-1, Fougere [1967] and POGO models are more representative of the mean values and have smaller rms deviations than the other models. The GSFC 12/66-1 model of *Cain et al.* [1967] gives the best overall fit. In this paper all the coefficients in each model are used for the calculations leading to Tables 1 and 2, and Figs. 4-19. For Table 3 all models are truncated at $n = m = 8$.

It is significant that in D all models read higher than the smoothed values by 0.3° on the average. This indicates possibly an under-estimation of secular variation in our updating routine.

Highly generalized residual charts in H and Z (Figs. 4-19) were drawn at 400γ contour intervals. The D-residual charts, at 2° intervals, are not shown, since they appeared to be quite meaningless around the dip pole area. Charts were examined for persistency of pattern, since this could mean that the smoothed values in an area were highly suspect, and for areas of disagreement among the models.

Persistent features are common to all models. These occur mainly around the borders of Canada, from Greenland, across the Arctic Ocean, down the west coast, and across the northern states as far east as Michigan. These are areas where either the number of observations is least (Fig. 1) or the secular change control is lacking (Fig. 3).

There are other persistent features for which no reasonable explanation can be made at present, such as the persistent "high" centered on James Bay or the persistent "low" west of Great Bear Lake in the H-residuals.

As expected, there are numerous areas of disagreement among the models. The following are some of the H-residual disagreements.

The Hurwitz et al. model (Fig. 8) shows a large

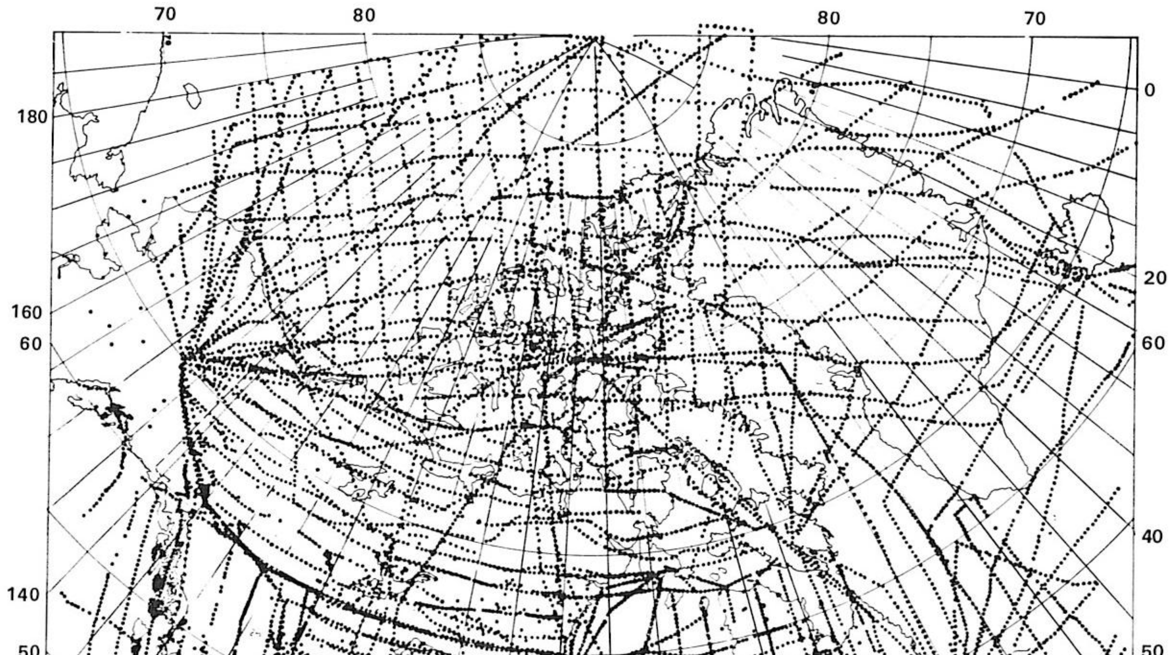

Fig. 1. Distribution of 18,000 Three-Component Observations.

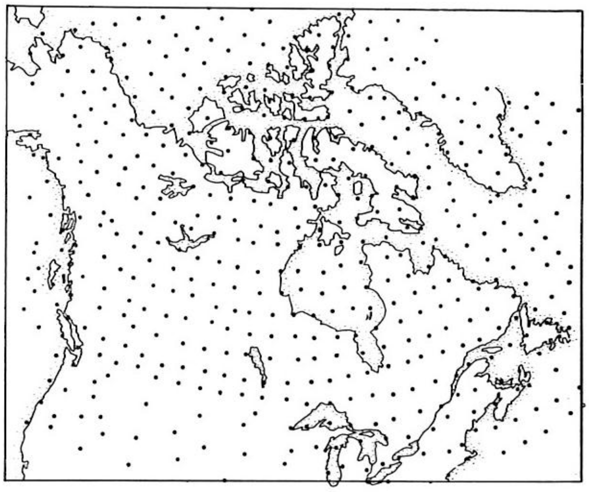

Fig. 2. Distribution of Mean Values of Horizontal Intensity.

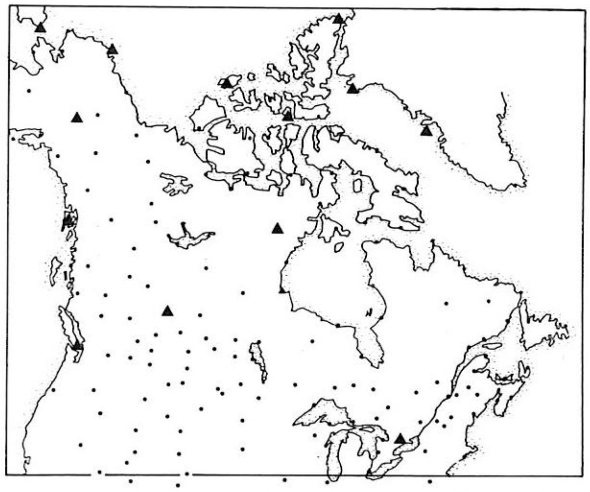

Fig. 3. Distribution of Observatories (▲) and Repeat stations (·).

positive residual area centered on Nova Scotia and stretching from Labrador to Maine. The POGO model (Fig. 11) shows this as a negative residual area indicating differences up to 800γ between these models in this area. The POGO model has a large band of positive residuals stretching from Alaska to Greenland and varying in width between latitudes 64° and 75°. The Malin model (Fig. 10) shows this primarily as an area of negative residuals.

The following are some examples of Z-residual disagreements. The Fougere 2 model (Fig. 15) has large negative residuals stretching southwest from the southern tip of Greenland. It encompasses a large segment of eastern Canada and eastern U.S.A. The Hurwitz et al. model (Fig. 16) shows this basically as an area of strong positive residuals. The area west from Great Slave Lake, enclosing British Columbia and the Alaskan panhandle, is depicted as an area of negative residuals by the Hurwitz model and as an area of positive residuals by the Leaton et al. model (Fig. 17).

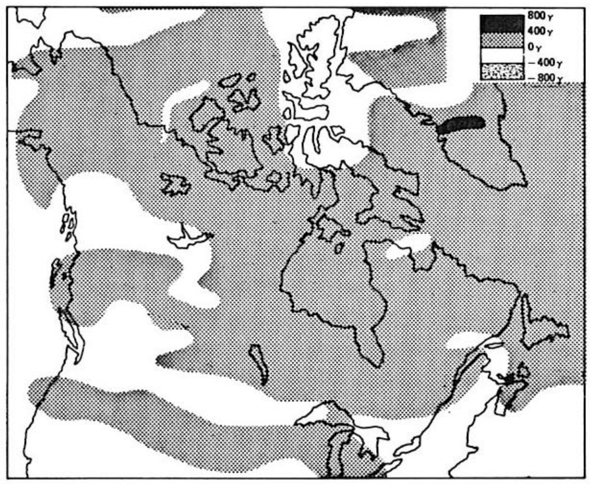

Fig. 4. H-Residual Chart, Observed Field Minus IZMIRAN Model.

The IZMIRAN model (Figs. 4 and 12) depicts large areas of positive residuals that are not consistent with those displayed by other models. This is probably because the coefficients for this model were derived from a preexisting set of coefficients, modified by COSMOS-49 F-data, with a limited latitude range of ±50°.

The results of the second test are shown in Table 2. Although, in general, 1960 and 1965 are the years with the lowest rms values, no model fits the data for 1965 better than any other year in all components. Some models, such as the IZMIRAN, Hurwitz et al., and POGO models, come close, reserving 1965 as their best fitting year in two of three components. Generally 1940, 1945, and 1970 are the poorest fitting years. No model fits the extrapolated data for 1970 better than any other year in any component except the Hurwitz et al. fit in Z.

The results for 1970 indicate that the POGO, GSFC 12/66-1, and Leaton models, in that order, are better predictors of the Canadian data than the other models. The results for 1965 indicate that the GSFC 12/66-1, POGO, and Fougere 1 models fit the data best, confirming the results of the first test.

TABLE 1

MODEL COMPARISONS (MEAN VALUE MINUS MODEL VALUE)

Number of Values	*IZMIRAN*	*GFSC 12/66-1 Cain et al.*	*Fougere [1967] 1*	*Fougere [1968] 2*	*Hurwitz et al.*	*Leaton et al.*	*Malin*	*POGO (Cain et al.)*
				Mean Differences				
D(°) 558	−0.3	−0.3	−0.3	−0.4	−0.2	−0.3	−0.3	−0.3
H(γ) 549	77	−15	5	19	−14	−4	−50	−22
Z(γ) 548	138	1	6	35	6	−112	11	−5
				Rms Deviations				
D(°) 558	2.6	1.7	1.7	1.8	2.6	1.7	2.2	1.7
H(γ) 549	167	142	153	151	168	155	157	145
Z(γ) 548	234	144	147	156	200	176	195	149

TABLE 2

MODEL COMPARISONS WITH OBSERVATORY AND REPEAT DATA, RMS DEVIATION (γ) AT FIVE-YEAR INTERVALS

Year	*IZMIRAN*	*GSFC*	*Fougere 1*	*Fougere 2*	*Hurwitz et al.*	*Leaton et al.*	*Malin*	*POGO*
			North Component (X)					
1940	338	253	263	232	362	342	316	511
45	291	230	249	232	315	294	267	409
50	264	217	229	225	275	256	239	313
55	250	218	221	224	257	240	231	255
60	243	221	220	226	244	234	234	229
65	234	221	226	228	238	231	238	224
1970	309	297	311	307	314	306	316	306
			East Component (Y)					
1940	289	199	233	201	308	248	243	362
45	270	211	249	219	274	226	223	297
50	246	208	228	213	241	210	208	249
55	227	217	225	220	228	214	212	229
60	214	212	213	213	216	211	211	214
65	215	215	216	216	225	215	217	214
1970	250	240	249	246	264	233	237	233
			Vertical Component (Z)					
1940	585	446	432	404	650	478	484	605
45	512	396	416	387	549	421	423	500
50	475	383	387	379	474	395	393	435
55	453	383	379	382	432	392	390	404
60	434	378	373	379	404	383	383	382
65	429	384	386	393	390	392	395	383
1970	432	395	416	416	390	399	406	392

TABLE 3

MODEL COMPARISONS (MEAN VALUE MINUS MODEL VALUE TRUNCATED AT ORDER 8)

Number of Values	*IZMIRAN*	*GFSC 12/66-1*	*Fougere 1*	*Fougere 2*	*Hurwitz et al.*	*Leaton et al.*	*Malin*	*POGO*
				Mean Differences				
D(°) 558	−0.3	−0.3	−0.4	−0.4	−0.1	−0.3	−0.3	−0.3
H(γ) 549	59	−34	−10	8	−24	−4	−50	−40
Z(γ) 548	146	11	14	42	−26	−112	11	8
				Rms Deviations				
D(°) 558	2.5	2.0	2.0	2.0	3.2	1.7	2.2	1.9
H(γ) 549	162	156	166	160	176	155	157	157
Z(γ) 548	229	196	204	194	232	176	195	192

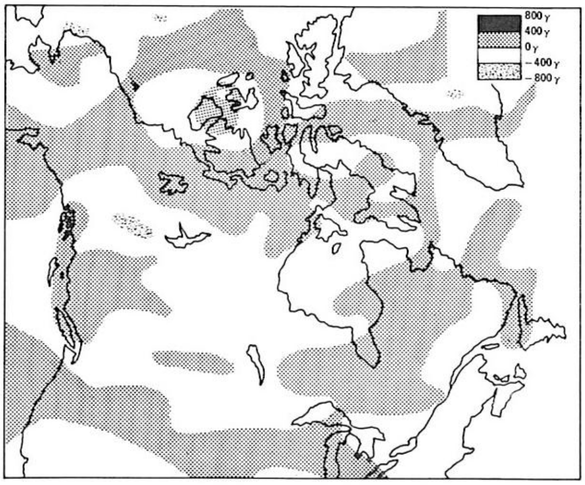

Fig. 5. H-Residual Chart, Observed Field Minus GSFC (12/66) Model.

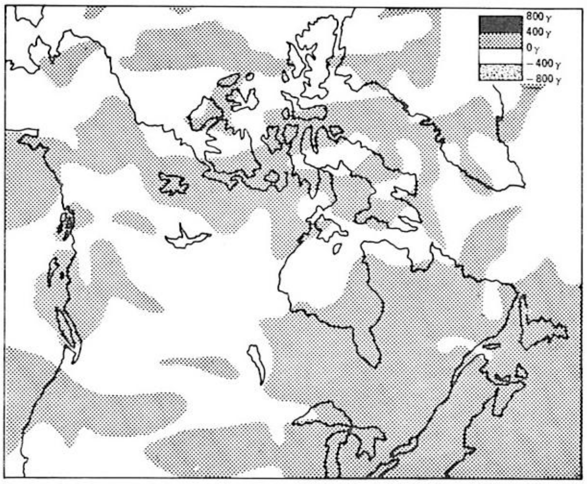

Fig. 6. H-Residual Chart, Observed Field Minus Fougere (1) Model.

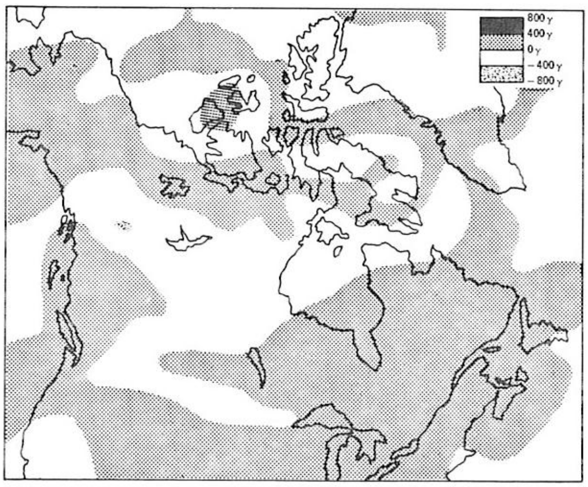

Fig. 7. H-Residual Chart, Observed Field Minus Fougere (2) Model.

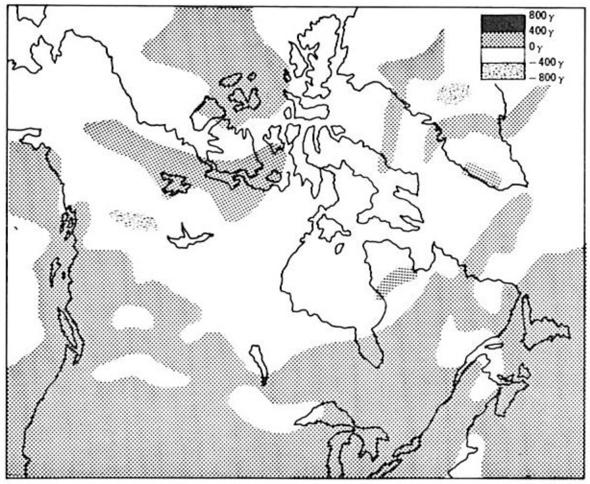

Fig. 8. H-Residual Chart, Observed Field Minus Hurwitz et al. Model.

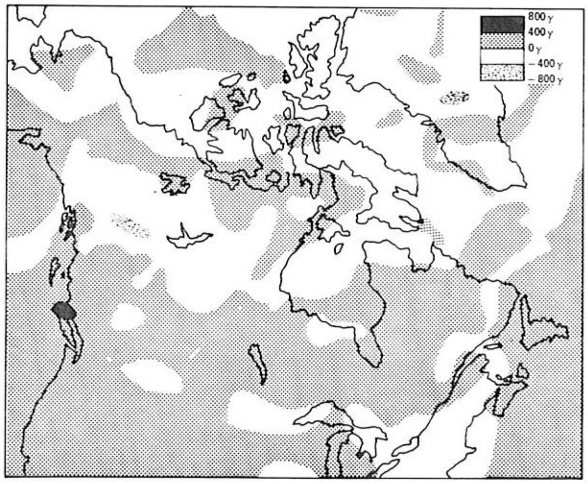

Fig. 9 H-Residual Chart, Observed Field Minus Leaton Model.

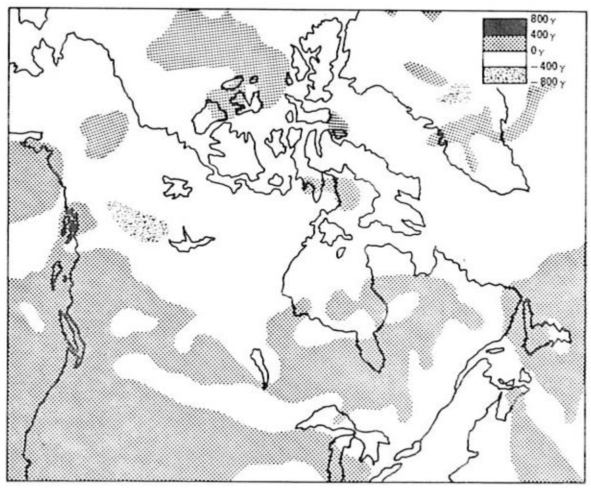

Fig. 10. H-Residual Chart, Observed Field Minus Malin Model.

