Physics of the Earth and Planetary Interiors, 48 (1987) 279–292
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

International Geomagnetic Reference Field: the fourth generation

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(Received January 3, 1986; revision accepted October 8, 1986)

Barraclough, D.R., 1987. International Geomagnetic Reference Field: the fourth generation. Phys. Earth Planet. Inter., 48: 279–292.

In August 1985 the International Association of Geomagnetism and Aeronomy revised the International Geomagnetism Reference Field (IGRF). This is the third revision since the first IGRF was produced in 1968. The revised IGRF now consists of 10 spherical harmonic models of the main geomagnetic field and its secular variation and covers the interval 1945–1990. For the interval 1965–1980 the constituent models are definitive (DGRFs), in the sense that it is not intended to revise them in the future. A brief description of the derivation of the revised IGRF is given, together with a brief review of basic formulae and a set of world contour maps of the geomagnetic elements for 1985.

1. Introduction

In August 1985 the International Geomagnetic Reference Field (IGRF) was revised by Working Group I-1 (Analysis of the main geomagnetic field and secular variations) of the International Association of Geomagnetism and Aeronomy (IAGA). The revised version, the fourth generation of the IGRF, now provides a means of generating values of the geomagnetic elements for the interval 1945–1990.

The IGRF is a description of the main geomagnetic field and its secular variation in terms of 10 spherical harmonic models. Of these, nine describe the main field at epochs 5 years apart from 1945 to 1985 and the tenth describes the predicted secular variation of the field for the interval 1985–1990. The models for 1965, 1970, 1975 and 1980 are definitive models (DGRFs), in the sense that it is not planned to revise them in the future. The three earlier DGRFs are identical with the DGRFs for these epochs in the third generation IGRF (Peddie, 1982).

The main field is that part of the total geomagnetic field that originates within the Earth, but excluding the field due to magnetic material in the crust and also the field caused by internal electric currents induced by external magnetic fields. The IGRF is thus intended to describe that part of the geomagnetic field whose sources lie, according to present ideas, within the Earth's fluid core.

A comprehensive account of the history of the IGRF since its introduction in 1968 has been given by Peddie (1982), together with a discussion of how the first three generations are interrelated. We shall therefore concentrate here on the most recent revision. After a brief description of how the fourth generation IGRF was produced from the candidate models submitted, a brief review of the basic formulae will be given.

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0031-9201/87/$03.50

2. The third generation IGRF

The original plans for the production of the fourth generation IGRF, as formulated by Working Group I-1 in 1983, called for the adoption of definitive main-field models (DGRFs) for 1945, 1950, 1955, 1960 and 1980, a main-field model for 1985 and a secular-variation model for the interval 1985–1990 (the latter two constituting IGRF 1985). The maximum degree and order (n^*) of the spherical harmonic models was planned to be 10 for the main-field models and eight for the secular-variation model.

Five groups (the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN) in the U.S.S.R., the National Aeronautics and Space Administration (NASA), the U.S. Geological Survey (USGS) and the U.S. Naval Oceanographic Office (USNOO) in the U.S.A. and the British Geological Survey (BGS) in the U.K.) submitted a total of 23 candidate models. Table I summarizes these models. It will be seen that some of the earlier main-field models were truncated at $n^* = 8$, rather than 10 as specified. With the exception of the GSFCMF A series of models, which have already been described by Langel et al. (1986), and the GSFCMF80 model, which has been described by Langel and Estes (1985), details of all the candidate models are given in the five papers that immediately follow this introduction.

The next group of eight papers describe assessments of the accuracy of some or all of the candidate models. Other assessments have been made by An et al. (1985) and by Kuhn et al. (1985). In deciding on the revised IGRF, Working Group I-1 took account of the results of all these assessments.

The fourth generation IGRF does not exactly conform to the specification laid down in 1983. Firstly, it became clear that all the candidate main-field models for 1945, 1950, 1955 and 1960 were capable of significant improvement. The truncation level of $n^* = 8$ for several of them is a

TABLE I

The IGRF candidate models

Epoch	Model name [a]	n^*	Authors
1945	GSFCMF45A S45	8	Langel et al. (1986)
1945	GSFCMF45B SFA45	8	Langel and Estes (1987)
1945	GSFCMF45C SFAS45	10	Langel and Estes 1987)
1950	GSFCMF50A S50	8	Langel et al. (1986)
1950	GSFCMF50B SFA50	8	Langel and Estes (1987)
1950	GSFCMF50C SFAS50	10	Langel and Estes (1987)
1950	BGSMF50		10 Barraclough and Kerridge (1987)
1955	GSFCMF55A S55	8	Langel et al. (1986)
1955	GSFCMF55B SFA55	8	Langel and Estes (1987)
1955	GSFCMF55C SFAS55	10	Langel and Estes (1987)
1960	GSFCMF60A S60	8	Langel et al. (1986)
1960	GSFCMF60B SFA60	8	Langel and Estes (1987)
1960	GSFCMF60C SFAS60	10	Langel and Estes (1987)
1960	BGSMF60		10 Barraclough and Kerridge (1987)
1980	GSFCMF80 GSFC(12/83)	10	Langel and Estes (1985)
1980	USNOOMF80		10 Quinn et al. (1987)
1980–1985	BGSSV82		8 Quinn et al. (1987)
1980–1985	IZMSV82		8 Golovkov and Kolomiitseva (1987)
1985	USGSMF85 MF-85	10	Peddie and Zunde (1987)
1985	USUKMF85		10 Quinn et al. (1987)
1980–1990	USGSSV87 SV-85	8	Peddie and Zunde (1987)
1985–1990	BGSSV87		8 Barraclough and Kerridge (1987)
1985–1990	IZMSV87		8 Golovkov and Kolomiitseva (1987)

[a] Where two model names are given, the second is that originally given by the authors.

TABLE II

Coefficient values for the 10 spherical harmonic models that make up the fourth generation IGRF. Units are nT for the nine main-field models and nT a^{-1} for the predictive secular-variation model for the interval 1985–1990 (SV). Note that the main-field models for 1965, 1970, 1975 and 1980 are definitive models (DGRFs)

	m	n	1945	1950	1955	1960	1965	1970	1975	1980	1985	SV
g	0	1	−30634	−30571	−30507	−30411	−30334	−30220	−30100	−29992	−29877	23.2
g	1	1	−2240	−2241	−2134	−2162	−2119	−2068	−2013	−1956	−1903	10.0
h	1	1	5806	5807	5796	5780	5776	5737	5675	5604	5497	−24.5
g	0	2	−1215	−1330	−1432	−1546	−1662	−1781	−1902	−1997	−2073	−13.7
g	1	2	2972	2978	2995	3007	2997	3000	3010	3027	3045	3.4
h	1	2	−1700	−1813	−1896	−1948	−2016	−2047	−2067	−2129	−2191	−11.5
g	2	2	1588	1579	1567	1572	1594	1611	1632	1663	1691	7.0
h	2	2	497	388	263	209	114	25	−68	−200	−309	−20.2
g	0	3	1274	1293	1308	1307	1297	1287	1276	1281	1300	5.1
g	1	3	−1833	−1878	−1955	−1987	−2038	−2091	−2144	−2180	−2208	−4.6
h	1	3	−512	−485	−487	−421	−404	−366	−333	−336	−312	5.3
g	2	3	1225	1271	1293	1288	1292	1278	1260	1251	1244	−0.6
h	2	3	185	228	235	230	240	251	262	271	284	2.3
g	3	3	926	890	897	879	856	838	830	833	835	0.1
h	3	3	−5	−67	−73	−130	−165	−196	−223	−252	−296	−10.8
g	0	4	980	975	964	962	957	952	946	938	937	0.1
g	1	4	771	795	794	804	804	800	791	782	780	−0.6
h	1	4	155	171	167	150	148	167	191	212	233	3.8
g	2	4	544	532	510	492	479	461	438	398	363	−7.8
h	2	4	−280	−306	−275	−272	−269	−266	−265	−257	−250	2.2
g	3	4	−408	−402	−392	−392	−390	−395	−405	−419	−426	−1.4
h	3	4	−68	−51	−44	1	13	26	39	53	68	2.5
g	4	4	300	310	292	267	252	234	216	199	169	−6.8
h	4	4	−158	−184	−249	−254	−269	−279	−288	−297	−298	0.9
g	0	5	−286	−255	−232	−236	−219	−216	−218	−218	−215	1.3
g	1	5	341	355	360	358	358	359	356	357	356	0.1
h	1	5	−14	−8	14	12	19	26	31	46	47	0.1
g	2	5	207	201	237	229	254	262	264	261	253	−1.5
h	2	5	80	101	111	121	128	139	148	150	148	−0.2
g	3	5	−25	−3	−13	−34	−31	−42	−59	−74	−94	−3.2
h	3	5	−65	−95	−90	−115	−126	−139	−152	−151	−155	−0.1
g	4	5	−156	−160	−176	−153	−157	−160	−159	−162	−161	0.1
h	4	5	−114	−100	−111	−106	−97	−91	−83	−78	−75	0.6
g	5	5	−88	−76	−68	−64	−62	−56	−49	−48	−48	−0.1
h	5	5	83	73	77	83	81	83	88	92	95	0.0
g	0	6	68	57	47	47	45	43	45	48	52	1.4
g	1	6	67	50	57	56	61	64	66	66	65	−0.3
h	1	6	9	−1	−7	−13	−11	−12	−13	−15	−16	−0.4
g	2	6	6	15	4	−3	8	15	28	42	50	1.7
h	2	6	118	100	101	106	100	100	99	93	90	−1.1
g	3	6	−244	−261	−250	−241	−228	−212	−198	−192	−186	0.6

TABLE II (continued)

	m	*n*	1945	1950	1955	1960	1965	1970	1975	1980	1985	SV
h	3	6	18	52	46	55	68	72	75	71	69	−0.8
g	4	6	−12	8	12	3	4	2	1	4	4	0.0
h	4	6	−9	−7	−16	−26	−32	−37	−41	−43	−50	−2.3
g	5	6	14	8	13	4	1	3	6	14	17	0.9
h	5	6	−12	−17	−6	−10	−8	−6	−4	−2	−4	−0.5
g	6	6	−100	−108	−105	−108	−111	−112	−111	−108	−102	1.2
h	6	6	−42	−21	−21	−16	−7	1	11	17	20	−0.1
g	0	7	72	67	80	72	75	72	71	72	75	0.2
g	1	7	−61	−48	−66	−52	−57	−57	−56	−59	−61	−0.6
h	1	7	−42	−44	−52	−53	−61	−70	−77	−82	−82	0.2
g	2	7	6	−3	2	4	4	1	1	2	2	−0.5
h	2	7	−39	−18	−37	−25	−27	−27	−26	−27	−26	1.0
g	3	7	6	16	4	11	13	14	16	21	24	0.8
h	3	7	2	−6	6	−8	−2	−4	−5	−5	−1	1.1
g	4	7	−44	−38	−46	−20	−26	−22	−14	−12	−6	1.0
h	4	7	−1	−8	−1	3	6	8	10	16	23	1.9
g	5	7	−2	1	−15	−4	−6	−2	0	1	4	0.4
h	5	7	25	32	29	28	26	23	22	18	17	0.3
g	6	7	18	9	8	15	13	13	12	11	9	−0.5
h	6	7	−19	−18	−20	−16	−23	−23	−23	−23	−21	0.2
g	7	7	27	11	14	6	1	−2	−5	−2	0	−0.1
h	7	7	−23	−22	−12	−18	−12	−11	−12	−10	−6	0.9
g	0	8	15	16	5	6	13	14	14	18	21	0.7
g	1	8	5	4	17	4	5	6	6	6	6	0.0
h	1	8	−7	2	12	7	7	7	6	7	7	0.1
g	2	8	−12	−8	−3	−3	−4	−2	−1	0	0	0.3
h	2	8	9	−2	1	−16	−12	−15	−16	−18	−21	−1.0
g	3	8	−21	−31	−30	−13	−14	−13	−12	−11	−11	0.4
h	3	8	0	−3	10	5	9	6	4	4	5	0.1
g	4	8	18	15	14	−5	0	−3	−8	−7	−9	−0.3
h	4	8	−13	−7	−20	−19	−16	−17	−19	−22	−25	−0.8
g	5	8	16	8	27	10	8	5	4	4	2	−0.3
h	5	8	5	6	5	5	4	6	6	9	11	0.2
g	6	8	−14	−17	−15	−6	−1	0	0	3	4	0.1
h	6	8	26	27	34	23	24	21	18	16	12	−0.8
g	7	8	1	7	1	15	11	11	10	6	4	−0.5
h	7	8	1	−6	4	−2	−3	−6	−10	−13	−16	−0.1
g	8	8	10	13	12	5	4	3	1	−1	−6	−0.8
h	8	8	−19	−22	−19	−18	−17	−16	−17	−15	−10	1.3
g	0	9				13	8	8	7	5	5	
g	1	9				5	10	10	10	10	10	
h	1	9				−22	−22	−21	−21	−21	−21	
g	2	9				4	2	2	2	1	1	