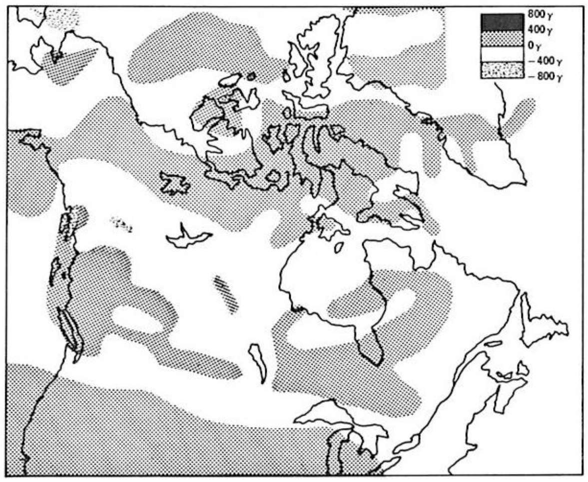

Fig. 11. *H-Residual Chart, Observed Field Minus POGO Model.*

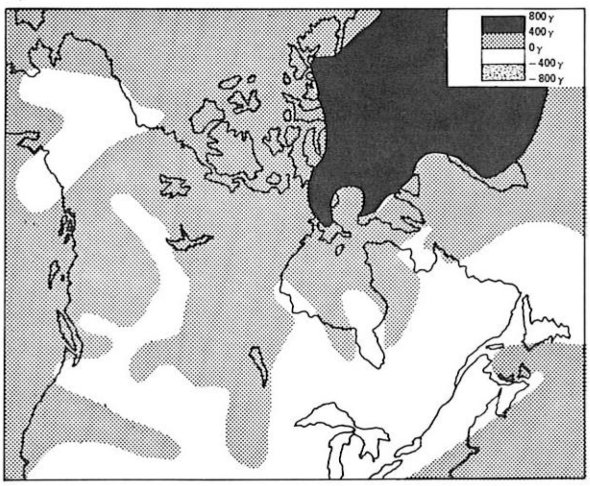

Fig. 12. *Z-Residual Chart, Observed Field Minus IZMIRAN Model.*

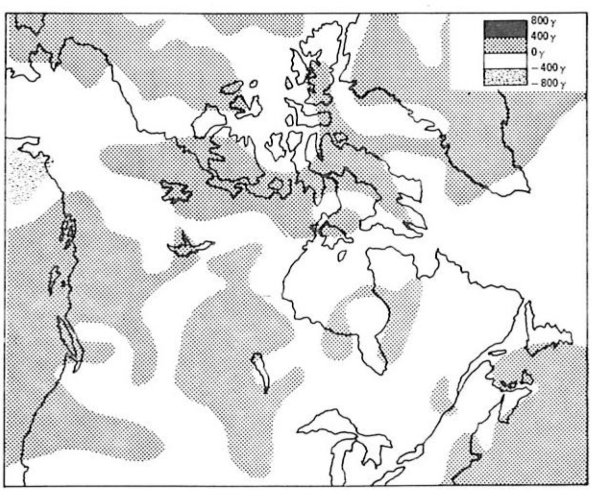

Fig. 13. *Z-Residual Chart, Observed Field Minus GSFC (12/66) Model.*

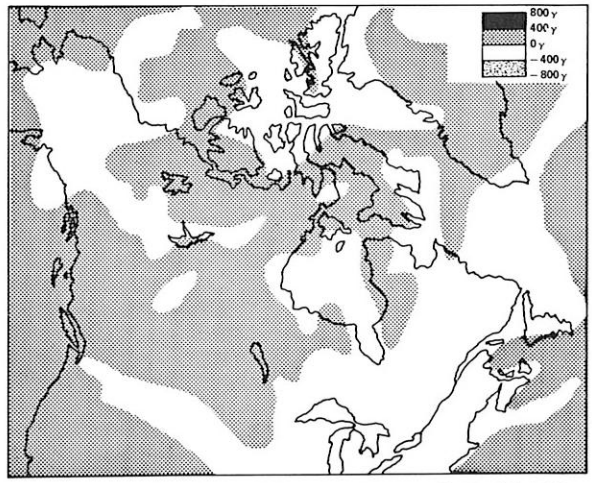

Fig. 14. *Z-Residual Chart, Observed Field Minus Fougere (1) Model.*

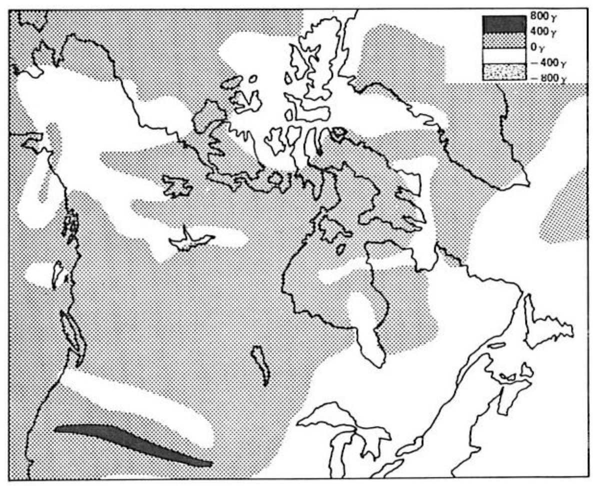

Fig. 15. *Z-Residual Chart, Observed Field Minus Fougere (2) Model.*

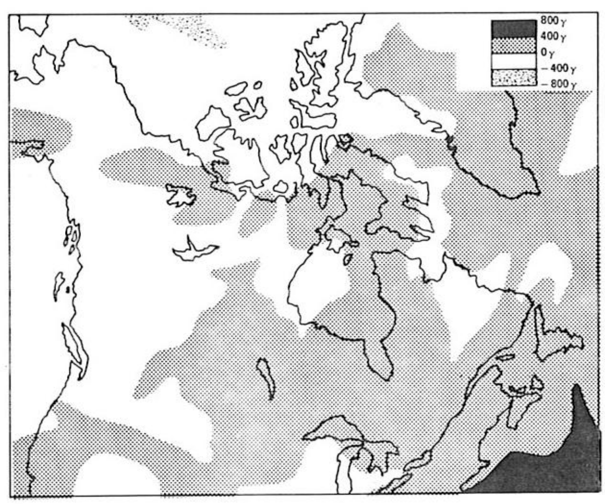

Fig. 16. *Z-Residual Chart, Observed Field Minus Hurwitz et al. Model.*

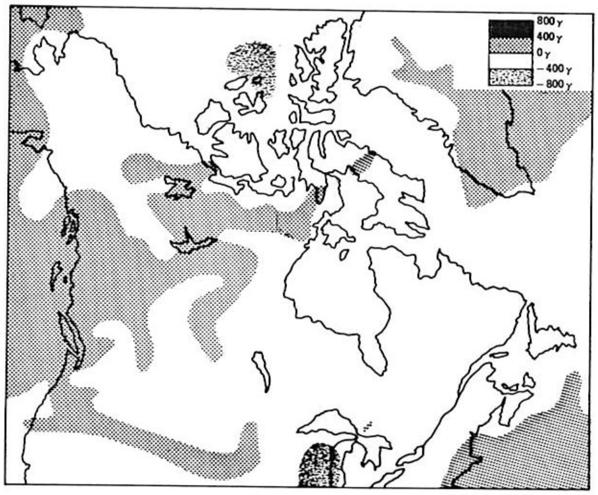

Fig. 17. Z-Residual Chart, Observed Field Minus Leaton et al. Model.

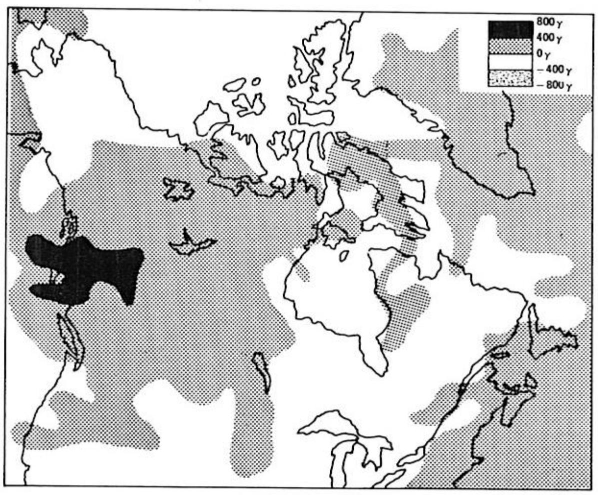

Fig. 18. Z-Residual Chart, Observed Field Minus Malin Model.

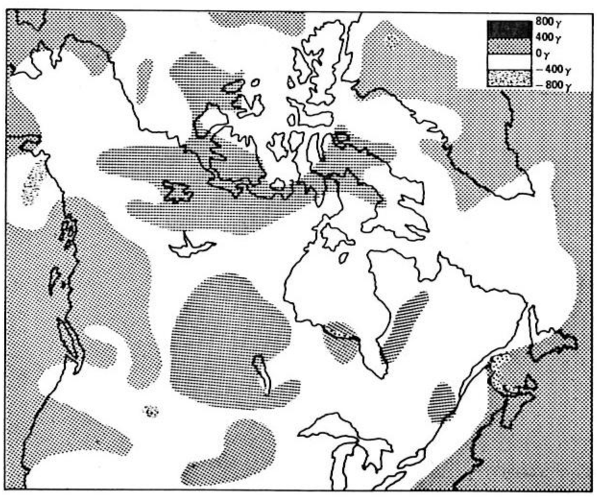

Fig. 19. Z-Residual Chart, Observed Field Minus POGO Model.

The preceding results lead to the following conclusions:

1. The best "definitive" fits are given by GSFC 12/66-1, the POGO, and the Fougere 1 models in that order.
2. The best "forecast" fits are given by the POGO, GSFC 12/66-1, and Leaton models in that order.
3. The results of the model comparisons with Canadian data verify the conclusions reached by *Cain et al.* [1965] using worldwide data regarding the tendency of field models to better fit data before the epoch of the chart. This points up the inability of most models, regardless of their consistency with potential theory, to fill in time or space gaps in the data. This is illustrated quite well with the POGO and IZMIRAN models. The POGO coefficients, based on data with a time range of 1965.8 to 1967.7, extrapolate backwards in time quite poorly when gauged against Canadian data. As pointed out earlier, the IZMIRAN coefficients, modified by data with a latitude range of $\pm 50°$, depicted large areas of positive residuals in Canada that were not consistent with those displayed by other models.
4. The POGO results illustrate that it is quite feasible to determine a vector magnetic field using only scalar values. They certainly indicate the future role of satellite measurements in determining accurate core field models including secular variation. The latter would require the necessity of repetitive orbital flights at different epochs.
5. The comparison of the proposed models with the mean data in D, H, and Z indicates that even over a well-surveyed area such as Canada, differences of the order of 800γ between field models are not uncommon. This is partially confirmed by Fig. 2 in *Benkova et al.* [1968], which shows a profile of residuals obtained comparing the proposed IGRF models with F-data for one revolution of the satellite COSMOS-49. Around latitude 45°N and longitude 65°W, the Hurwitz et al. and Fougere residuals are completely out of phase, with differences of the order of 400γ at an altitude of 300 km. It is interesting to speculate in what other large areas of the earth the residuals, depicted by the proposed models, are out of phase with one another. Two examples picked from Fig. 2 in *Benkova et al.* [1968] show that the residuals from the Fougere and Leaton et al. models are completely out of phase by 200 to 350γ at altitudes of 450 to 325 km over large parts of North Africa and the Madagascar areas. Tests were made on all models to see whether or not the field gradients had any unusual features present, but the results were negative.

6. On the average, the Z rms values derived from the comparisons with the smoothed values are 200γ lower than those obtained using the graphical observatory and repeat values for 1965. This implies the presence of a high crustal component in the latter values.

7. Finally, it seems unfortunate that the decision of the St. Gall meeting regarding the limit set on the number of coefficients was not emphasized, since the residual-reduction method of testing models naturally favors, in most cases, the model with the largest number of terms. Without drawing any conclusions and despite arguments against arbitrarily truncating a given series, Table 3 shows the results obtained from a comparison of the smoothed values in D, H, and Z with model values truncated at order 8.

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The eight models were compared using survey data supplied by the U.S. Coast and Geodetic Survey (see article by Fabiano and Cain in this volume). The tape, containing 200,000 observations (mainly surface) obtained since 1900, was edited as follows: first, the data were sorted by latitude and longitude and then by time. Observations made at the same location and within a few months of each other were averaged. The majority of such observations took place only a few hours or days apart. With the GSFC 12/66-1 and *Fougere* [1968] models as guides, observations with residuals of over 4000γ were rejected completely. Those with residuals between 1000 and 4000γ were initially retained for further examination, but subsequently were also rejected. What was the justification for rejection of these latter observations? Initially, it was a guess that these were bad points: either very erroneous or very anomalous. This guess was fully confirmed when all eight models agreed that these were, indeed, bad points. The overall root mean square (rms) for these points was calculated for all models, and all rms's agreed to within a small fraction of 1%. Further, these large residuals were all highly correlated over all eight models. Inspection of point-by-point plots of residuals was sufficient to reveal a remarkable correlation. The number of bad points was only about 1% of the original total.

What remained was a tape containing observations fitting the GSFC 12/66-1 and *Fougere* [1968] models to within 1000γ. From this tape a 10% sample consisting of every tenth observation was selected, and residuals for all eight harmonic sets were determined. For five years of data centered on a given year, Fig. 1 shows the overall rms values for the years 1930 to 1960. It is obvious that before

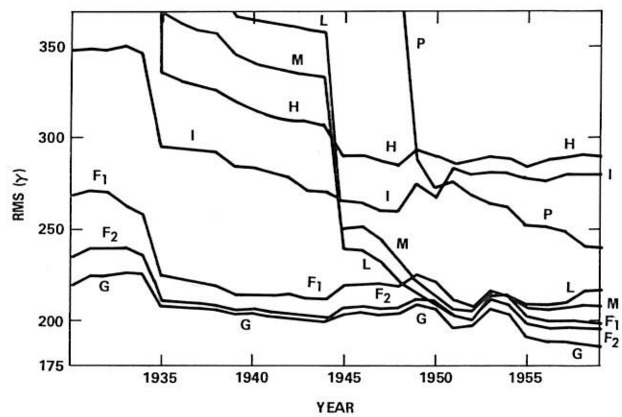

Fig. 1. Five-Year Running RMS, Survey Data. See Text for Further Discussion.

1950 only three models are at all reliable: the models labeled G (for GSFC 12/66-1), F_2 (for *Fougere* [1968]), and F_1 (for *Fougere* [1967]). Beyond about 1950, these three models and those labeled M (for *Malin* [1968]) and L (for *Leaton et al.* [1965]) are reliable, the results differing at most ~15% from each other with overall rms values around 200γ. The three remaining models are not as good. Of these three the most erratic is the P (for POGO) model, which deviates before 1950 but gives apparently moderate results after that. Finally, the H (for *Hurwitz et al.* [1966] and *Hurwitz* [1968]) and I (for IZMIRAN) models show rms's around 280γ since 1945. For the entire time period the G model fits best, while the two F models rank second and third most often.

The next set of data examined was observatory annual means. Overall rms values in gammas for data obtained since 1940 are:

Model	γ
F_1	264
F_2	272
G	283
M	320
L	356
I	368
H	378
P	494

The fit to various satellite data is the following:

Model	Vanguard (γ)	OGO 2 Group 1 (γ)	OGO 2 Group 2 (γ)
G	29	16	18
F_1	<10	25	44
F_2	41	41	43
B	43	84	87
L	49	78	88
M	49	54	60
P	54	11	13
H	>500?	>500?	175

It is immediately obvious that the satellite data are fit to almost an order of magnitude better than the ground-based data. It is therefore very difficult (if not impossible) to give a number characterizing the fit to all data samples. The best that can be done is to combine data sets that are comparable in accuracy.

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In a circular letter to the Working Group dated November 22, 1966, Leaton and Malin suggested that the adopted International Geomagnetic Reference Field (IGRF) be a composite model based on several existing models to make it genuinely international, to incorporate as much observational data as possible, and so as not to favor any one out of a number of possible candidates. On examining possible models for inclusion in the IGRF it was found that some contained a number of coefficients considerably different from those in the other sets, and it was decided to select the median value of each coefficient rather than take a straight mean. When the IGRF was discussed at the St. Gall meeting of the International Union of Geodesy and Geophysics (IUGG) there were several criticisms of the median field:

A. It was shown that a number of individual fields provided a better fit to independent sets of data than did the median field [*Heuring et al.*, 1968; *Cain et al.*, 1967].
B. The median field was not an analytical model; i.e., it was not simply related to the observed data used for the derivation of its constituent models.
C. The five sets of coefficients from which the median was deduced were not strictly comparable, since one of them (GSFC 12/66-1 of *Cain et al.* [1967]) allowed for the oblateness of the earth, while the other four assumed the earth to be spherical [*Kahle et al.*, 1966].
D. New (and presumably better) models were about to be produced that would outdate any proposed IGRF.

It now appears to be generally agreed that the following points are desirable for an IGRF:

a. It should provide as accurate as possible a model of the geomagnetic field, both at ground level and in space.
b. Since the effect of the earth's oblateness is both known and appreciable, this should be allowed for in deducing the model.
c. Because of the accuracy, uniformity, and coverage of satellite data, these should be included with the surface and airborne data in deducing the model. (It is not realistic to deduce a model from satellite data alone, since the time base is insufficient for a reliable determination of secular variation.)
d. The harmonic expansion should be truncated at $m = n = 8$ (agreed at St. Gall).
e. To avoid further delays, only those models already submitted to Dr. Zmuda should be considered.

The objectives outlined in the opening sentence of this note still seem valid, providing they do not conflict with the other desiderata for an IGRF. Consequently, it was proposed that the adopted IGRF be the mean of the following models: *Cain et al.* [1967], *Fougere* [1968], IZMIRAN [1967a, b], and *Malin* [1968]. We may examine how this proposed IGRF meets the requirements outlined above:

A. It would be very difficult to show that any of the IGRF models was appreciably better than the others (see section, "Testing of Models"). The mean would certainly not be worse than the worst constituent member.
B. Since the spherical harmonic expansion is linear, it is valid to combine different models by taking the mean. The resultant model is that which would have been obtained from an analysis of all four of the constituent data sets, giving each set an equal weight.
C. All four sets are now strictly compatible, i.e., oblate earth models.
D. These are, in fact, the new models.

a. The meaning of "the most accurate field" is examined later.
b. Allowance has been made for the earth's oblateness.

c. Satellite, surface, and airborne data have been incorporated.

The IGRF is now genuinely international.

The differences between the four sets of coefficients are very much smaller than when the original median model was proposed. A straight mean is now acceptable.

TESTING OF MODELS

It is not a test of the quality of a model to compare the residuals from the data set used in the computation of the model with the residuals of other models from the same data set. Providing the worker has not made any computational errors, his own model will inevitably be the "best" since this is a property of the method of least squares.

If two models are compared against a sample of data incorporated in the first but not in the second, the result will obviously be biased in favor of the first model.

If two models are compared against a sample of data that was included in both, the result will tend to favor the model that used the smaller data set. This can be seen by considering the limiting case when the first model was deduced from the test data alone, but the second model was based on the test data plus other data. The first model will provide the best possible fit to the test data, and the second model will inevitably provide a worse fit.

Thus the only valid test of the two models is to compare them both with data that were not used in either. Inevitably these must be recent data, so they will reveal little about the secular variation. Also, it is likely to be fairly local. "Local" in this sense would include data at the satellite level only.

Rather than try to test the various models against new data, it might be better to assume that the best model is the one that is based on the greatest amount of data. This will be correct if the following conditions apply:

1. The reduction and analysis have been carried out correctly.
2. The data used were well distributed in space and time.
3. The data were all of good quality.

Unless the results of tests against independent data clearly favor one model and the independent data are well distributed, we should adopt the criterion suggested in the preceding paragraph. There seems little reason to doubt that conditions 1, 2, and 3 apply to all four models. If this is so, the mean is the best model since this incorporates all the data used in the four contributing models.

There is an interesting precedent for the use of a mean field in the study of gravimetry [*Kaula*, 1966] that shows that the mean field is better than any individual field. The following quotation from this paper concerning this mean field would appear to be relevant to the present discussion:

"Some orbit analysts would disapprove of such combination and truncation on the grounds that each solution should be regarded as a complete set, the truncation of which constitutes a different representation of the gravity field than would have been obtained by analysing the same data for a set comprising the same terms as the truncation. However, their objection applies when 'optimum representation' is defined as approximating as closely as possible to the satellite orbits from which the sets were determined. These orbits in themselves are of rather evanescent interest; it seems geophysically more interesting to define optimum representation as approximating as closely as possible the acceleration of gravity at the earth's surface."

Although four models have been suggested for inclusion, this could equally well be extended to include the *Cain et al.* [1968b] POGO model and the *Fougere* [1967] model, if desirable. The only fields omitted would then be those of *Hurwitz et al.* and *Leaton et al.* These are the oldest of the models, do not allow for the earth's oblateness, and do not incorporate satellite data. Both models were based on very similar data sets that were virtually identical with those made available on magnetic tape by the U.S. Coast and Geodetic Survey. These data will make their presence felt in the mean model, since they formed an important part of the data used in deducing at least two of the other models.

Leaton, when submitting his model, suggested that it should be used only if separate ground and satellite models were considered.

Hurwitz formally submitted only his secular variation model. This may be incorporated in the mean secular variation if desired.

SECULAR ACCELERATION

A number of models of the second time derivative of the geomagnetic field have recently appeared. Three of the proposed IGRF models contain such coefficients.

Although it is clear that secular variation changes with time, it is equally clear that there is as yet little agreement on the nature of its changes. Consider the following models:

1. *Cain et al.* [1967] — Analysis of satellite and survey data for main field, secular variation, and secular acceleration.
2. *Fougere* [1968] — As above, using virtually the same data.
3. *Malin* [1969] — Analysis of observatory annual mean values specifically for secular acceleration (with secular variation as a byproduct) (presented at St. Gall).
4. *Orlov et al.* [1969] — Analysis of observatory annual mean values for secular variation and secular acceleration.

It will be seen that, although the four analyses were carried out independently, items 1 and 2 are very similar in method and data; likewise, items 3 and 4 are similar, so these two pairs should strongly resemble one another. This is confirmed by calculating the correlation coefficients between the different sets of spherical harmonic (s.h.) coefficients. Three correlation coefficients were calculated for each pair of models: up to $m = n = 4$, up to $m = n = 5$, and up to $m = n = 6$. The results are presented in Table 1.

TABLE 1
CORRELATION COEFFICIENTS

	Cain et al.	*Fougere*	*Malin*	*n max*
	0.943			4
Fougere	0.932			5
	0.922			6
	0.068	−0.008		4
Malin	0.061	−0.012		5
	0.077	−0.005		6
	0.429	0.341	0.681	4
Orlov et al.	0.499	0.374	0.636	5
	0.498	0.374	0.622	6

Significance < 0.001 if $k > 0.618$
Significance > 0.01 if $k < 0.5$

Both 1 and 2, and 3 and 4 are significantly correlated at the 0.001 level, but no other combinations reach even the 0.01 level. Thus with the exceptions already noted, there is a distinct possibility that the models are not even correlated, let alone comparable.

It is suggested, therefore, that the IGRF should contain only the first time derivative.

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The recent surveys of the main geomagnetic field provided us with much data on the main field, and now a problem of mastering them properly has arisen. But for the secular variation (s.v.) investigation, now as before, the principal difficulty is shortage and unevenness of surface data, as indicated in Fig. 1. In essence, this is all the information we have obtained to represent the world secular variation of the vector field. It is evident that the s.v. distribution is not, practically, secured and may be obtained only very approximately; hence, essential errors are inevitable. The results of observations at the repeat stations of different countries should be considered only as some subsidiary data, as they are available only for the last periods with an essential delay. We have no practical evidence to expect this situation to be varied significantly in the near future, since we have not, so far, any practical base for organization of some additional observatories or repeat stations in the regions difficult to assess, first of all, on the world oceans. The special survey, such as *Zarya*'s, requires a long time and the results, though most significant, are still not sufficient.

Until the last two decades the s.v. distribution was presented in the form of a graphically compiled chart, striking examples of which were shown by *Vestine et al.* [1947] who consolidated the data covering almost half a century (1902 - 1947). For the period since 1947 various authors compiled isoporic charts for shorter intervals, as a rule for intervals of five years. Owing to the shortage and extensive gaps in information, they reached rather conflicting results, even in the charts compiled for the same epoch. To improve the s.v. presentation and to restrict the

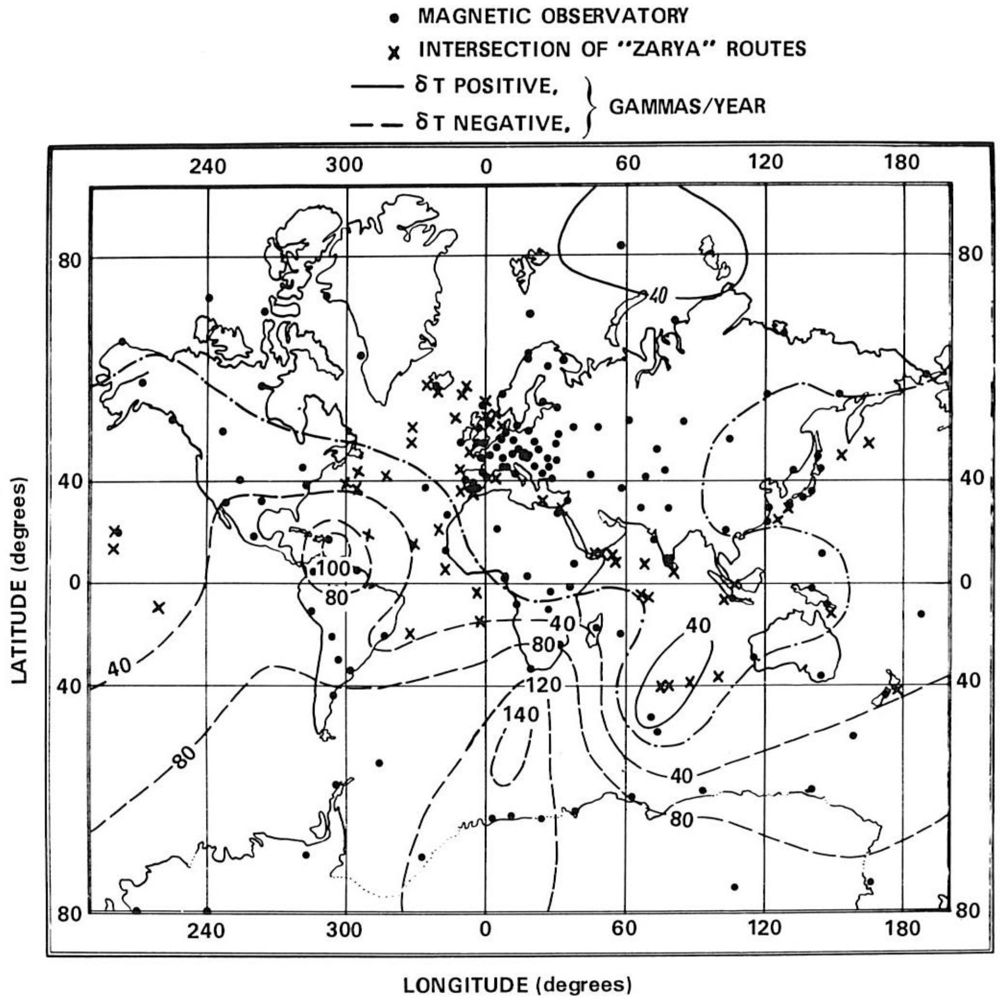

Fig. 1. The Worldwide Network of Magnetic Observatories, Intersections of Zarya Cruises Carried Out in Certain Time Intervals, and, as a Background, a Schematic δT Distribution.

authors' personal influence, another approach to the problem was tried. The spherical harmonic analysis was applied to the discrete s.v. values at the magnetic observatories. With the development of computers, performing spherical harmonic analyses was greatly facilitated and the number of s.v. analyses increased sharply during the last decade. But it seems that the authors' personal opinions are still presented even in analytical s.v. descriptions, and lie in the choice of a method of analysis, the combination of weights of different components (δX, δY, and δZ), truncation of the spherical harmonic series, etc.

The main directions of the approach to the problem of s.v. presentation are as follows:

1. Use as input data for the spherical harmonic analysis the changes of the mean annual values at the world magnetic observatories. An assumption is made that nonpotential and external parts of the s.v. filed are negligible; then the coefficients obtained by using different field components may be considered equivalent. To reach the agreement between

the sets of coefficients the different combinations of the weights are used, the input data are corrected (where possible), and three or four successive procedures (analysis synthesis) are performed. When the agreement between different sets of coefficients becomes more or less satisfactory, the mean final set is obtained [*Leaton et al.*, 1965; *Malin*, 1968]. Sometimes, the weight combination and successive analyses are replaced by application of special filters; as a result the most erroneous coefficients are rejected [*Bazarzhapov and Kolomiitzeva,* 1967]. In both cases the final coefficients depend to a great degree on weight combination, estimation of input-data accuracy to determine the filter, and the size of the filter.

2. Fit numerically to all the observational data available. A set of s.v. spherical harmonic coefficients is obtained in addition to the main field coefficients, using linear or parabolic time dependence [*Cain et al.*, 1967]. No preference is given to the observatory or repeat station data. In this case the s.v. pattern obtained contains many changes, even if these changes were produced by other, and not s.v., sources. The experiment with *Zarya,* Project MAGNET, and a number of other precise oceanic surveys showed that one should carry out a very careful investigation of the anomalous field in the locality of the survey profiles; otherwise, the computed s.v. values might be erroneous.

3. Apply precise satellite surveys, carried out in different years, or compare satellite data and a smoothed field along the profiles of precise survey at or on the ground [*Cain et al.*, 1968; *Kolomiitzeva and Tyurmina*, 1968]. The application of satellite data is by all means of great value, but for the total intensity only; so far, it is not clear that these data would be as successful for obtaining the secular variation of field components. In Fig. 2 the isolines show the differences in Z-components between the two computed fields: D (COSMOS) [*Tyurmina*, 1968] and POGO 3/68, [*Cain et al.*, 1968]; the numbers correspond to the differences between secular change, or δZ, values obtained at the magnetic observatories and computed using the POGO model. As one may see, the areas of great ΔZ correlate rather well with large differences in Z secular variation (which rise to 120γ/year). Hence, the s.v. errors would be not only large, but would contain some false regularity. When the satellite and surface surveys are compared, the basic restriction is to find a method of smoothing surface data to the same degree, otherwise the comparison would not be a correct one. We are quite sure that in the future only satellite surveys will provide data for the precise s.v. estimates, but not for the current epoch.

To illustrate the degree of reliability of s.v. presentation for the current epoch, Fig. 3 shows the contours of discrepancies exceeding 30γ/year for the

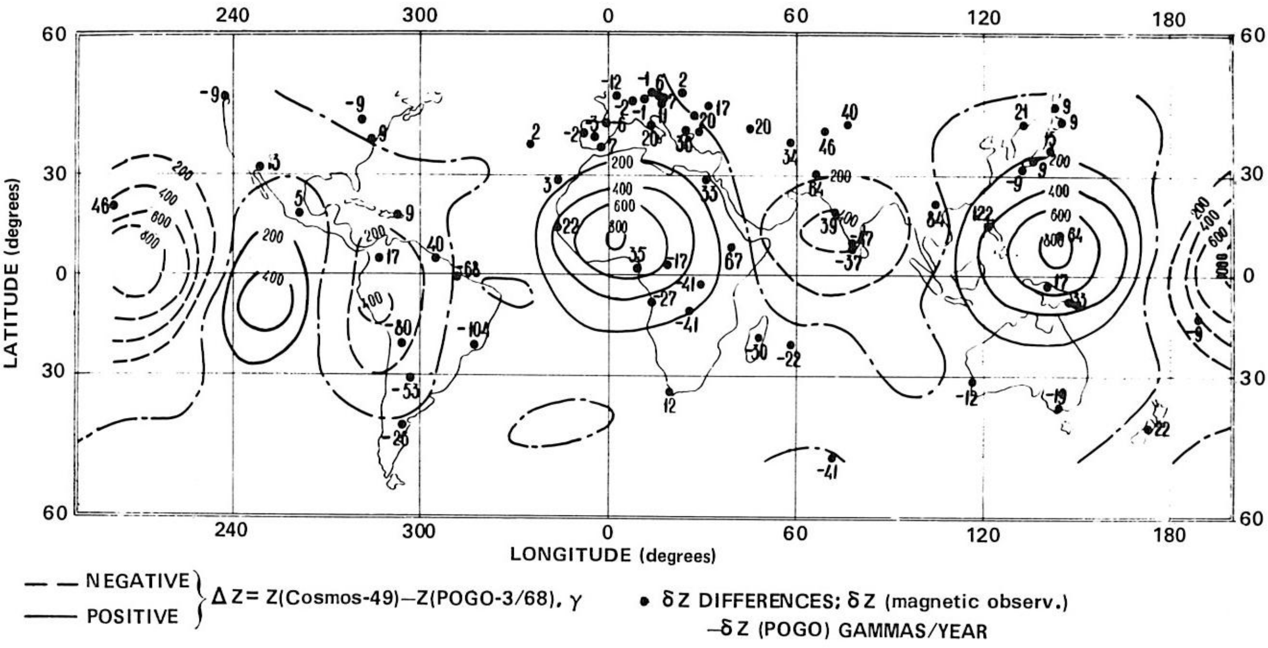

Fig. 2. Differences between Values of the Vertical Component and Differences in its Secular Change. See Text for Further Discussion.

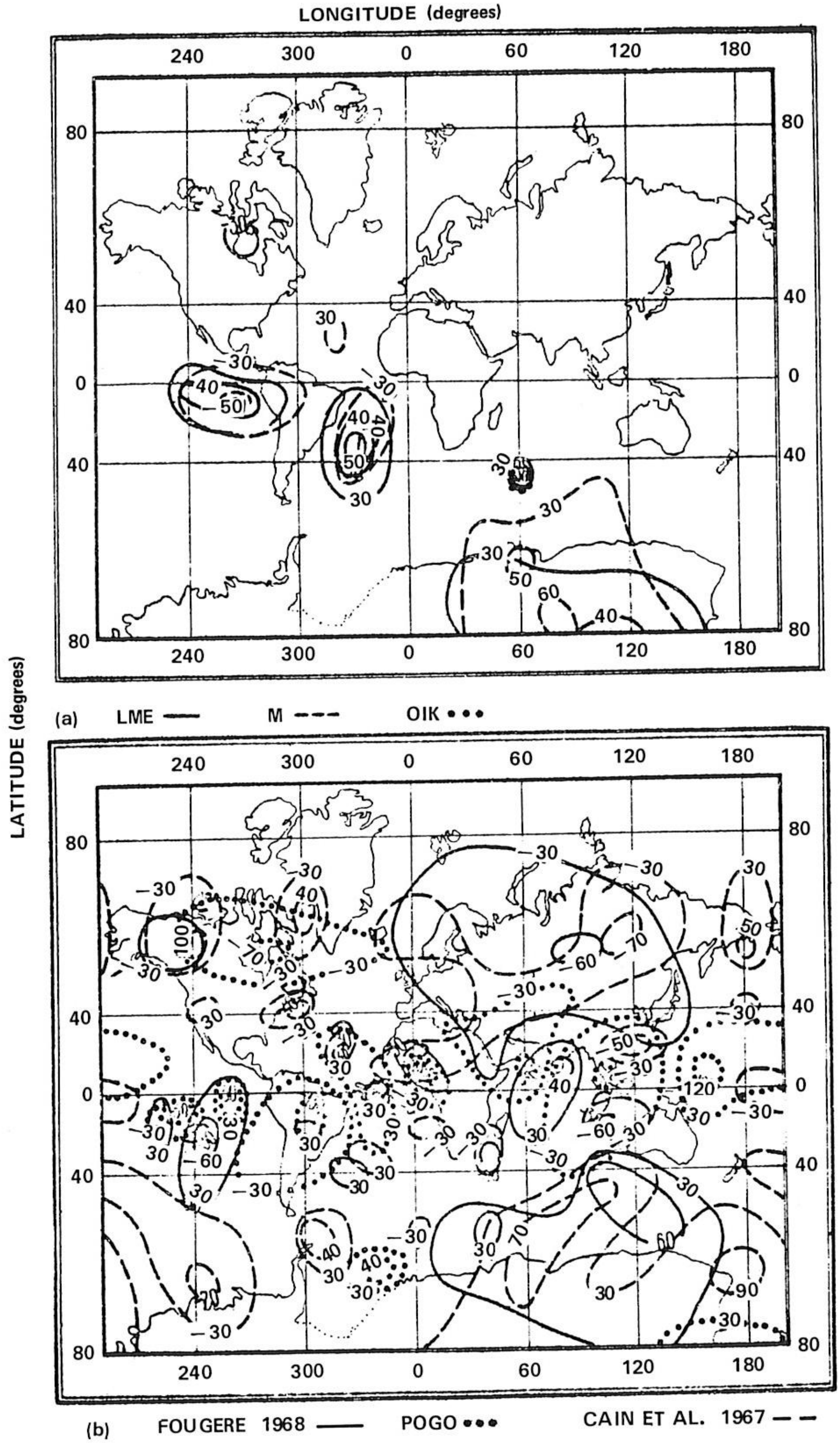

Fig. 3. Contours of Differences between Chart and Computed Values of the Secular Change of the Vertical Component, Gammas/Year.

different s.v. models. These differences are taken in the sense: δZ, read off the graphical chart minus δZ, computed using different analytical models. Inspection of the figure reveals that δZ differences of 30-50γ/year are quite usual over most of the earth's surface. However, over the southern hemisphere and near the equator they rise to 60-70 and even 100γ/year. It is worth noting that often large negative areas belonging to one model are overlapped by the areas of another model of the same size but are positive. In this figure LME is the abbreviation for the Leaton, Malin, Evans model; M, for Malin; and OIK, for the model of the present authors.