h	2	9	14	15	16	16	16	16
g	3	9	−12	−13	−12	−12	−12	−12
h	3	9	5	7	6	7	9	9
g	4	9	14	10	10	10	9	9
h	4	9	−5	−4	−4	−4	−5	−5
g	5	9	5	−1	−1	−1	−3	−3
h	5	9	0	−5	−5	−5	−6	−6
g	6	9	−2	−1	0	−1	−1	−1
h	6	9	11	10	10	10	9	9
g	7	9	0	5	3	4	7	7
h	7	9	10	10	11	11	10	10
g	8	9	0	1	1	1	2	2
h	8	9	2	−4	−2	−3	−6	−6
g	9	9	−1	−2	−1	−2	−5	−5
h	9	9	−2	1	1	1	2	2
g	0	10	−5	−2	−3	−3	−4	−4
g	1	10	−2	−3	−3	−3	−4	−4
h	1	10	3	2	1	1	1	1
g	2	10	0	2	2	2	2	2
h	2	10	0	1	1	1	0	0
g	3	10	−5	−5	−5	−5	−5	−5
h	3	10	4	2	3	3	3	3
g	4	10	−2	−2	−1	−2	−2	−2
h	4	10	3	6	4	4	6	6
g	5	10	8	4	6	5	5	5
h	5	10	−4	−4	−4	−4	−4	−4
g	6	10	3	4	4	4	3	3
h	6	10	−2	0	0	−1	0	0
g	7	10	0	0	1	1	1	1
h	7	10	−3	−2	−1	−1	−1	−1
g	8	10	1	2	0	0	2	2
h	8	10	5	3	3	3	4	4
g	9	10	0	2	3	3	3	3
h	9	10	3	0	1	1	0	0
g	10	10	−1	0	−1	−1	0	0
h	10	10	−3	−6	−4	−5	−6	−6

reflection of this. It was therefore decided not to designate the constituent IGRF models for these epochs as DGRFs. It is hoped to adopt DGRFs for these four epochs at the next IAGA meeting in 1987.

Secondly, the derivation of the main-field model for 1985 differed slightly from that planned. The procedure used was as follows. Having decided on the DGRF for 1980, we selected the best secular-variation model for the interval 1980–1985. The IGRF 1985 was then produced by adding 5 years of this secular variation to the DGRF 1980 coefficients.

The results of the revision process that produced the fourth generation IGRF are as follows. The main-field models for 1945, 1950 and 1955 are the three GSFCMF B series models for these three epochs. It should be noted that these three (non-definitive) IGRFs extend only to $n^* = 8$. The main-field model for 1960 is the BGSMF60 model ($n^* = 10$). The DGRF 1980 model is the GSFCMF80 (also known as GSFC (12/83)) model, truncated at $n^* = 10$. The main-field model for 1985 was produced, as described above, from the DGRF 1980 and a secular-variation model for the interval 1980–1985. The secular-variation model used is a mean of the BGSSV82, IZMSV82 and USGSSV87 models. Although this secular-variation model extends only to $n^* = 8$, the main-field model extends to $n^* = 10$. The degree 9 and 10 coefficients are thus identical to those of the DGRF 1980. The predictive secular-variation model for the interval 1985–1990 is a mean of the BGSSV87, IZMSV87 and USGSSV87 models. It is truncated at $n^* = 8$.

The spherical harmonic coefficients of the 10 models that constitute the fourth generation IGRF are given in Table II. They are in the Schmidt quasi-normalized form (Chapman and Bartels, 1940) and refer to a sphere of radius 6371.2 km.

3. Review of basic formulae

It is assumed that the main geomagnetic field can be expressed as the gradient of a scalar potential (V) which is the solution of Laplace's equation

$$\nabla^2 V = 0 \tag{1}$$

In spherical polar coordinates, the solution of eq. 1 may be written as a series expansion in spherical harmonics

$$V = \bar{a} \sum_{n=1}^{N} \sum_{m=0}^{n} (a/r)^{n+1} \times (g_n^m \cos m\lambda + h_n^m \sin m\lambda) P_n^m(\cos\theta) \tag{2}$$

where $\bar{a}$ denotes the mean radius of the Earth (6371.2 km), r the distance from the centre of the Earth, θ the geocentric colatitude, λ the longitude, P_n^m the associated Legendre polynomial (Schmidt quasi-normalized) of degree n and order m and g_n^m and h_n^m denote the spherical harmonic coefficients (in nT) that constitute the models that make up the IGRF.

The geocentric components of the main geomagnetic field are derived by partial differentiation of eq. 2

$$X' = (1/r)(\partial V/\partial\theta) \tag{3a}$$

$$Y' = (-1/r \sin\theta)(\partial V/\partial\lambda) \tag{3b}$$

$$Z' = \partial V/\partial r \tag{3c}$$

where X', Y' and Z' denote the northward, eastward and radially inward components, respectively, of the field. (In the case of the secular variation V, X', Y', Z' and the coefficients g_n^m and h_n^m are to be regarded as representing the time rates of change of the quantities referred to above.)

It is often necessary to work in geodetic rather than geocentric coordinates and to use field components (X, Y, Z) referring to this coordinate system. The usual procedure is, firstly, to convert the geodetic coordinates θ' (colatitude), λ (longitude) and h (orthometric height above mean sea-level) to geocentric coordinates. The geocentric field components (X', Y', Z') are computed from eqs. 3 and 4 and are then converted back to geodetic field components (X, Y, Z). In these conversions the Earth is assumed to be an oblate spheroid. For the purposes of the IGRF, the International Astronomical Union (1966) ellipsoid is recommended. It has an equatorial radius (a) of 6378.16 km and a reciprocal flattening ($1/f$) of 298.25.

IGRF 1985

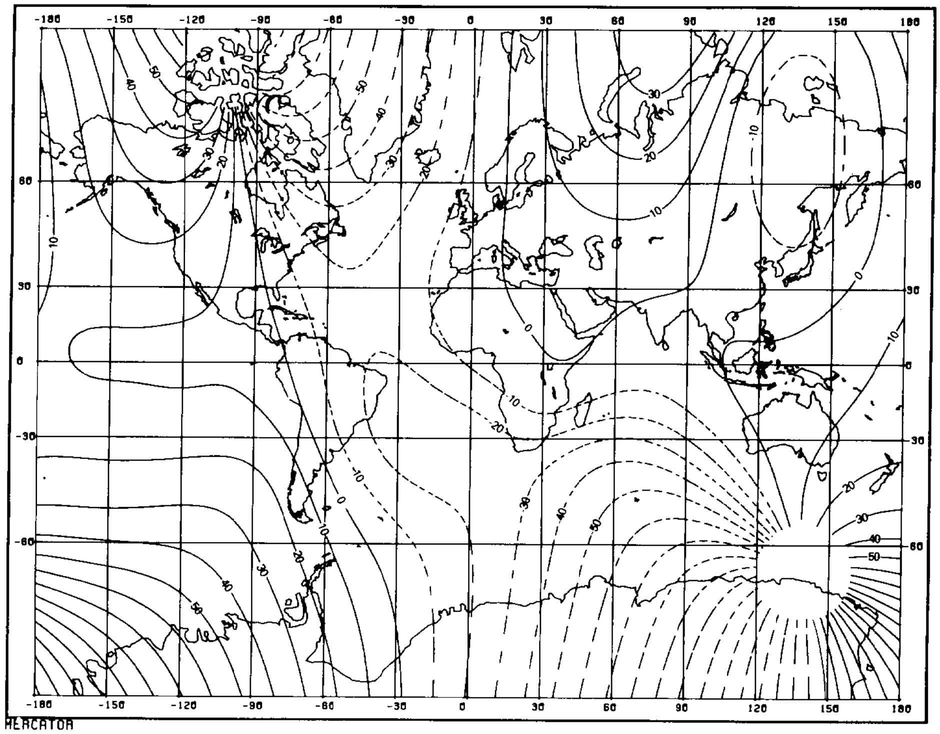

Fig. 1. Declination (D) in degrees.