The information on s.v. has to comply with the following requirements: to be delivered in a simple, compact form, convenient for digital computations; to cover the time interval corresponding to the time of the main recent magnetic surveys (surveys of Canada, Project MAGNET, Japan, etc.); and to include the current epoch. These are the requirements for the s.v. model we propose.

The described ways to solve the s.v. problem are based on s.v. values at the discrete points without any cartographical generalization. We consider preliminary generalization to be very useful when interpolating s.v. values from data obtained at observatories spaced far apart. Preliminary graphical representation permits deriving additional information though it is not convenient for analytical description. It will help to define more accurately extremum areas, to represent more accurately the s.v. gradients, etc., although without exact quantitative estimates. The spherical harmonic analysis is then performed to conform the charts of separate components and to give the mathematical approximation convenient for further usage. The graphical charts will not be uniform over all the earth's surface, but, since one of their main purposes is to compile magnetic charts, it would be reasonable to make them more detailed there, where we have rather reliable data.

The proposed s.v. model (hereafter often referred to as the OIK model) covers the time interval from 1950 to 1970. It is presented by the two sets of the spherical harmonic coefficients: δg_n^m and δh_n^m up to $n = m = 6$ for the interval 1960 - 1965 (1962.5) and their time derivatives $\delta \dot{g}_n^m$ and $\delta \dot{h}_n^m$, the assumption being made on the linear character of the s.v. time dependence. This model is suggested to provide for the current epoch; the information later than 1970 has to be prepared for the XV General Assembly of IAGA that will be held in 1971. Some corrections to the model, after obtaining the final s.v. distribution, may become necessary.

The s.v. charts for the interval 1960 - 1965 were compiled on the basis of the 1965 annual means at the magnetic observatories, some repeated surveys, and the intersections of *Zarya* cruises. The results of comparison of Vanguard-III and COSMOS-49 data with a number of oceanic profiles were also taken into account. Then, these charts were subjected to the spherical harmonic analysis. The result of that work was reported at the General Assembly of IAGA in 1967. Since then only some insignificant corrections were made in these charts [*Orlov et al.*, 1969]. To get the change of δg_n^m and δh_n^m with time, we used the results of all the s.v. analyses available to us.

The graphs of δg_n^m and δh_n^m were compiled, and the approximate linear time dependence for every coefficient was derived for the period 1950 - 1970. Though this dependence was obtained for all 48 coefficients, which are available from us or the editor, for higher harmonics ($n \geqq 4$), $\delta \dot{g}_n^m$ and $\delta \dot{h}_n^m$ are negligible and may be practically accepted as zero. One need not take this conclusion as an affirmation of s.v. higher harmonics' perfect stability; it is rather a result of their low accuracy. The relative time changes in higher harmonics may be large, but in order to reveal it we should have much better initial data. The most changeable are the coefficients with $n = 1$ and 2; $\delta \dot{g}_1^0 = 0.87\gamma/\text{year}^2$, $\delta \dot{g}_2^0 = -0.34\gamma/\text{year}^2$, and $\delta \dot{h}_2^1 = 0.35\gamma/\text{year}^2$.

To check the adopted δg_n^m and δh_n^m, the following comparison was carried out between the magnetic observatory data and the two models [*Cain et al.*, 1967 (GSFC 12/66) and *Fougere*, 1968], for the whole interval of 1950 - 1970. The results are illustrated in Fig. 4. There are plotted δX, δY, δZ, and δT values at six specially chosen observatories, situated in both hemispheres, with different s.v. types. On the observatories' graphs, corresponding graphs are superimposed, computed using three s.v. models and their first time derivative [*Fougere*, 1968; *Cain et al.*, 1967, and OIK]. The inspection of the graphs reveals that:

1. Observatory data are fitted better by the Fougere and OIK models.

2. The approximation of δX and δY by both models is equivalent, but δZ is fitted better by OIK (with the exception of the variation at Hermanus).

To evaluate the coefficients δg_n^m and δh_n^m, the following comparisons were carried out:

1. For six s.v. models (Table 1) δX, δY, δZ, and δT are computed and compared with the ones obtained at the magnetic observatories (Table 2).

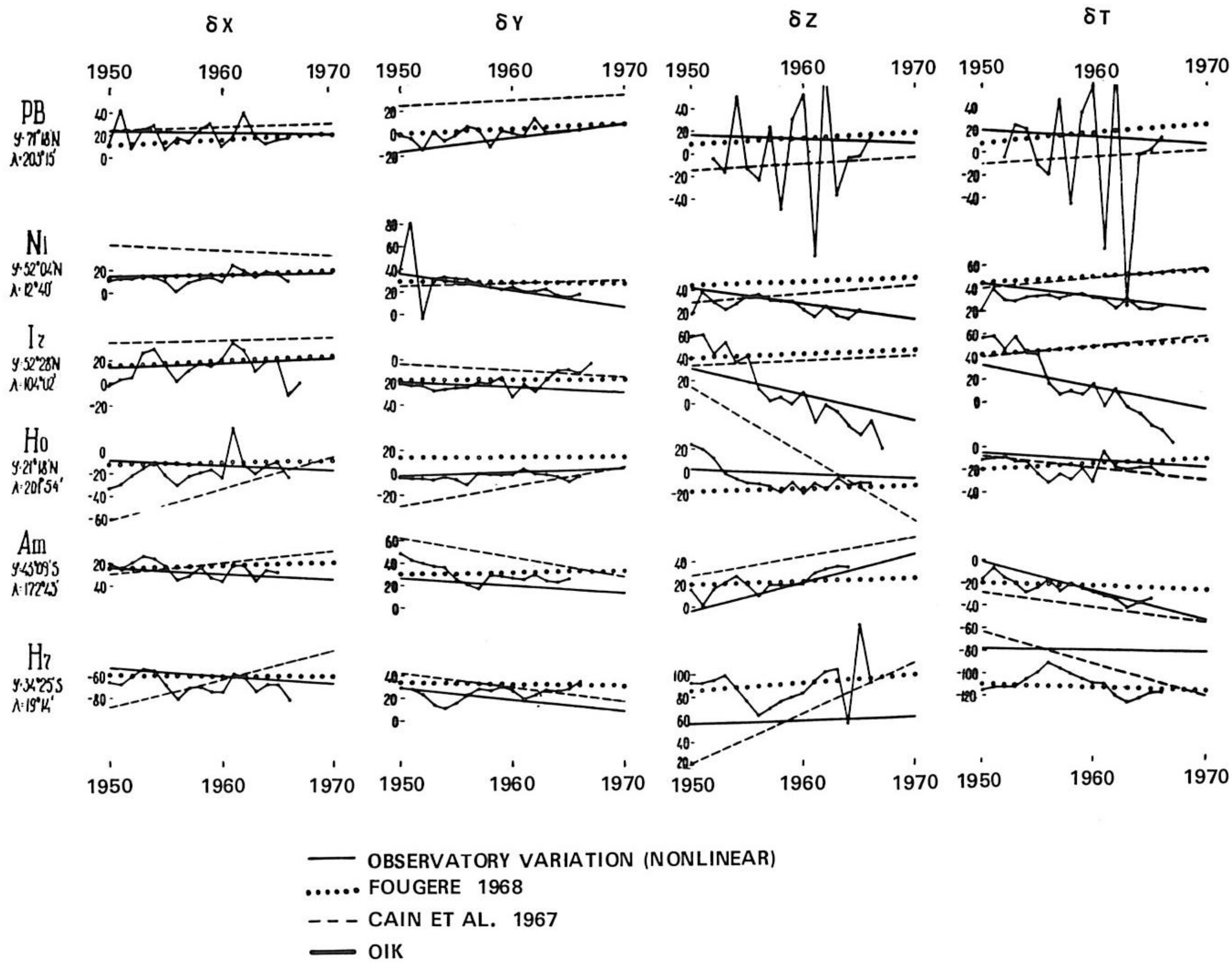

Fig. 4. Observed and Computed Values, in Gammas/Year, of Secular Changes, for Six Observatories.

TABLE 1

HARMONIC DESCRIPTION SUGGESTED FOR SECULAR VARIATION

Model	*Abbreviation*	*No. of Coefficients*	*Data for Analysis*	*Time Interval*
Orlov, Ivchenko, and Kolomiitzeva	OIK	48, n = m = 6 first derivative of s. v.	Charts of δX, δY, δZ	1950 - 1970
Leaton, Malin, and Evans [1965]	LME	48, n = m = 6	Magnetic observatory values of δX, δY, δZ	1965
Malin [1968]	M	48, n = m = 6	Magnetic observatory values of δX, δY, δZ	Suggested for IGRF 1965.0
Fougere [1968]	F_2	120, n = m = 10 first derivative s. v.	Some data from all surveys and from observatories	1900 - 1970
Cain, Hendricks, Langel, and Hudson GSFC 12/66-1 [1967]	C_2	120, n = m = 10 first derivative of s. v.	Derived from all magnetic surveys and T observed from the OGO 2	1900 - 1964
Cain, Hendricks, and Langel [1968b]	POGO 3/68	99, n = m = 9	A fit to a selection of OGO 2 and 4 data	1965.8 - 1967.6

TABLE 2

THE RMS AND MAXIMUM DIFFERENCES BETWEEN S.V. VALUES AT THE MAGNETIC OBSERVATORIES AND ANALYTICAL REPRESENTATION BY DIFFERENT MODELS, γ/YEAR

Model	$\Delta\delta X$ mean	$\Delta\delta X$ max		$\Delta\delta Y$ mean	$\Delta\delta Y$ max		$\Delta\delta Z$ mean	$\Delta\delta Z$ max		* $\Delta\delta T$ mean	$\Delta\delta T$ max	
OIK	± 7	−28	+22	± 7	− 40	+ 39	±10	− 30	+ 28	± 8	−41	+24
LME	± 7	−28	+25	± 9	− 28	+ 20	±15	− 66	+ 30	±14	−46	+59
M	± 5	−21	+18	± 5	− 29	+ 37	±12	− 77	+ 36	±11	−64	+30
F_2	± 9	−48	+31	±12	− 65	+ 56	±30	− 50	+ 96	±23	−58	+45
C_2	±14	−46	+45	±15	− 70	+ 70	±26	− 78	+ 73	±23	−76	+65
POGO	±16	−41	+87	±22	−108	+124	±21	−104	+122	±16	−48	+53

* For these differences δT is computed using the formula: $\delta T = \frac{X}{T}\delta X + \frac{Y}{T}\delta Y + \frac{Z}{T}\delta Z.$

TABLE 3

THE RMS AND MAXIMUM DIFFERENCES BETWEEN S.V. VALVES FROM THE GRAPHICALLY COMPILED CHARTS AND FROM ANALYTICAL REPRESENTATION BY DIFFERENT MODELS, γ/YEAR

Model	$\Delta\delta X$ mean	$\Delta\delta X$ max		$\Delta\delta Y$ mean	$\Delta\delta Y$ max		$\Delta\delta Z$ mean	$\Delta\delta Z$ max		$\Delta\delta T$ mean	$\Delta\delta T$ max	
OIK	± 8	− 15	+22	± 7	− 30	+ 16	± 8	− 34	+ 27	± 8	−32	+47
LME	± 8	− 30	+30	± 7	− 38	+ 20	±17	− 45	+ 52	±13	−60	+54
M	± 8	− 22	+37	± 8	− 32	+ 34	±13	− 50	+ 51	±12	−52	+32
F_2	±11	− 54	+42	±16	− 62	+ 52	±22	− 60	+ 99	±19	−75	+34
C_2	±16	−111	+49	±18	− 59	+ 62	±26	− 80	+ 99	±20	−80	+68
POGO	±18	− 37	+95	±22	−110	+113	±30	−171	+161	±19	−49	+64

2. Values from the same six models were compared with the values taken from graphical charts. In this case the mean deviation obtained for OIK defines only the error of the graphical chart approximation; these charts were subjected to the spherical harmonic analysis to derive the OIK model (Table 3).

As may be seen, the models OIK, M, and LME reveal better conformity with the chart data than the models based on the satellite data (or with the great percentage of the satellite data). The discrepancies in δX, δY, δZ, and δT, up to 100γ/year, as illustrated for δZ in Fig. 3, are spread over wide areas all over the earth. The deviations between "observatory" models and charts are, as a rule, less in magnitude and are revealed only in the regions far from the observatories.

The inspection of the six s.v. models, in our opinion, showed that to obtain a reliable s.v. pattern with the data available is practically impossible. But the s.v. distribution based on the observatory data has a certain advantage, though over the world oceans and high southern latitudes these models may contain considerable errors.

When the satellite data are used to get the s.v. representation, δT values are to be computed as a difference between the two scalar fields, referred to the different epochs. The δT error here would be much smaller.

The secular variation of the geomagnetic field is one of the most striking and the least investigated geophysical phenomena. Because of its rather complicated geographical distribution, small amplitudes, and slow time variation, the s.v. investigations require a prolonged series of continuous, accurate observations at uniformly distributed stations. But only little attention is now paid to this very important and necessary work.

It seems that the recent satellite surveys cannot solve the s.v. problem until the component measurements are available. Because of the s.v. regional distribution, to derive the secular variation using the scalar changes only without information on direction changes would not be reasonable. Therefore, the magnetic observatory and repeat stations remain the bases of s.v. studies. The oceanic surveys are not less necessary, but only *Zarya* and Project MAGNET provide component definition though the accuracy of the components is not sufficient (about 100γ).

We consider that urgent measures should be taken to improve the situation.

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When there are available several harmonic analyses conducted for the same epoch, the accuracy of individual harmonic coefficients may be roughly estimated by comparing the corresponding terms between different analyses [*Yukutake*, 1968], though there might be a particular model that could ideally represent the actual field.

Let (g_{nA}^{m}, h_{nA}^{m}) and (g_{nB}^{m}, h_{nB}^{m}) be two different sets of harmonic coefficients for the same epoch and let δg_n^m, δh_n^m, and C_n^m be defined as follows:

$$\delta g_n^m = g_{nA}^m - g_{nB}^m,\ \delta h_n^m = h_{nA}^m - h_{nB}^m$$

$$C_n^m = \left[\left\{\frac{g_{nA}^m + g_{nB}^m}{2}\right\}^2 + \left\{\frac{h_{nA}^m + h_{nB}^m}{2}\right\}^2\right]^{\frac{1}{2}}. \quad (1)$$

If δg_n^m (or δh_n^m) is of the same order of magnitude as the primary amplitude C_n^m, or if the ratio $|\delta g_n^m|/C_n^m$ (or $|\delta h_n^m|/C_n^m$) is close to or exceeds unity, one or more of the coefficients may be considered to be erroneous.

Discrepancies between the results of different analyses may be produced partly by the quality of the original data and partly by the technique or the method employed. It does not seem relevant to expand a series exceeding a limitation raised by the accuracy of the original data. In this paper, the extent the results scatter due to the quality of the data is first examined. Then a comparison of different models is made to investigate whether the discrepancies between the models exceed the error level imposed by the quality of the data.

Harmonic coefficients calculated from different components of the geomagnetic field are not necessarily identical. Discrepancies between these different sets of coefficients may be regarded as due to the incompleteness of the original data, if it is assumed that the earth's field is entirely of internal origin and does not include the nonpotential part.

Figure 1 shows results found when the spherical harmonic coefficients obtained from the north (X) and east (Y) components are compared with those from the vertical component (Z) for the harmonic analysis by *Leaton et al.* [1965]. For almost all the harmonics the ratios are small, indicating that the discrepancies between different components are insignificant. However, for n = 6, m = 5 the ratio exceeds unity. Whatever discrepancy exists may be caused partly by the external origin part included

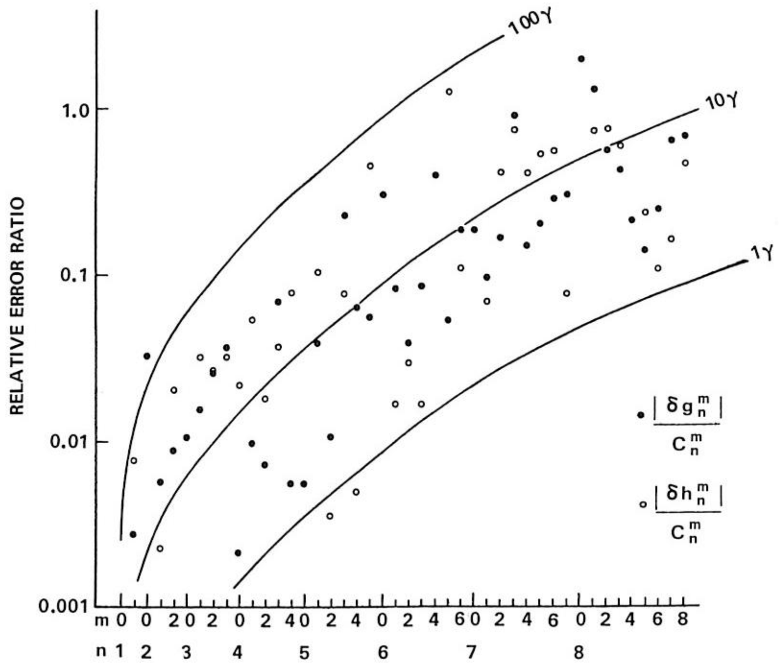

Fig. 1. Comparison of Spherical Harmonic Coefficients Calculated from X and Y Components with Those from Z Component, Based on the Analysis of Leaton et al. [1965].

with different content in the coefficients from different components and partly by the nonpotential part ignored in the analysis. However, from the standpoint of adopting an IGRF model that should only relate to the field of internal origin, the data in the figure can be regarded as showing a certain error level for individual harmonics originating from the quality of the data. The solid lines indicate approximate values of $|\delta g_n^m| / C_n^m$ and $|\delta h_n^m| / C_n^m$ when the absolute differences $|\delta g_n^m|$ and $|\delta h_n^m|$ between the different sets of coefficients become 1γ, 10γ and 100γ, respectively (a characteristic also applied in Figs. 2 and 3).

A comparison was also made between the coefficients of the GSFC 12/66-1 model of *Cain et al.* [1967] and the coefficients in the POGO model of *Cain et al.* [1968b]. Here discrepancies are due mostly to the effects of local anomalies and external disturbances. The results of comparison, as shown in Fig. 2, are very similar to those for the Leaton et al. analysis in Fig. 1. They seem to suggest an upper limit of the accuracy of the analysis when it is based on the observational data available at present.