IGRF 1985

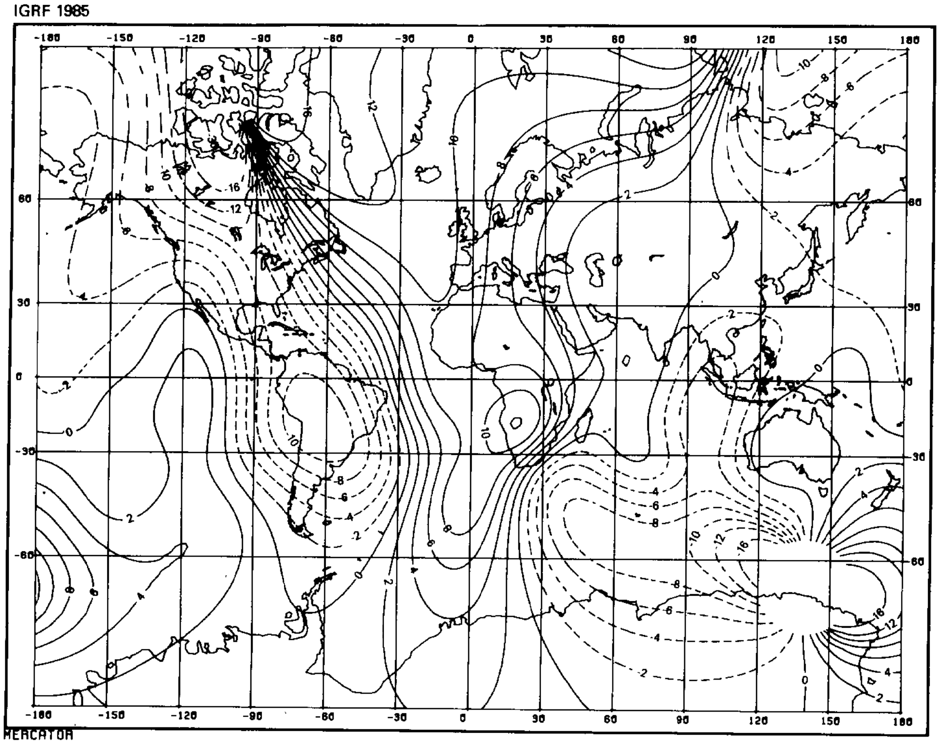

Fig. 2. Annual change of declination ($\dot{D}$) in min a^{-1}.

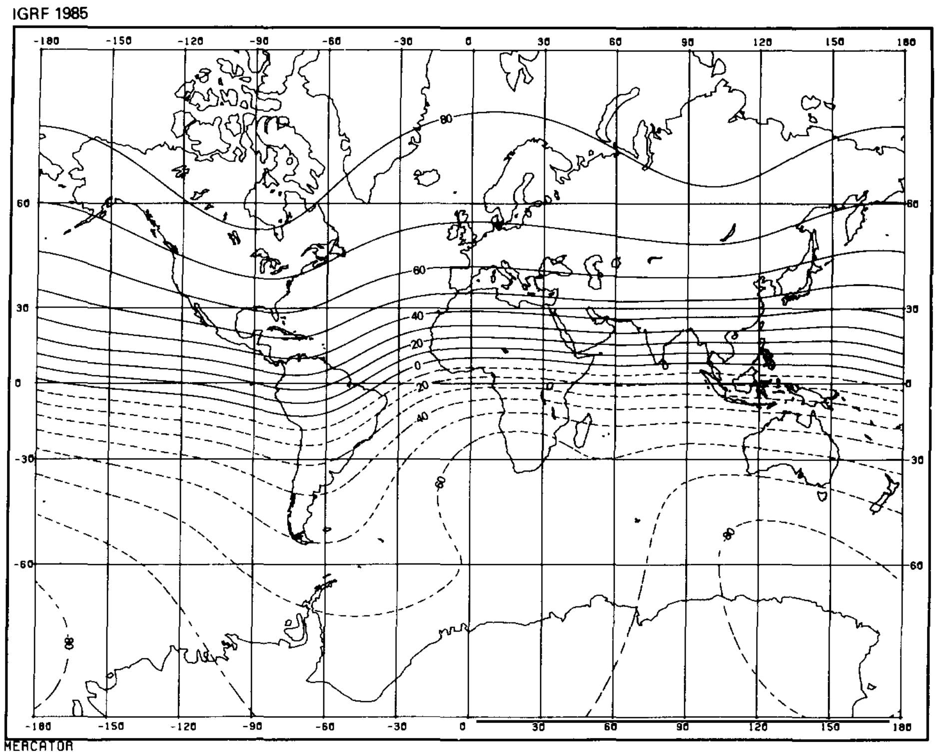

Fig. 3. Inclination (I) in degrees.