The same procedures were repeated for various combinations of eight models presented as candidates for the IGRF, and one set of the results is shown in Fig. 3. No model definitely exceeds the error levels imposed by the quality of the data. It may be concluded, therefore, that the discrepancies between the models are caused mostly by the data used and do not depend on the techniques employed for the analyses.

Up to $n = 6$, the relative error ratios $|\delta g_n^m| / C_n^m$ and $|\delta h_n^m| / C_n^m$ are smaller than unity except for $n = 6$, $m = 5$, indicating that all the presented models are quite reliable as far as $n = 6$. For $n = 6$, the relative errors distribute between 0.01 and 1.0, their average being ~ 0.1. For $n = 7, 8, 9$, the ratios are still smaller than unity, but the errors involved in the coefficients reach roughly 30 to 40% of the original amplitude.

Absolute differences $|\delta g_n^m|$ and $|\delta h_n^m|$ are approximately in the range between 1γ and 100γ and tend to become small with the increase in degree and order, whereas the $|\delta g_n^m| / C_n^m$ increases with the increment of degree and order. This suggests that low-harmonic coefficients can be improved in order to better the overall fit of the model to observations.

Secular variation models were also treated, but the detailed results are not presented here. There exist much greater discrepancies between the models

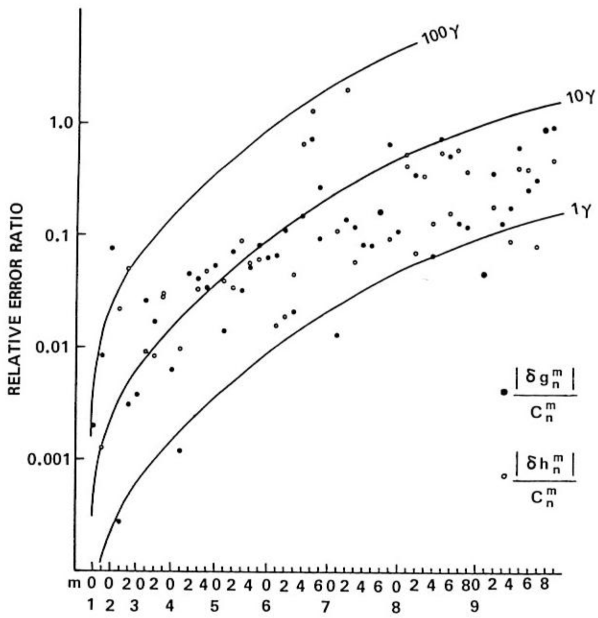

Fig. 2. Comparison of Harmonic Coefficients in the GSFC 12/66-1 Model of Cain et al. [1967] with those in the POGO Model of Cain et al. [1968].

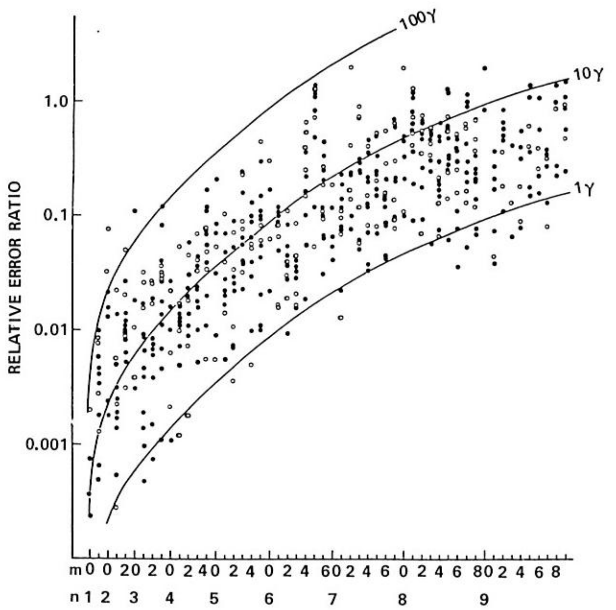

Fig. 3. Comparison of Spherical Harmonic Coefficients between the POGO and Other IGRF Models. Both $|\delta g_n^m| / C_n^m$ and $|\delta h_n^m| / C_n^m$ are Shown by Full Circles, and the Results in Figs. 1 and 2 are Reproduced by Open Circles for Comparison.

of the secular variation than in the case of the main field. Even in such a low harmonic as that with n = 3 and m = 0 and that with n = 4 and m = 0, the relative error ratio exceeds unity. For the harmonics higher than n = 4, it is difficult to find agreement even for the first digit of the coefficient. In order to improve the secular change model it seems necessary to increase the number of reliable observations and to improve the global distribution.

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Harmonic coefficients considered for an IGRF were evaluated by comparing computed values of the scalar magnetic intensity to those representative of the observations with satellite 1964-83C. *Zmuda et al.* [1968] and *Heuring et al.* [1968] treat the satellite experiment and results; Fig. 1 in the article "Satellite 1964-83C" in this volume by Zmuda shows the regions surveyed by the satellite and the resultant isodynamic contours. Data for points at an altitude of about 1100 km were obtained in and near the following regions: the southern part of the United States, northern and southern Atlantic, eastern Europe, Africa, South America, Australia, and an area 10 to 15° north of Hawaii.

From the totality of the satellite data, 1331 observations scattered throughout the surveyed region were used in the determination of the root mean square (rms) difference between observed and computed intensities for a varying number of terms in the harmonic series, as shown in Table 1. For example, when n = m = 1, the harmonic series is truncated at the h_1^1 term, and only the three terms of the centered-dipole field are used in the calculations; when n = m = 2, truncation occurs at the h_2^2 term, and the series contains eight coefficients.

With only the centered-dipole terms, the series of each model leads to an rms difference of about 3400γ, this partial series representing about 85% of the total observed field, whose average intensity equals 22,417γ. As the number of terms increases, the rms difference for each model decreases rapidly, then decreases slowly, and ultimately reaches a plateau value when n = m ≈ 8, with essentially no change as the number of terms increases beyond this stage. While this behavior is characteristic of all the models, some values are quoted only for the GSFC 12/66-1 field of Cain et al. The rms difference between observed and computed intensities equals 72γ for 63 terms, 69γ for 80 terms, and 67γ for 99 as well as 120 terms. Stated differently, the last 21 terms do not contribute to the description of the field in this satellite region, and the preceding 19 terms give an improvement of only 2γ.

The models in the table are listed according to their fit to the observations, with the best fit listed first. Considering the partial series ending at h_8^8, the lowest rms difference (and hence best fit) is obtained with the POGO 3/68 field and equals 68γ, 1γ less than the rms from the GSFC 12/66-1 field of Cain et al., 2γ less than the rms from the IZMIRAN model, 8γ less than the rms from Fougere's [1968a] model, and 15γ less than the rms from Malin's model. A total of 15γ separates the rms differences of the first five models, and each one is capable of describing this satellite field to within about 0.3%.

With respect to the remaining models, note that Fougere's first set is inferior to his second set. The models of Leaton et al., suggested for a surface reference, and of Hurwitz et al. yield respective rms differences of 106γ and 117γ. These two models are derived from data that did not include satellite observations and thus are at a disadvantage in a comparison of the present type.

TABLE 1

THE RMS DIFFERENCE BETWEEN OBSERVED AND COMPUTED INTENSITIES, γ

Model		*Parial harmonic series ending at h_n^m*											
	n = m	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Cain et al. [1968] - POGO 3/68	—	3428	2097	846	327	175	94	73	68	67	—	—	—
Cain et al. [1967] - GSFC 12/66-1	—	3429	2099	846	326	171	95	72	69	67	67	—	—
IZMIRAN [1967]	—	3439	2099	864	321	186	99	76	70	69	—	—	—
Fougere [1968]	—	3429	2094	847	322	166	100	80	76	75	76	—	—
Malin [1968]	—	3436	2096	862	343	185	105	87	83	—	—	—	—
Fougere [1967]	—	3426	2086	847	326	170	111	93	90	90	90	—	—
Leaton et al. [1965]	—	3451	2099	872	353	205	126	111	106	—	—	—	—
Hurwitz et al. [1966]	—	3459	2095	890	365	212	135	122	119	117	117	117	117

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IGRF 1965.0

IAGA Commission 2 Working Group 4 on Analysis of the Geomagnetic Field

At an open meeting in Washington, D.C., on October 24, 1968, the Working Group Members and Consultants chose the International Geomagnetic Reference Field (IGRF) 1965.0. The reference field was endorsed by the International Association of Geomagnetism and Aeronomy (IAGA) World Magnetic Survey Board on October 28, 1968, and by the IAGA Executive Committee in February 1969.

The reference is a series of solid spherical harmonics and their derivatives in geocentric spherical coordinates, describing the geomagnetic potential V and the field components through

$$V = a \sum_{n=1}^{n=8} \sum_{m=0}^{m=n} \left(\frac{a}{r}\right)^{n+1} \cdot [g_n^m \cos m\lambda + h_n^m \sin m\lambda] P_n^m(\cos\theta)$$

$$X = \frac{1}{r}\frac{\partial V}{\partial \theta} = \sum_{n=1}^{n=8} \sum_{m=0}^{m=n} \left(\frac{a}{r}\right)^{n+2} \cdot [g_n^m \cos m\lambda + h_n^m \sin m\lambda] \frac{d}{d\theta} P_n^m(\cos\theta)$$

$$Y = \frac{-1}{r \sin\theta}\frac{\partial V}{\partial \lambda} = \sum_{n=1}^{n=8} \sum_{m=0}^{m=n} \left(\frac{a}{r}\right)^{n+2} \frac{-m}{\sin\theta} \cdot [-g_n^m \sin m\lambda + h_n^m \cos m\lambda] P_n^m(\cos\theta)$$

$$Z = \frac{\partial V}{\partial r} = \sum_{n=1}^{n=8} \sum_{m=0}^{m=n} -(n+1) \left(\frac{a}{r}\right)^{n+2} \cdot [g_n^m \cos m\lambda + h_n^m \sin m\lambda] P_n^m(\cos\theta),$$

where X, Y, and Z represent, respectively, the northward, eastward, and downward components of the intensity in geocentric coordinates; a, the radius (6371.2 km) of the reference sphere; r, the radial distance from the center of the reference sphere; θ, the colatitude, or $90° - \beta$ where β is the latitude; λ the east longitude measured from Greenwich; $P_n^m(\cos\theta)$, an associated Legendre function of degree n and order m and of the Schmidt quasi-normalized type [*Chapman and Bartels*, 1940b]; and g_n^m and h_n^m, spherical harmonic coefficients. Each series has 80 terms, up to $n = m = 8$. The scalar intensity $F = [X^2 + Y^2 + Z^2]^{1/2}$; the horizontal intensity $H = [X^2 + Y^2]^{1/2}$; the declination $D = \tan^{-1}\left[\frac{Y}{X}\right]$; the inclination $I = \tan^{-1}\left[\frac{Z}{H}\right]$. The function $P_n^m(\cos\theta)$ may be written as

$$P_n^m(\mu) = \frac{1}{2^n n!}\left[\frac{\epsilon_m (n-m)!(1-\mu^2)^m}{(n+m)!}\right]^{\frac{1}{2}} \frac{d^{m+n}(\mu^2-1)^n}{d\mu^{m+n}}$$

where $\mu = \cos\theta$; $\epsilon_m = 1$ for $m = 0$ and $\epsilon_m = 2$ for $m \geqq 1$.

The epoch is $t_0 = 1965.0$ and the value of a harmonic coefficient for another time t is obtained from

$$C_n^m(t) = C_n^m(t_0) + \dot{C}_n^m(t - t_0)$$

where $\dot{C}_n^m$ equals the secular change of the coefficient in gammas/year ($1\gamma = 10^{-5}$ gauss).

Table 1 shows the IGRF coefficients, which apply to the period 1955.0 - 1972.0. For dates after the

TABLE 1
IGRF 1965.0 COEFFICIENTS

		Main Field (γ)		*Secular Change* (γ/yr)	
n	*m*	g_n^m	h_n^m	$\dot{g}_n^m$	$\dot{h}_n^m$
1	0	−30339		15.3	
1	1	−2123	5758	8.7	−2.3
2	0	−1654		−24.4	
2	1	2994	−2006	0.3	−11.8
2	2	1567	130	−1.6	−16.7
3	0	1297		0.2	
3	1	−2036	−403	−10.8	4.2
3	2	1289	242	0.7	0.7
3	3	843	−176	−3.8	−7.7
4	0	958		−0.7	
4	1	805	149	0.2	−0.1
4	2	492	−280	−3.0	1.6
4	3	−392	8	−0.1	2.9
4	4	256	−265	−2.1	−4.2
5	0	−223		1.9	
5	1	357	16	1.1	2.3
5	2	246	125	2.9	1.7
5	3	−26	−123	0.6	−2.4
5	4	−161	−107	0.0	0.8
5	5	−51	77	1.3	−0.3
6	0	47		−0.1	
6	1	60	−14	−0.3	−0.9
6	2	4	106	1.1	−0.4
6	3	−229	68	1.9	2.0
6	4	3	−32	−0.4	−1.1
6	5	−4	−10	−0.4	0.1
6	6	−112	−13	−0.2	0.9
7	0	71		−0.5	
7	1	−54	−57	−0.3	−1.1
7	2	0	−27	−0.7	0.3
7	3	12	−8	−0.5	0.4
7	4	−25	9	0.3	0.2
7	5	−9	23	0.0	0.4
7	6	13	−19	−0.2	0.2
7	7	−2	−17	−0.6	0.3
8	0	10		0.1	
8	1	9	3	0.4	0.1
8	2	−3	−13	0.6	−0.2
8	3	−12	5	0.0	−0.3
8	4	−4	−17	0.0	−0.2
8	5	7	4	−0.1	−0.3
8	6	−5	22	0.3	−0.4
8	7	12	−3	−0.3	−0.3
8	8	6	−16	−0.5	−0.3

epoch 1972.0, recommendations will be made at the XV General Assembly of the International Union of Geodesy and Geophysics (IUGG) in 1971; future modifications of the IGRF are likely to apply only to the secular change coefficients. For the period near but preceding 1955.0, the 1945.0 field of *Vestine et al.* [1947] is suggested. A Fortran program to compute field values from the IGRF 1965.0 is obtainable from the U.S. National Space Science Data Center, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A., 20771; the Institute of Geological Sciences, Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, Sussex, England; or the World Data Center A for Geomagnetism, U. S. Coast and Geodetic Survey—ESSA, Rockville, Maryland, U.S.A., 20852.

The centered dipole of the IGRF has a magnetic moment of 8.01×10^{25} gauss cm^3 for 1965.0, and its axis intercepts the earth's surface at the point with $\beta = 78.6°$N and $\lambda = 290.2°$E, and at that with $\beta = 78.6°$S and $\lambda = 110.2°$E.

The main field coefficients represent a composite from four sets listed in order of importance in Table 2 and weighted proportional to $1/\sigma^2$ with the σ values shown in the table. The secular change coefficients are the resultant from the five sets of Table 2, all with equal weights. The coefficients were published in three journals [*IAGA*, 1969].

TABLE 2
HARMONIC SETS INCLUDED IN IGRF 1965.0

Title and/or Authors	*Main Field, Weight σ*	*Secular Change*
GSFC 12/66 - 1, *Cain, Hendricks, Langel and Hudson* [1967]	40	All five sets had equal weights for the secular change coefficients
Fougere [1968]	70	
Malin [1968]	80	
IZMIRAN, main field coefficients from *IZMIRAN* [1967a]; secular change from *IZMIRAN* [1967b]	100	
Hurwitz [1968] (Secular change only)		

It will sometimes be desirable to transform from geodetic to geocentric coordinates and from the vector field in geodetic coordinates to that in geocentric. Fundamental considerations have been discussed in a number of publications: coordinate transformations for points on the earth's surface [*Bomford*, 1962]; and coordinate and field transformations and their importance at the earth's surface [*Kahle et al.*, 1964, 1966; *Kahle*, 1968] and at points above the earth's surface [*Cain*, 1966; *Cain et al.*, 1967; *Cain et al.*, 1968c; *Malin and Pocock*, 1969]. The following treatment incorporates various parts from these publications.

For use with the IGRF, the earth's surface has an equatorial radius A and flattening f from the International Ellipsoid recently adopted by the International Astronomical Union [*Transactions of the International Astronomical Union*, 1966]:

$$A = 6378.160 \text{ km} \tag{1}$$

$$f = \frac{A - B}{A} = \frac{1}{298.25} = 0.0033529 \tag{2}$$

where B is the polar radius (6356.775 km).

The mean radius $\frac{2A + B}{3}$ of this ellipsoid equals

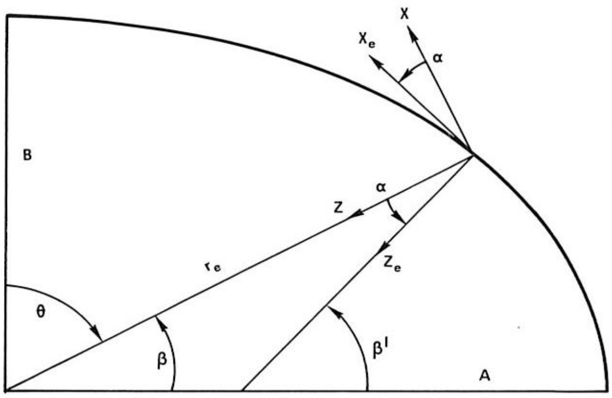

Fig. 1. Geocentric and Geodetic Coordinates and Vector Field Components Referred to a Sphere and to a Spheroid. See Text for Discussion.

6371.03 km and is less than the radius a (6371.2 km) of the IGRF reference sphere that is, however, retained because of its use in deriving the harmonic coefficients, though it represents also the mean radius of an earlier ellipsoid.

The latitude of a point on the surface of the earth as determined astronomically refers to the local vertical, normal to the geoid (here taken to be the spheroid).

This is the geodetic latitude, β' (Fig. 1) which relates to the geocentric latitude β through

$$\tan \beta = (1 - e^2) \tan \beta' \quad (3)$$

where $e^2 = \frac{A^2 - B^2}{A^2}$ with e the eccentricity and

where, following the normal practice, each latitude is positive in the northern hemisphere and negative in the southern.

The geocentric radial distance, r_e, to the surface of the spheroid can be found from the equations

$$\begin{aligned} r_e^2 &= x^2 + y^2 + z^2 \\ x &= \nu \cos \beta' \cos \lambda \\ y &= \nu \cos \beta' \sin \lambda \\ z &= (1 - e^2)\nu \sin \beta' \\ \nu &= \frac{A}{(1 - e^2 \sin^2 \beta')^{\frac{1}{2}}} \end{aligned} \quad (4)$$

with λ the east longitude.

For a point h above the earth's surface and along the normal to the ellipsoid, the geocentric colatitude and geodetic latitude connect through

$$\cos \theta = \frac{\sin \beta'}{[P \cos^2\beta' + \sin^2 \beta']^{\frac{1}{2}}} \quad (5)$$

where

$$P = \frac{h[A^2 - (A^2 - B^2) \sin^2 \beta']^{\frac{1}{2}} + A^2}{h[A^2 - (A^2 - B^2) \sin^2 \beta']^{\frac{1}{2}} + B^2}. \quad (6)$$

The geocentric radial distance r relates to the geodetic latitude β' and height h through

$$r^2 = h^2 + 2h[A^2 - (A^2 - B^2) \sin^2 \beta']^{\frac{1}{2}} + \frac{A^4 - (A^4 - B^4) \sin^2 \beta'}{A^2 - (A^2 - B^2) \sin^2 \beta'}. \quad (7)$$

Additional relationships of interest are

$$\cos \alpha = \frac{1}{r} [h + \sqrt{A^2 \cos^2 \beta' + B^2 \sin^2 \beta'}], \quad (8)$$

$$\sin \alpha = \frac{1}{r} [A^2 - B^2][A^2 \cos^2 \beta' + B^2 \sin^2 \beta']^{-\frac{1}{2}} \cos \beta' \sin \beta', \quad (9)$$

$$\cos \beta = \cos \beta' \cos \alpha + \sin \beta' \sin \alpha, \quad (10)$$

$$\sin \beta = \sin \beta' \cos \alpha - \cos \beta' \sin \alpha, \text{ and} \quad (11)$$

$$\alpha = \beta' - \beta. \quad (12)$$

Transformation equations between field components (X, Y, and Z) derived in the geocentric coordinates of the IGRF and those (X_e, Y_e, and Z_e) referenced to a geodetic coordinate system are

$$\begin{aligned} X_e &= X \cos \alpha + Z \sin \alpha \\ Y_e &= Y \\ Z_e &= -X \sin \alpha + Z \cos \alpha. \end{aligned} \quad (13)$$

Both sets of field components can be obtained from the Fortran programs mentioned earlier.

IGRF CHARTS

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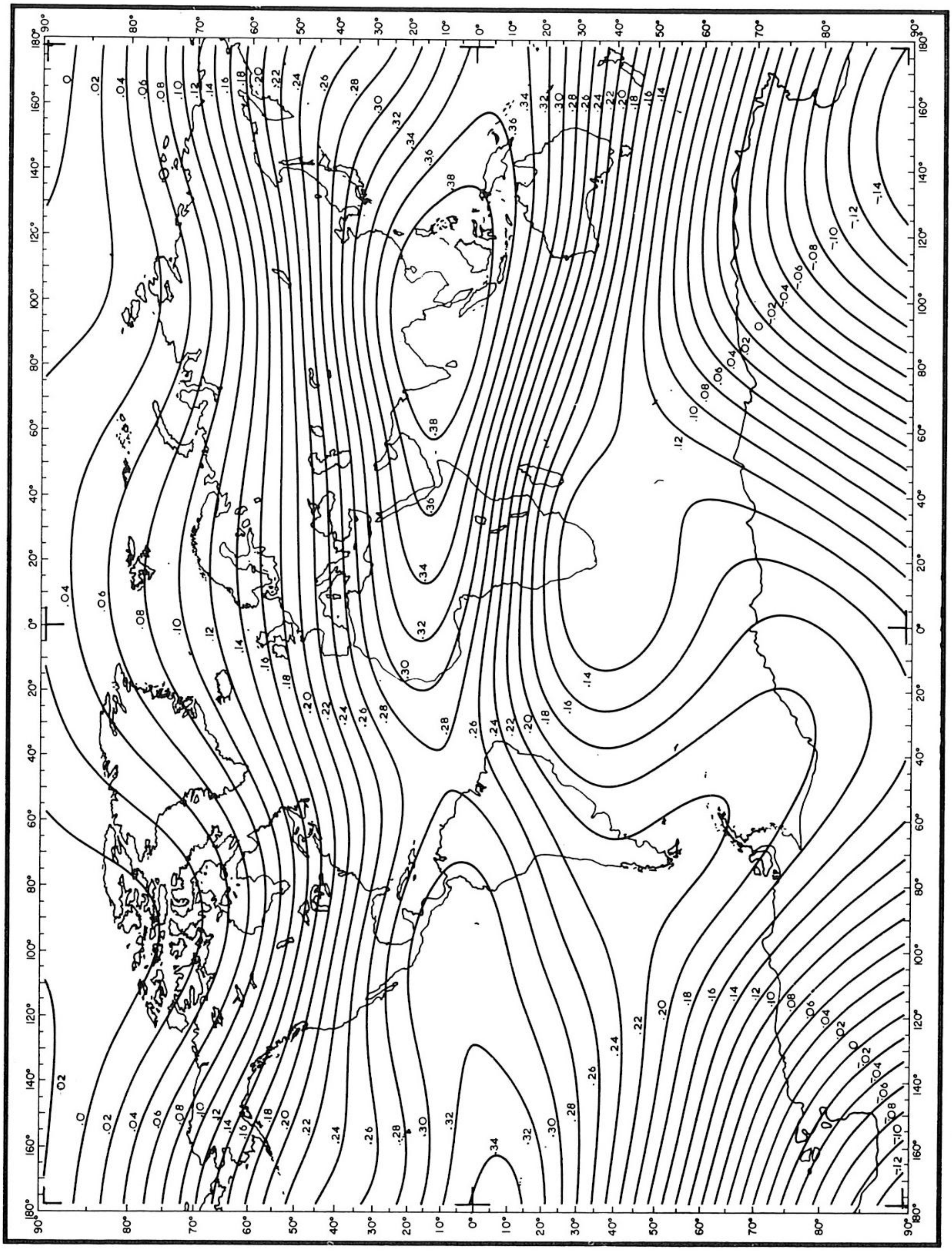
Charts for all seven elements and annual secular change are given in Figs. 1-14 for the surface of the earth. A stereographic projection has been used to enable worldwide data to be shown on one sheet. These charts are meant to correspond to the IGRF.

Draft charts were produced using a computer contour program at NASA-Goddard Space Flight Center, U.S.A., under the supervision of Dr. J. C. Cain. The charts were completed manually by Mr. M. Fisher at the Institute of Geological Sciences, U.K. This work involved the removal of plotter waviness, supplying where necessary the missing lines (mostly in D and $\dot{D}$), labeling, and general tidying.

Grid values for the elements and their secular change are given in IAGA Bulletin no. 29 by myself and D. R. Barraclough.