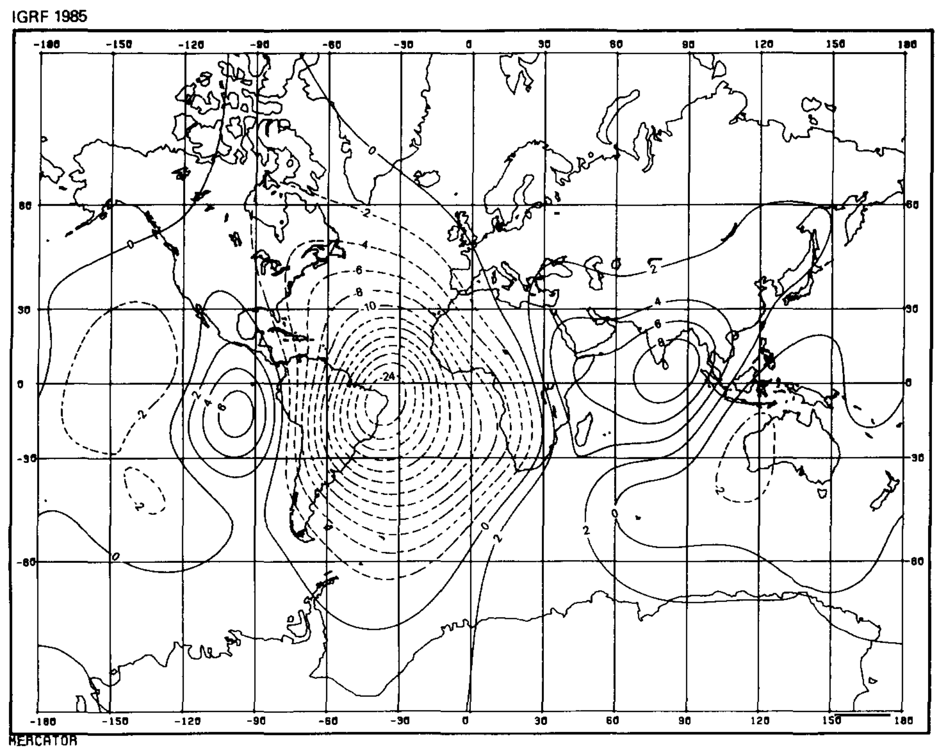

Fig. 4. Annual change of inclination ($\dot{I}$) in min a^{-1}.

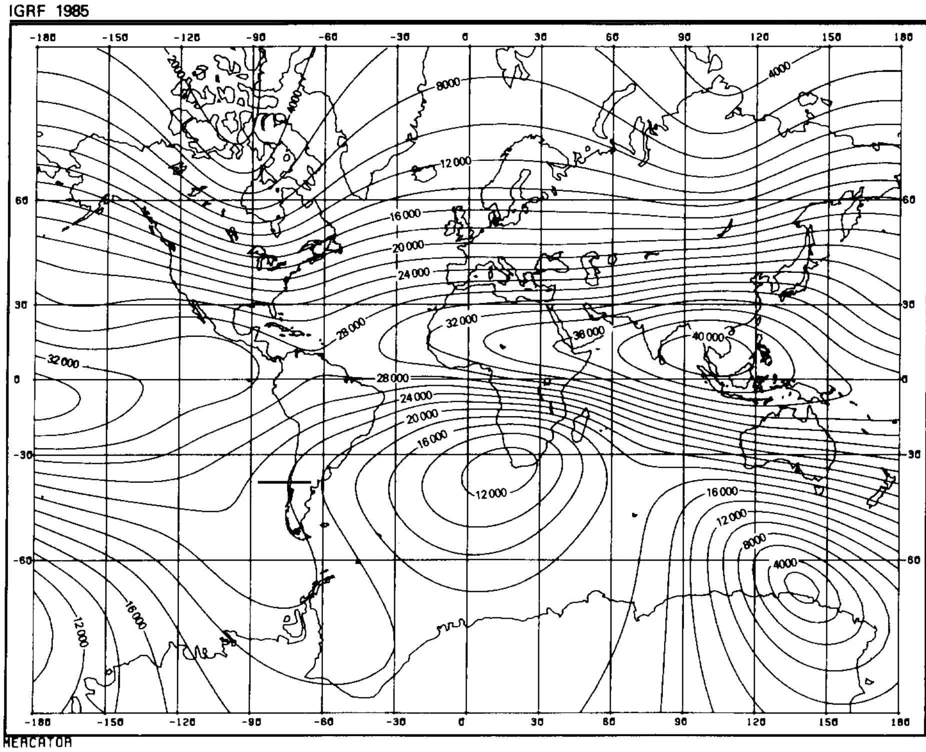

Fig. 5. Horizontal intensity (H) in nT.

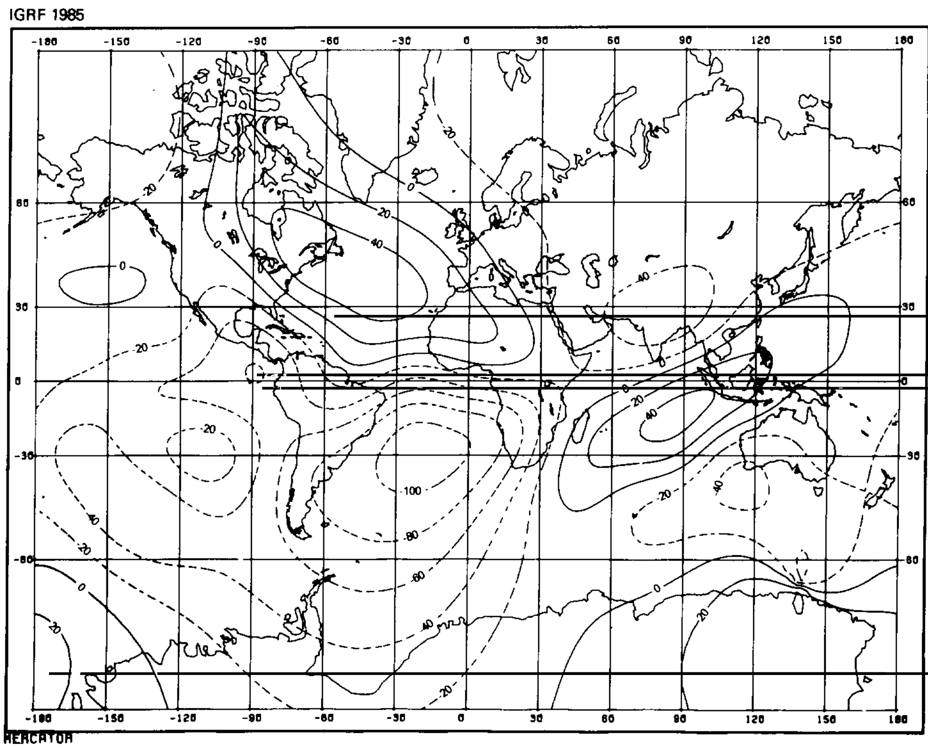

Fig. 6. Annual change of horizontal intensity ($\dot{H}$) in nT a^{-1}.

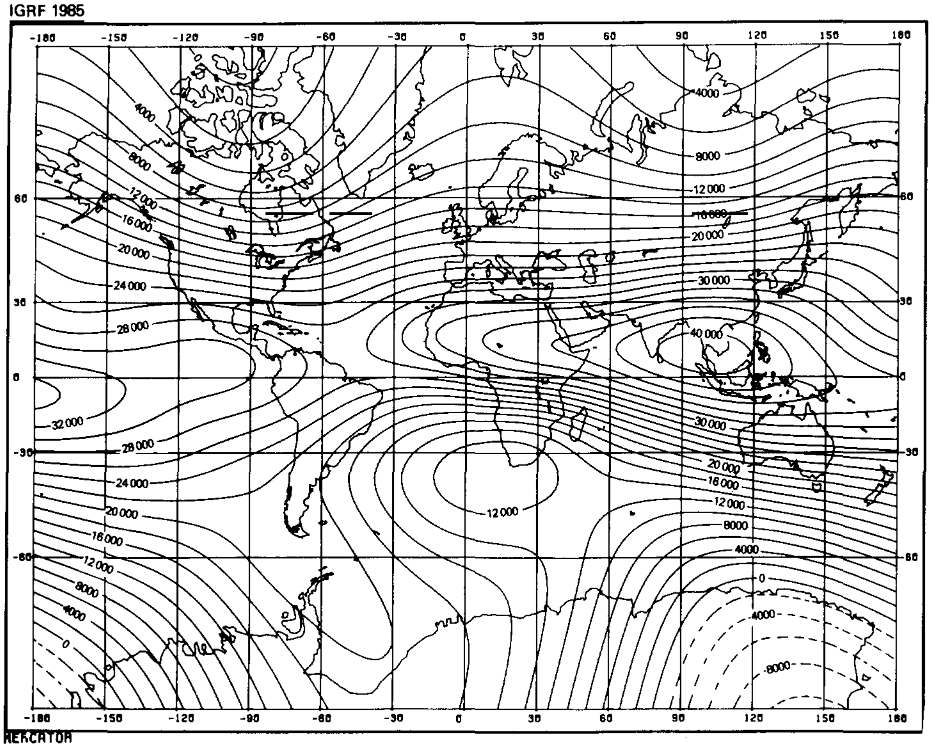

Fig. 7. North component (X) in nT.

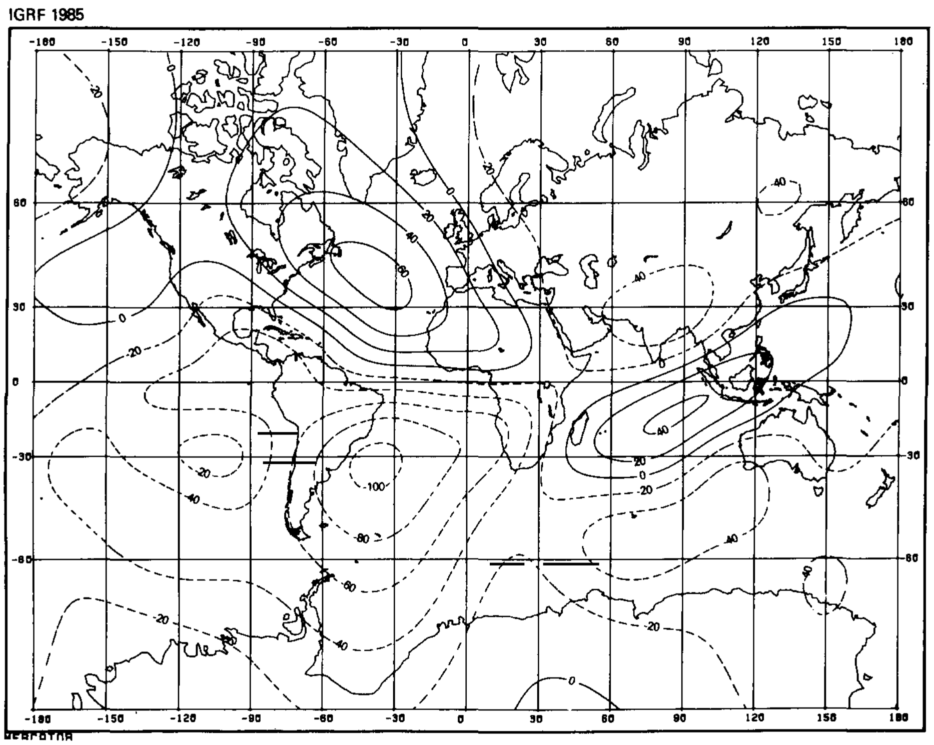

Fig. 8. Annual change of north component ($\dot{X}$) in nT a^{-1}.

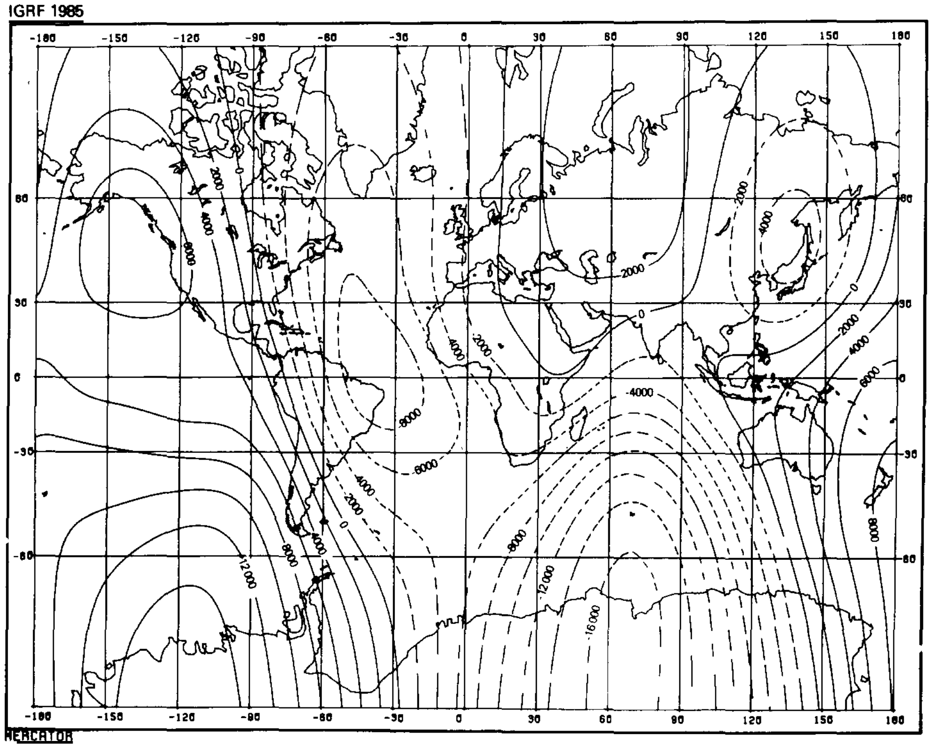

Fig. 9. East component (Y) in nT.