NORTH COMPONENT (gauss) X



IGRF 1965·0

Fig. 1

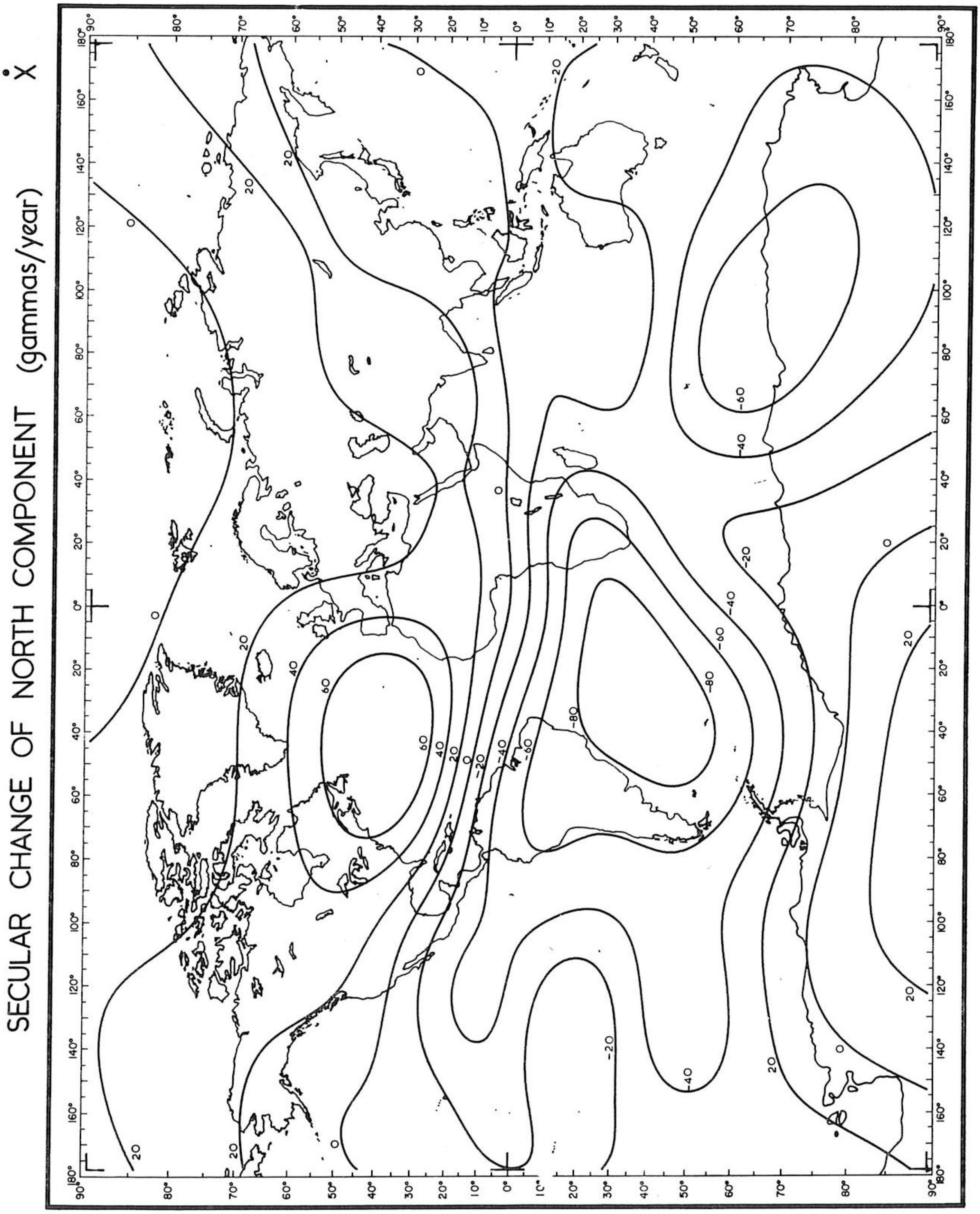

SECULAR CHANGE OF NORTH COMPONENT (gammas/year) $\dot{X}$
IGRF 1965·0

Fig. 2

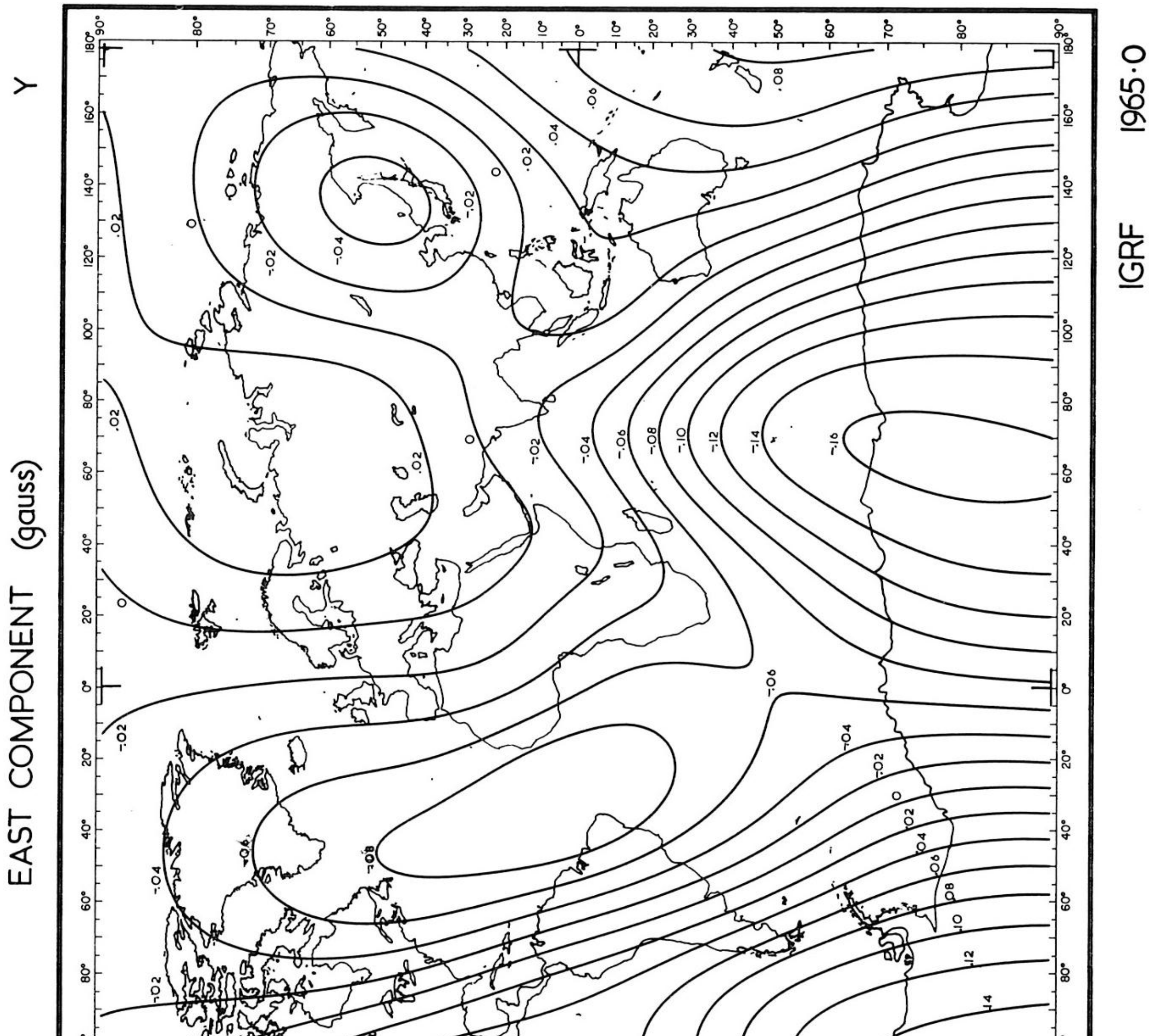


Fig. 3

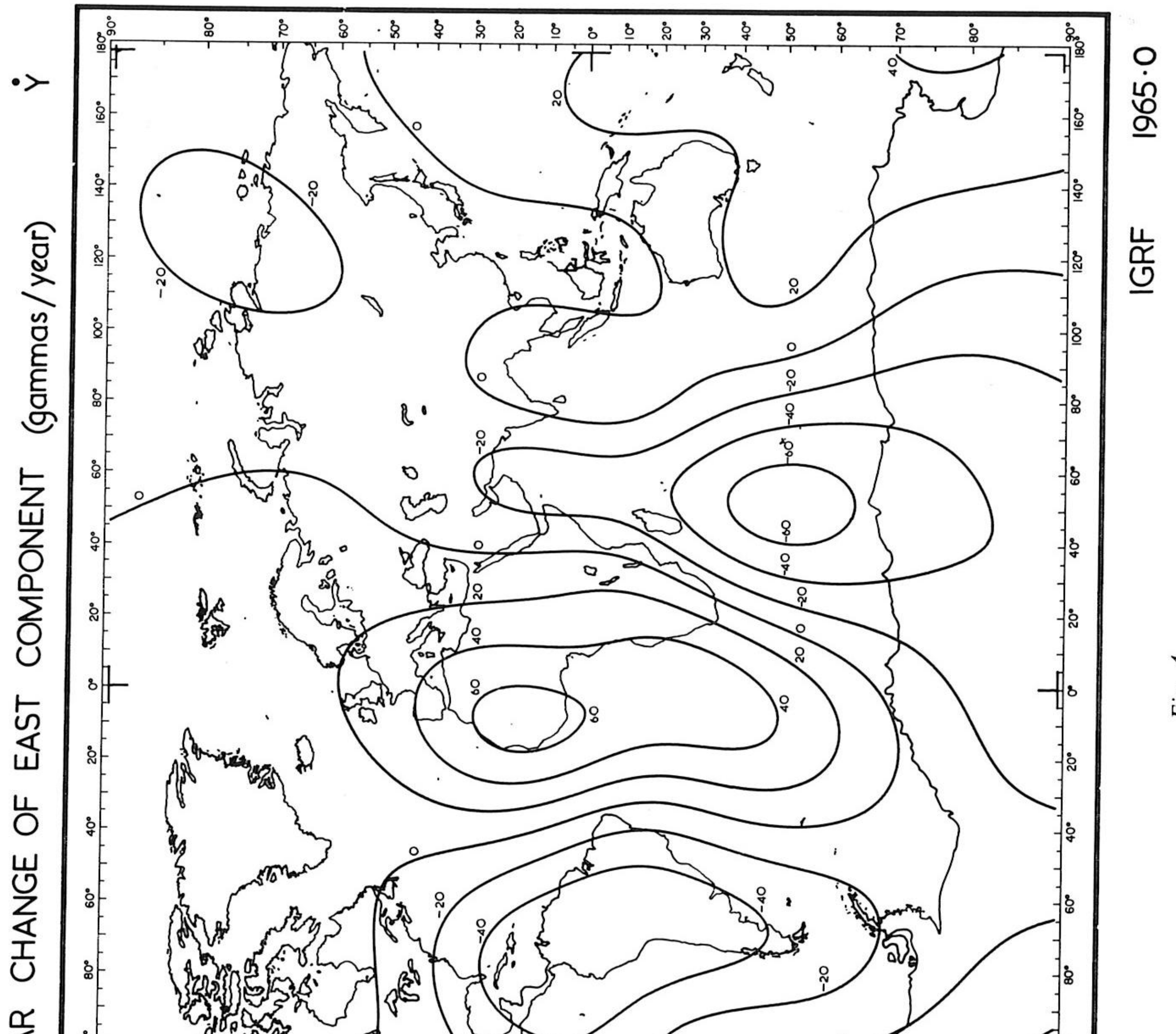


Fig. 4

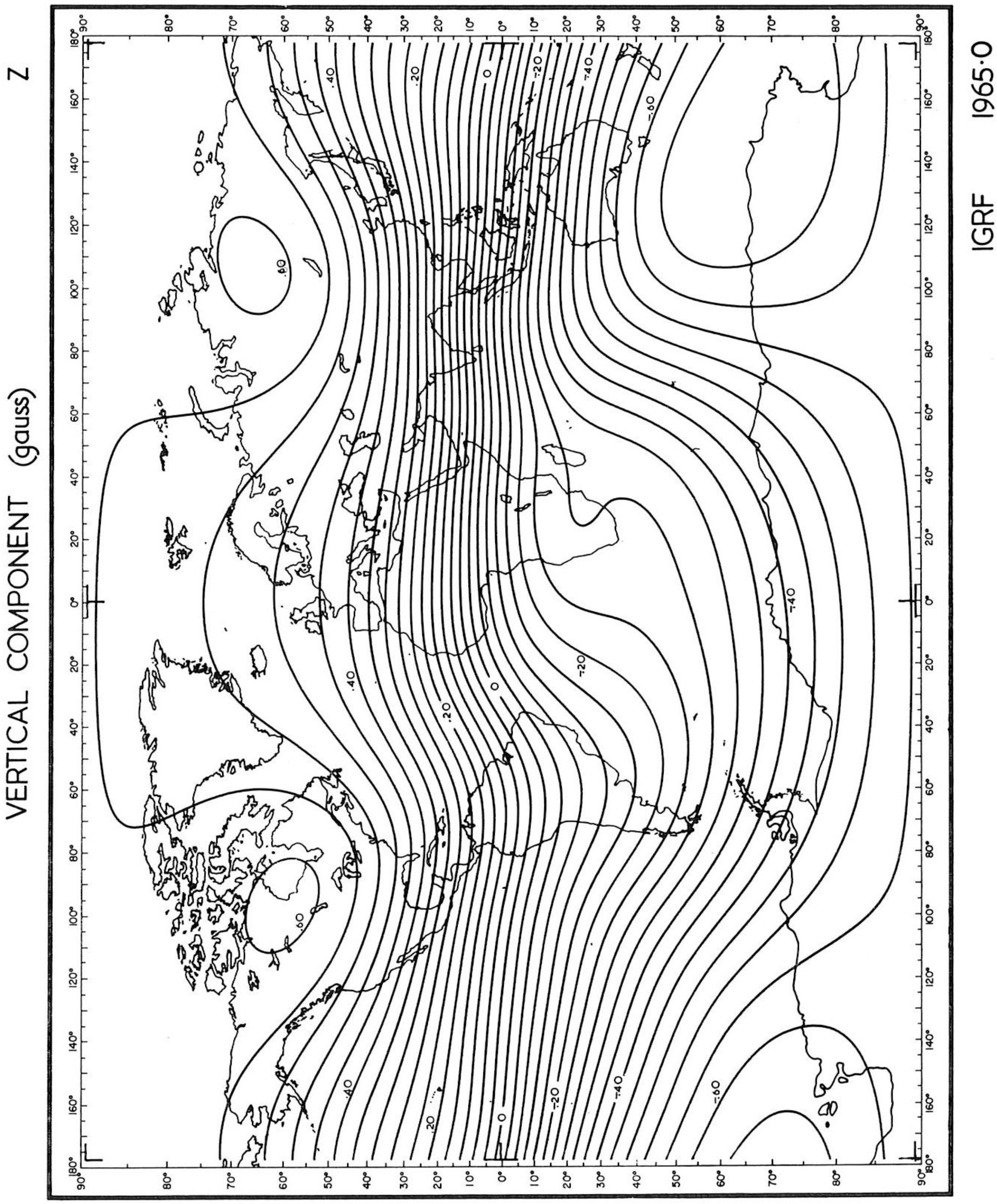


Fig. 5

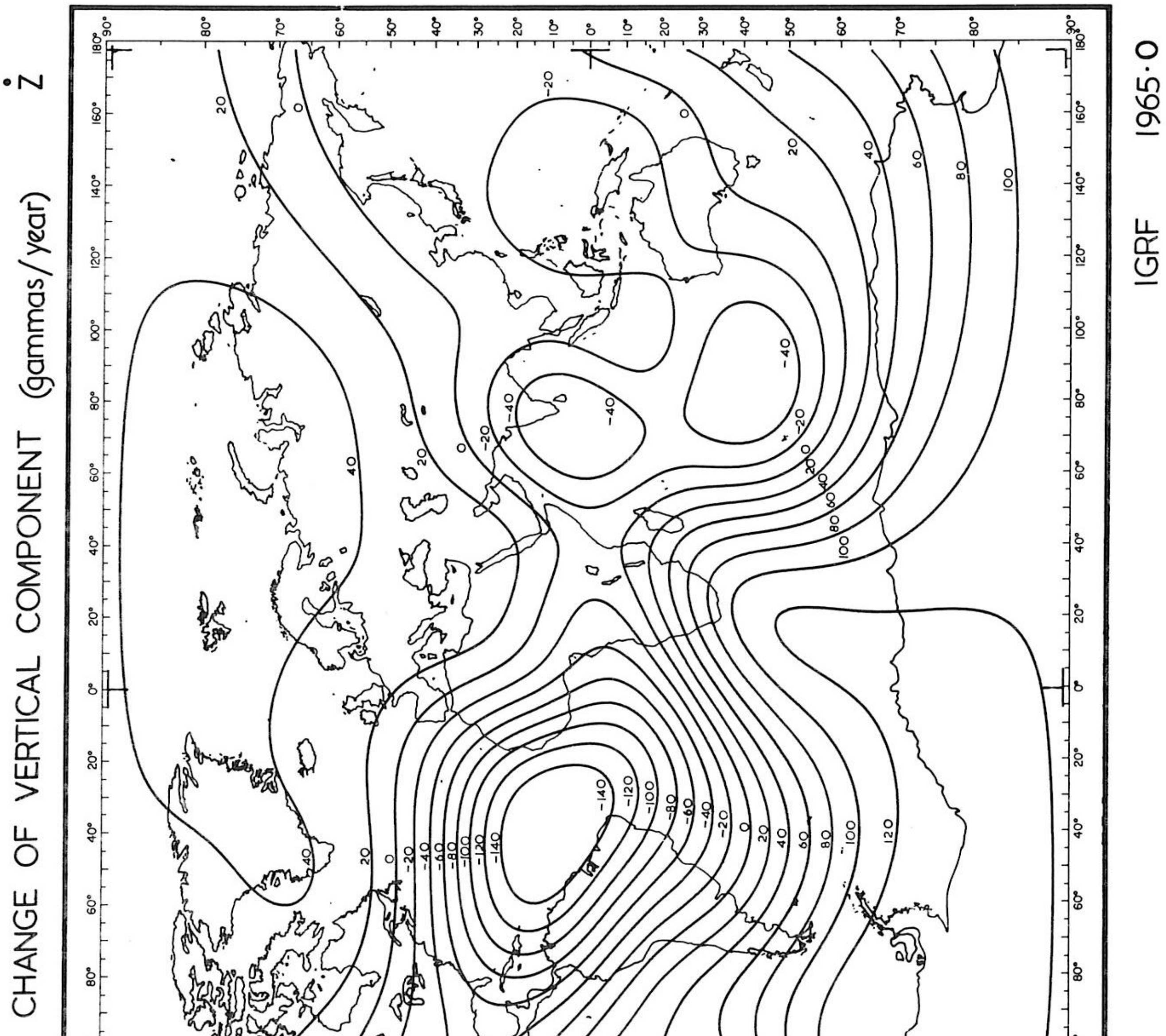

SECULAR CHANGE OF VERTICAL COMPONENT (gammas/year) Ż
IGRF 1965·0

Fig. 6

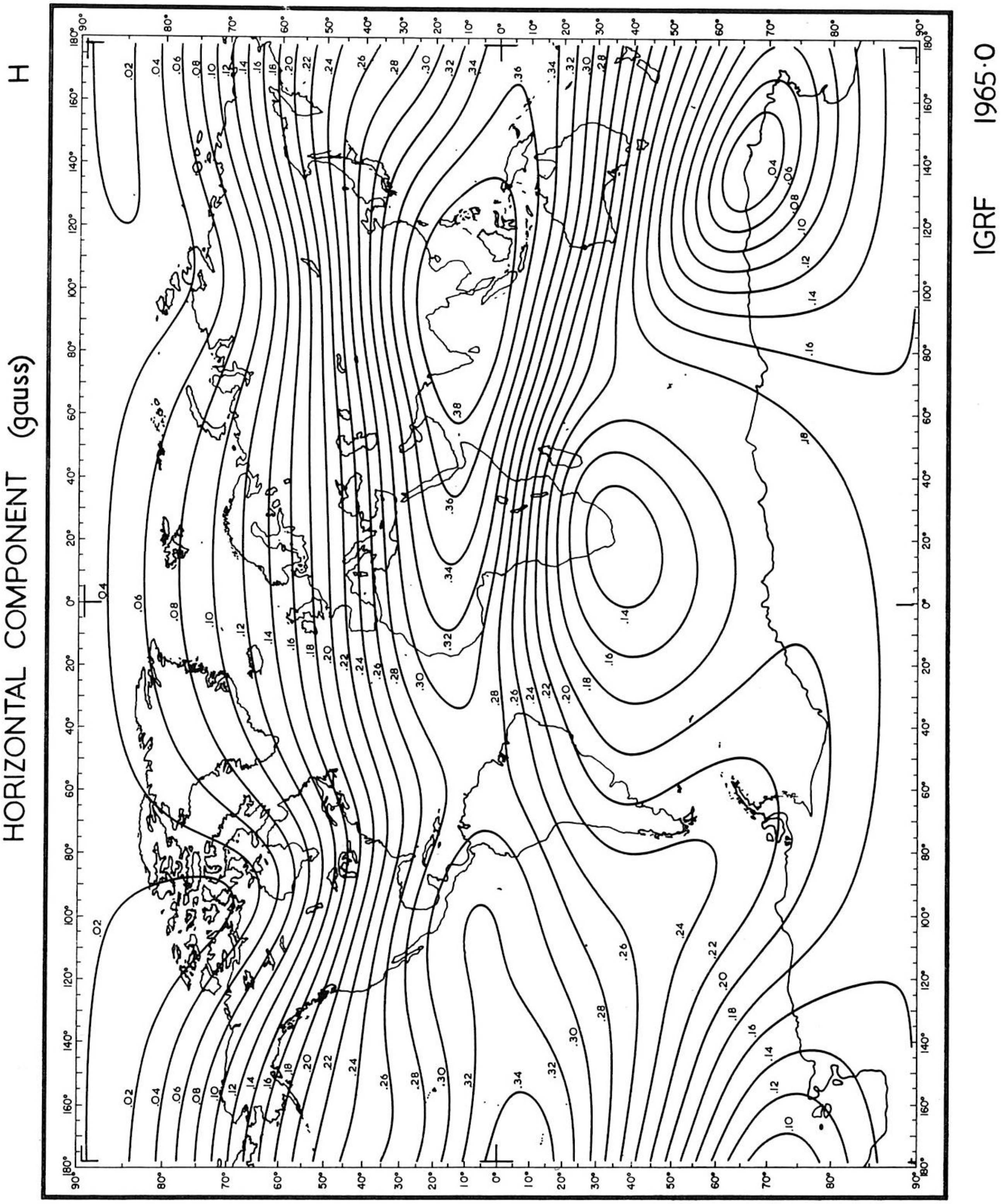


Fig. 7

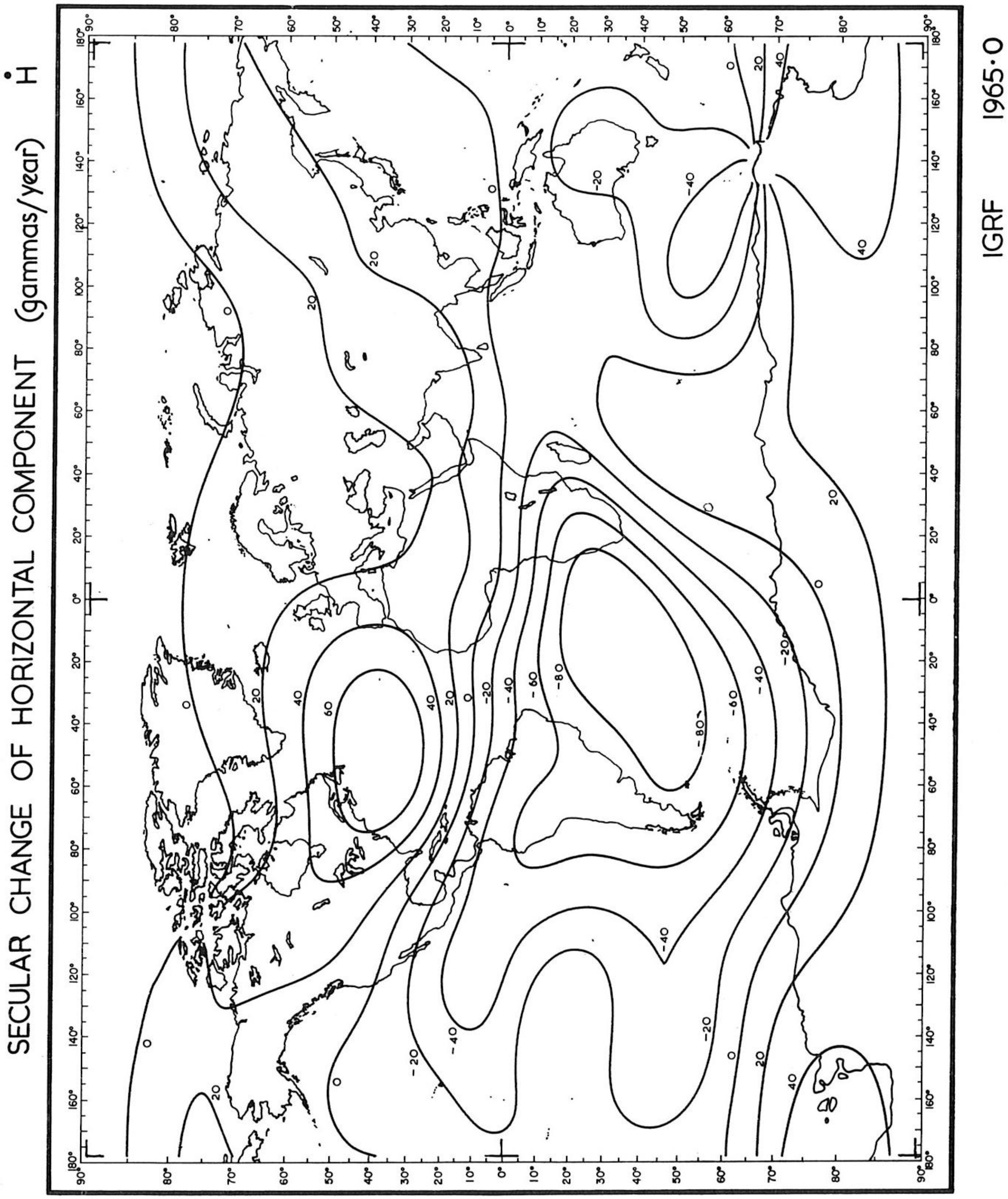