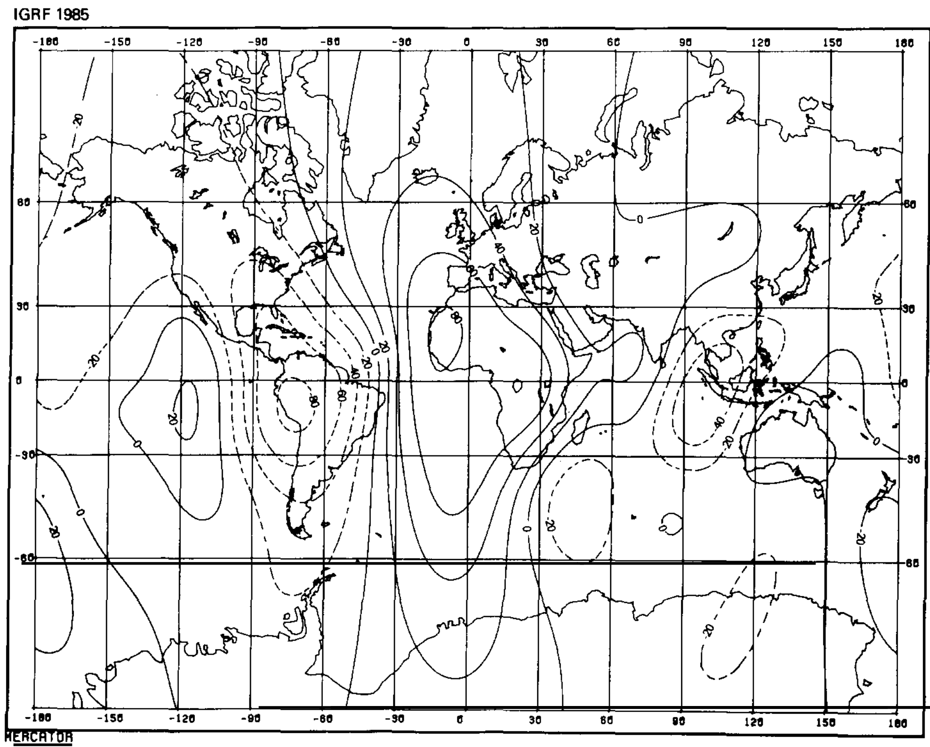

Fig. 10. Annual change of east component ($\dot{Y}$) in nT a^{-1}.

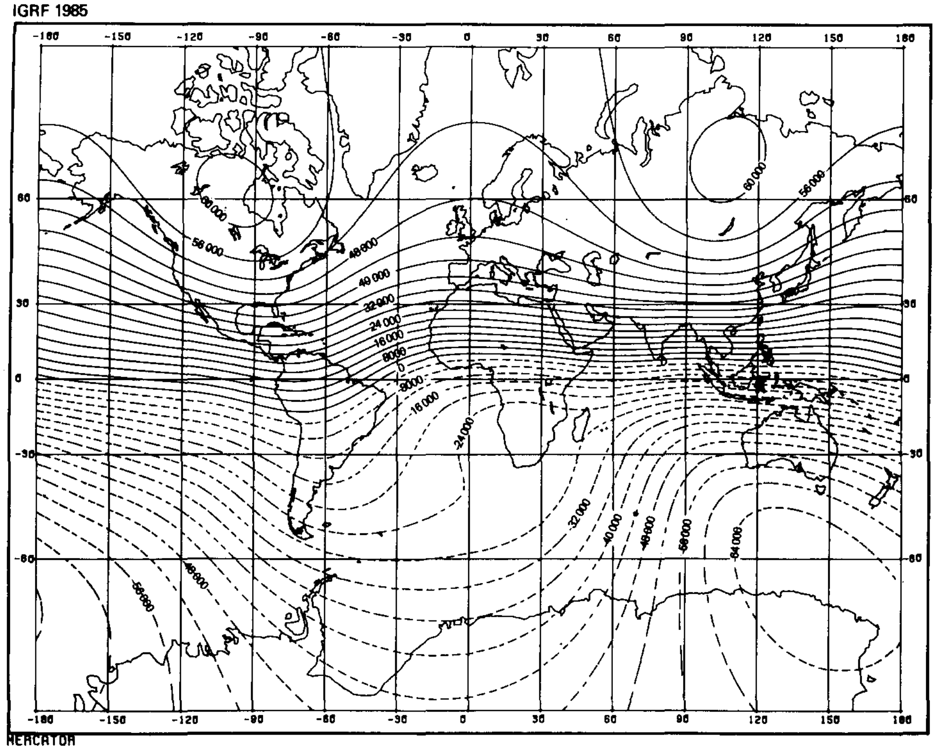

Fig. 11. Vertical component (Z) in nT.

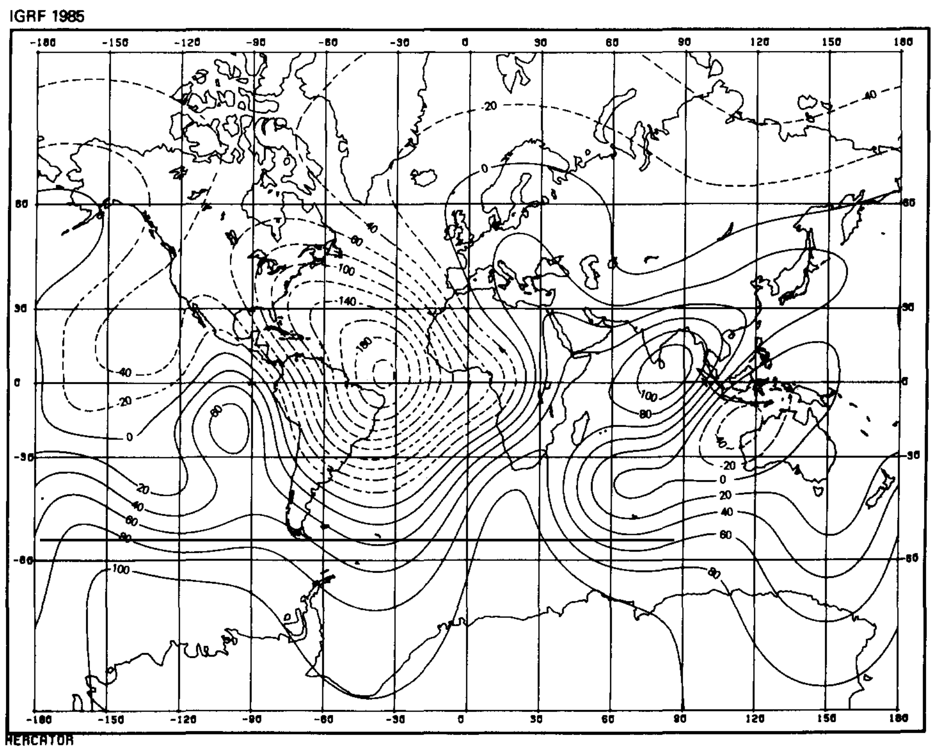

Fig. 12. Annual change of vertical component ($\dot{Z}$) in nT a^{-1}.

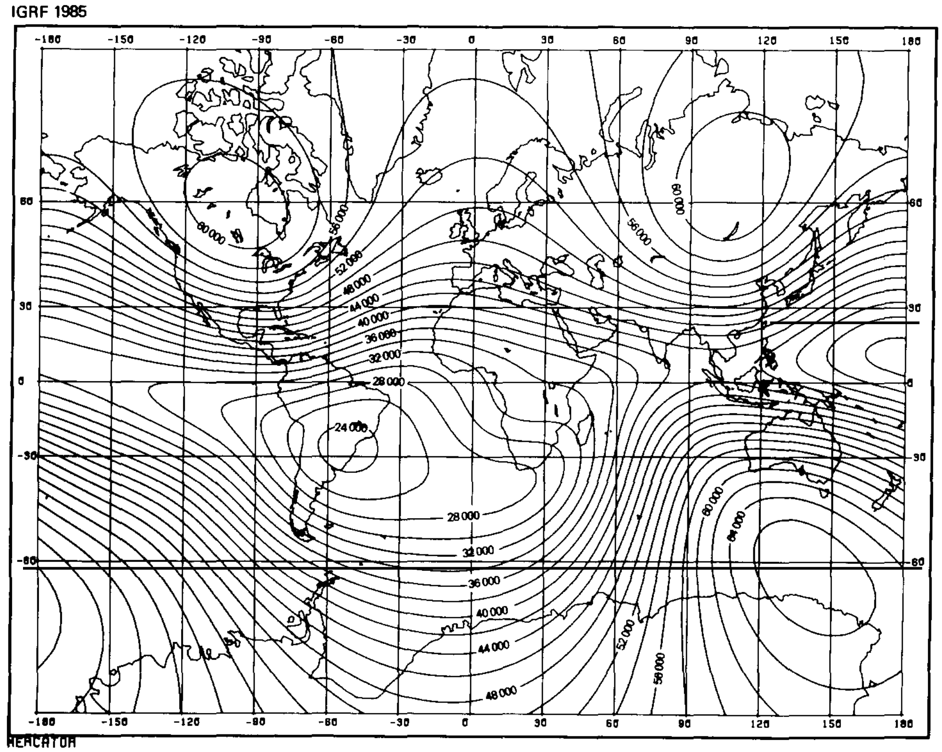

Fig. 13. Total intensity (F) in nT.

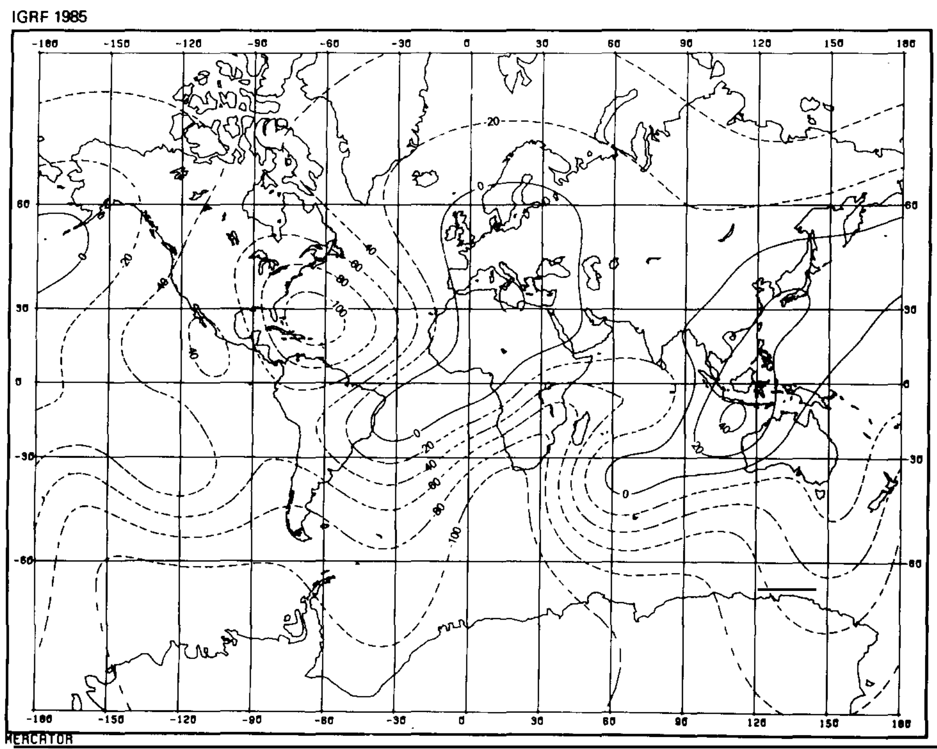

Fig. 14. Annual change of total intensity ($\dot{F}$) in nT a^{-1}.

The equations for the conversion from geodetic to geocentric coordinates are

$$r = \left[h(h+2\rho)(a^4 \sin^2\theta' + b^4 \cos^2\theta')/\rho^2\right]^{1/2}$$

$$\cos\theta = \cos\theta' \cdot \cos\delta - \sin\theta' \cdot \sin$$

$$\sin\theta = \sin\theta' \cdot \cos\delta + \cos\theta' \cdot \sin\delta$$

where

$$\rho = (a^2 \sin^2\theta' + b^2 \cos^2\theta')^{1/2}$$

$$\cos\delta = (h+\rho)/r$$

$$\sin\delta = (a^2 - b^2) \cdot \cos\theta' \cdot \sin\theta'/\rho r$$

Here b denotes the polar radius of the ellipsoid ($= a[1-f]$), and $\delta = \theta - \theta'$.

The other geomagnetic elements (declination (D), inclination (I), horizontal intensity (H) and total intensity (F)) can be computed using the following relations

$$D = \arctan(Y/X) \tag{4a}$$

$$I = \arctan(Z/H) \tag{4b}$$

$$H = (X^2 + Y^2)^{1/2} \tag{4c}$$

$$F = (X^2 + Y^2 + Z^2)^{1/2} \tag{4d}$$

When computing values of the geomagnetic elements for dates between 1945 and 1985 that do not coincide with the epochs of the main-field models, linear interpolation between the two main-field models for the epochs immediately before and immediately after the desired date is to be used. For dates between 1985 and 1990, the main-field model for 1985 and the predictive secular-variation model for the interval 1985–1990 are to be used. When calculating the elements that are not linear functions of the spherical harmonic coefficients (D, I, H, F), the components X, Y, Z must first be calculated using linear interpolation. The non-linear elements are then computed from these values using eqs. (4a–d).

Global contour maps of the values at sea-level and at 1985.0 for the geomagnetic elements D, I, H, X, Y, Z and F are shown in Figs. 1–14. They are based on IGRF 1985 and are taken from Barraclough and Kerridge (1986), who also include tables of grid-point values.

The IGRF coefficients in computer-readable form and computer programs for calculating field-component values are available from the following Data Centres:

World Data Center A for Rockets and Satellites, Code 601, NASA/Goddard Space Flight Center, Greenbelt, MA 20771, U.S.A.

World Data Center A, National Oceanic and Atmospheric Administration, NESDIS/NGDC (E/GC11), 325 Broadway, Boulder, CO 80303, U.S.A.

World Digital Data Centre C1, British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, U.K.

Acknowledgement

This paper is published with the approval of the Director, British Geological Survey (NERC).

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