SECULAR CHANGE OF HORIZONTAL COMPONENT (gammas/year) Ḣ
IGRF 1965·0

Fig. 8

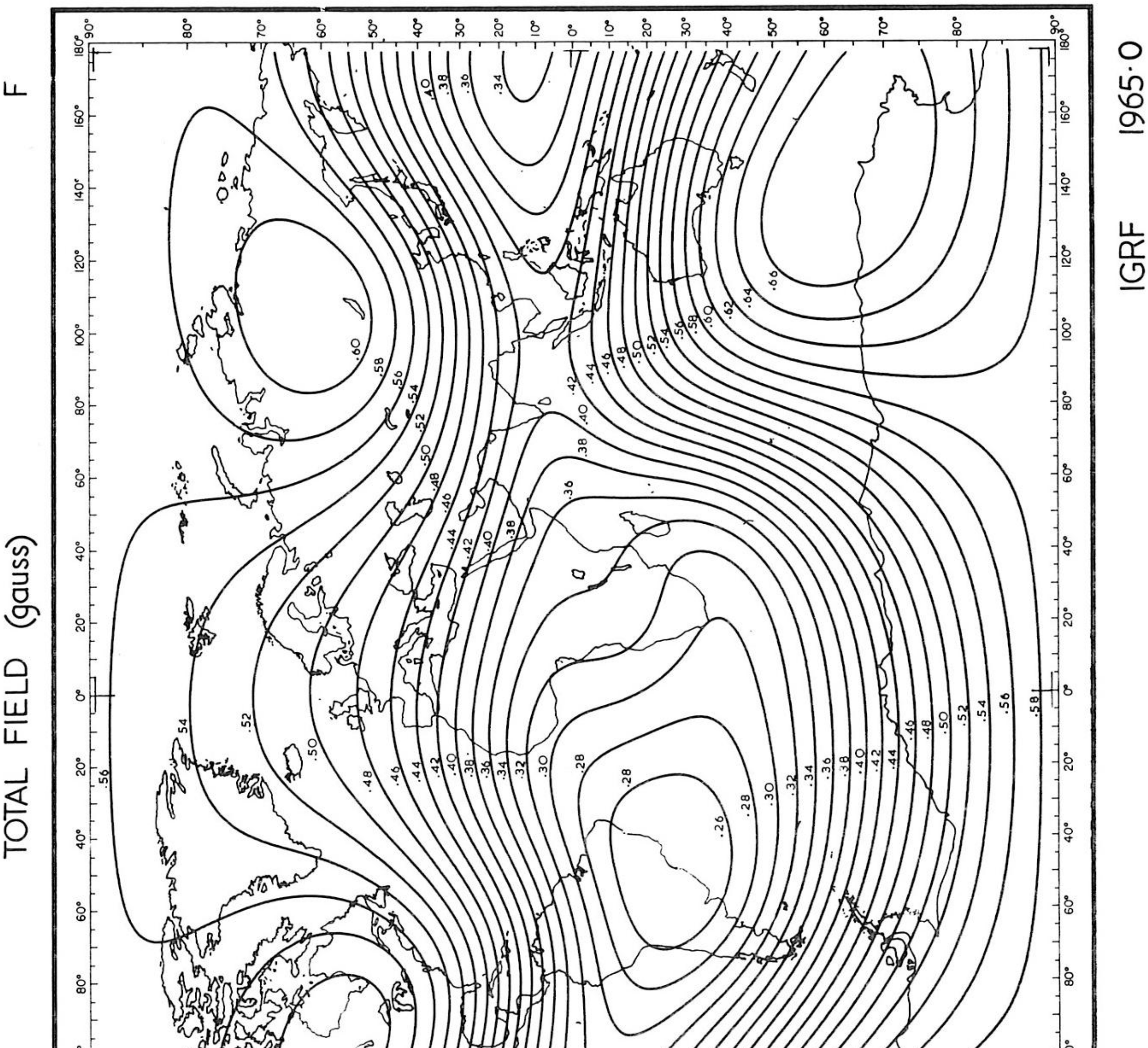


Fig. 9

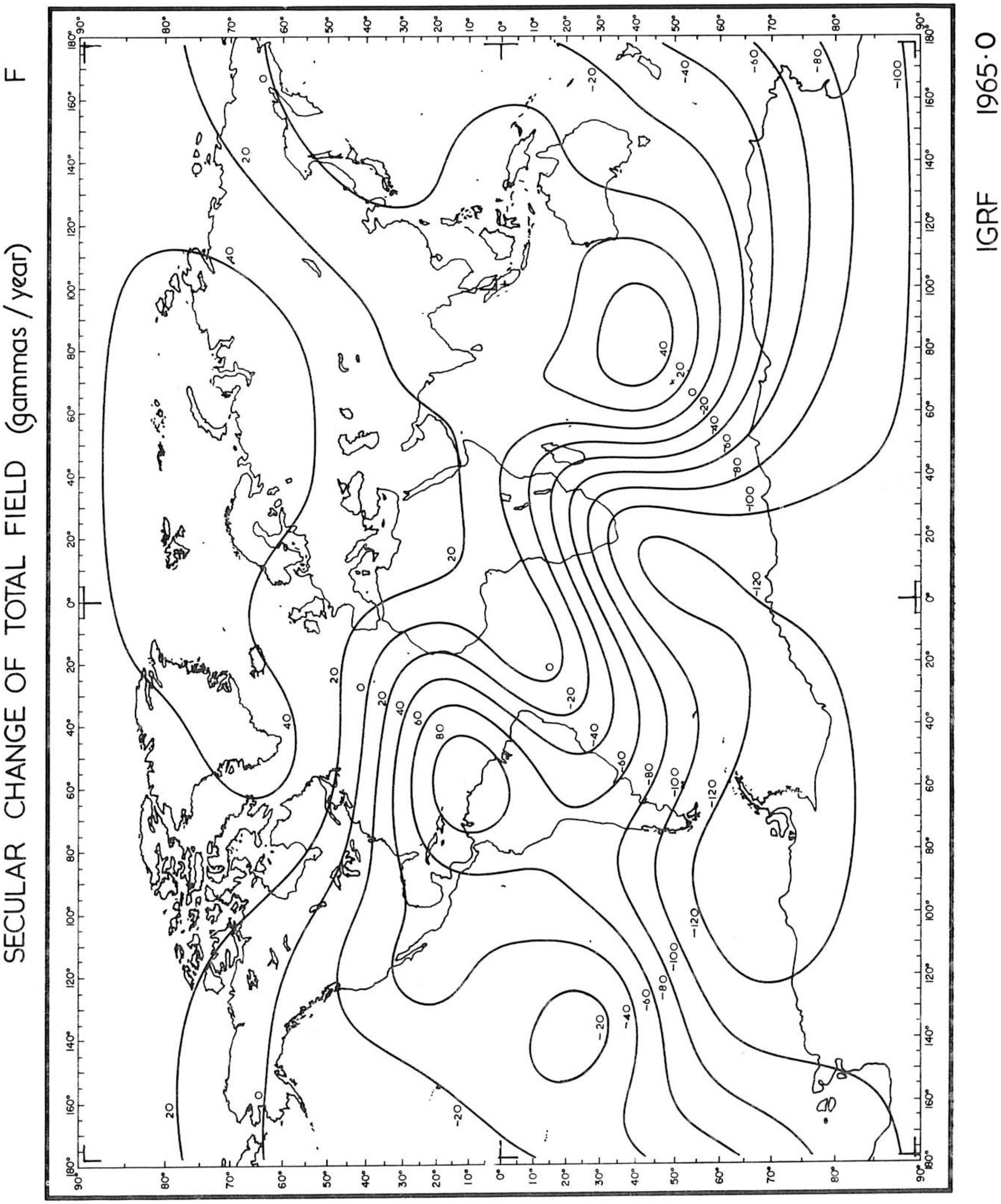


Fig. 10

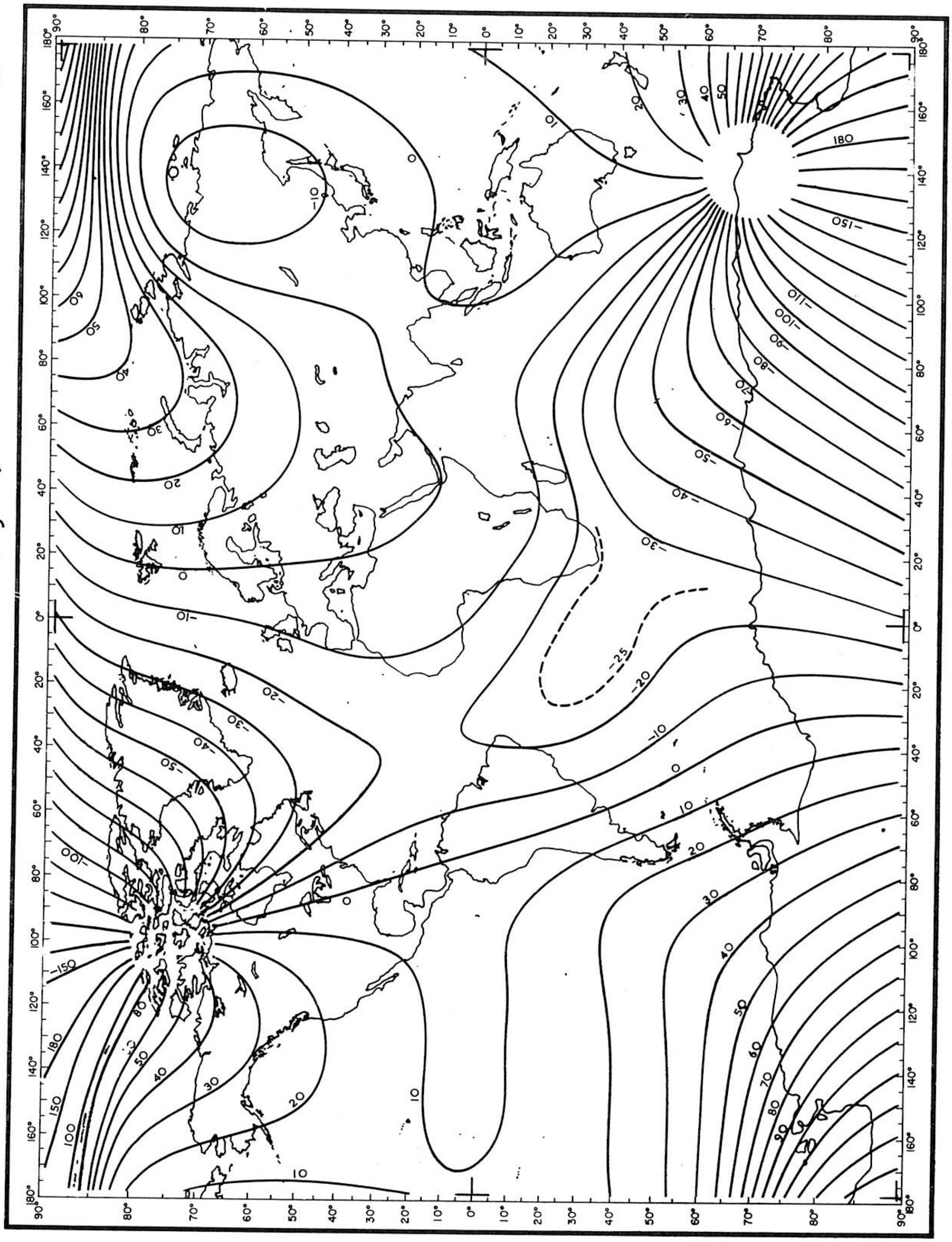
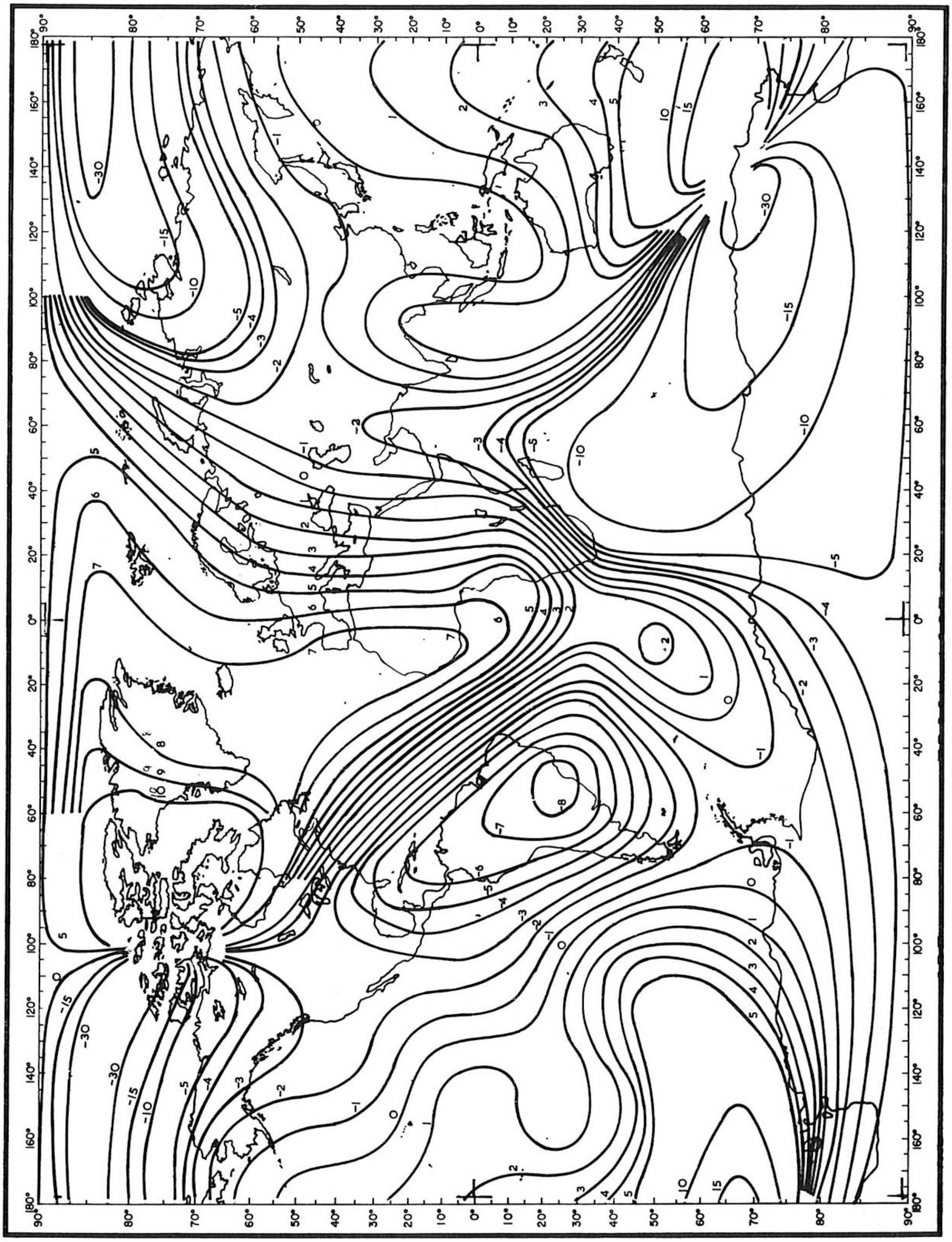


Fig. 11

SECULAR CHANGE OF DECLINATION (minutes/year) Ḋ



IGRF 1965·0

Fig. 12

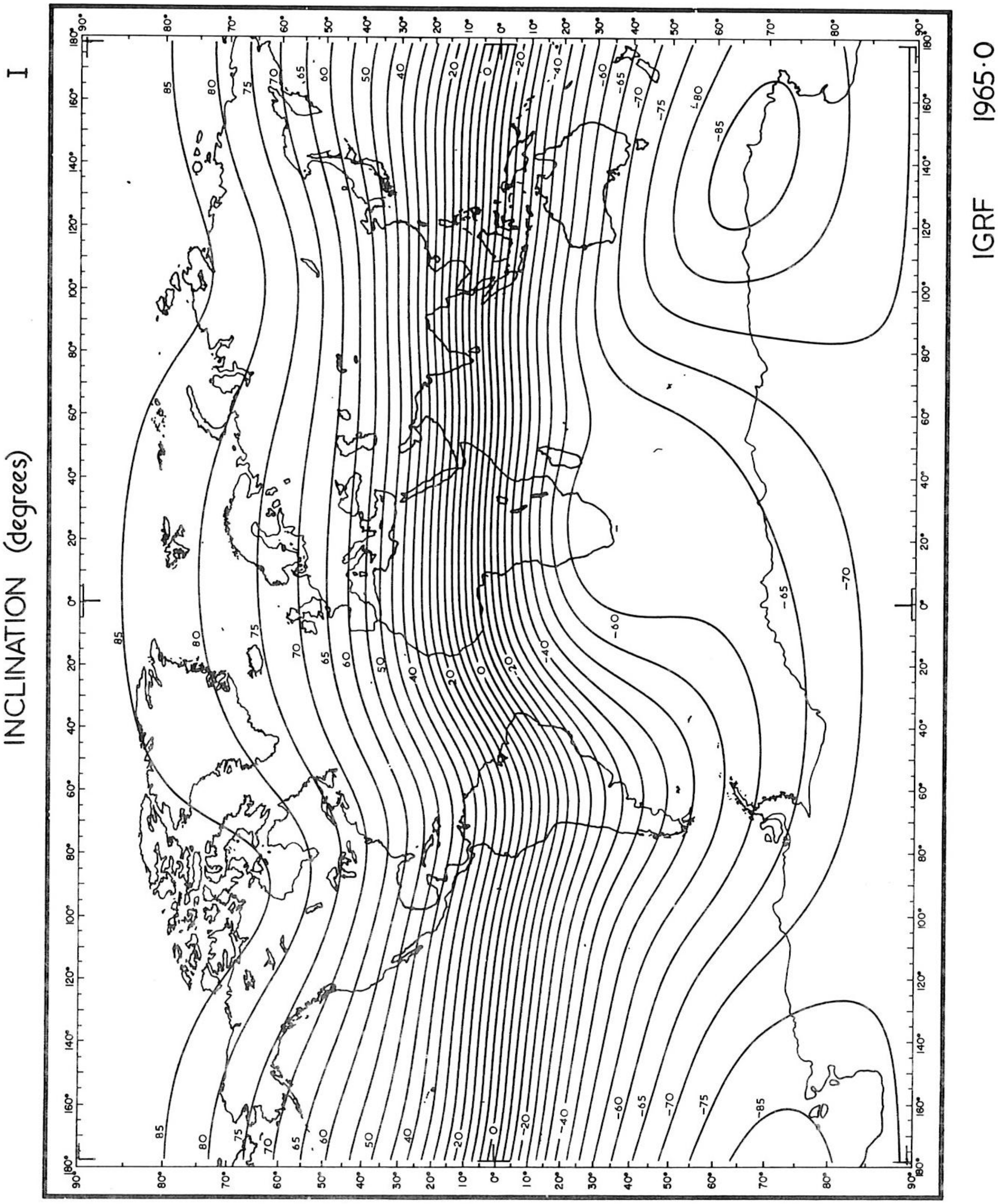


Fig. 13

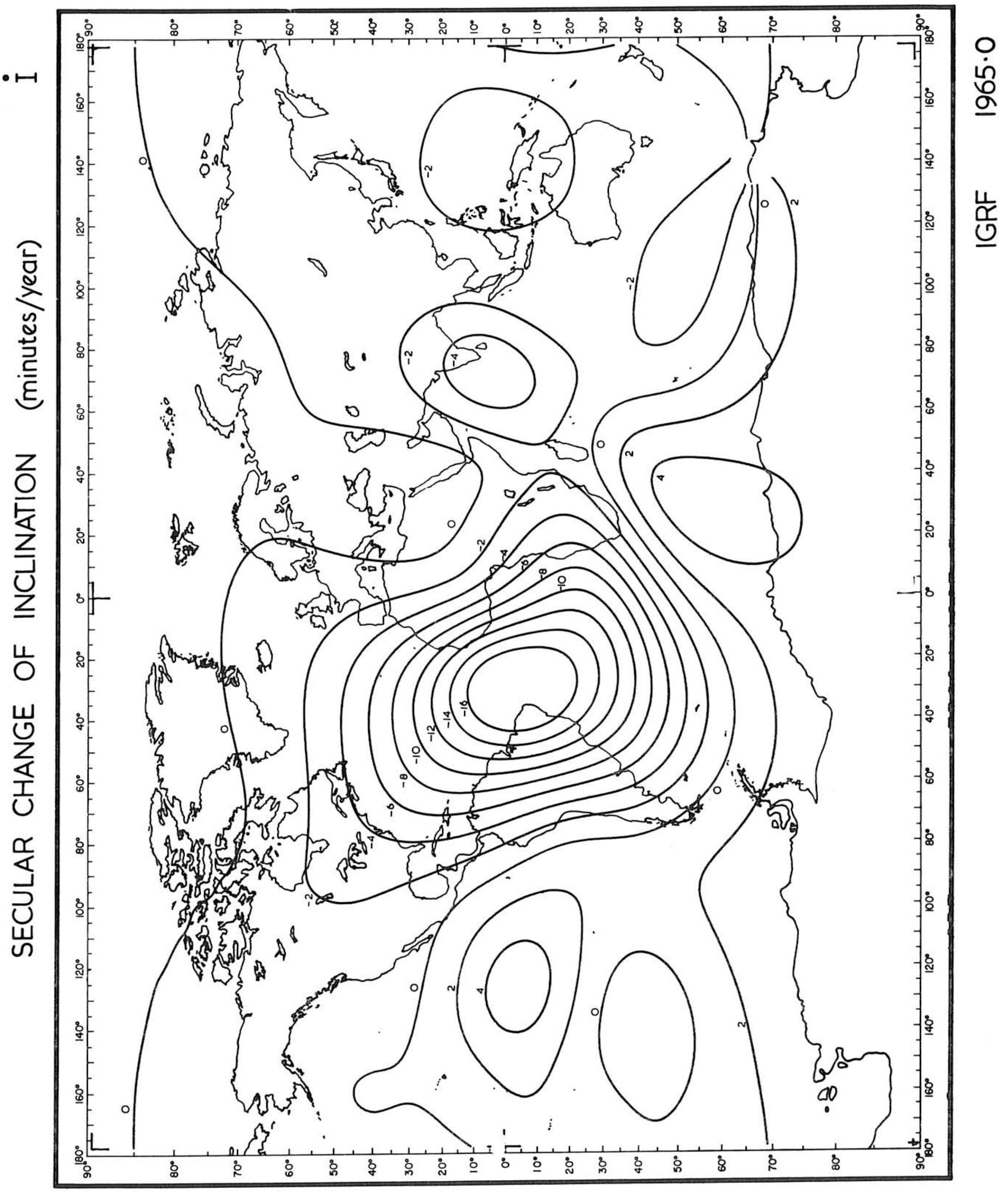


Fig. 14

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