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International Geomagnetic Reference Field: The Sixth Generation

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In August 1991 the International Association of Geomagnetism and Aeronomy revised the International Geomagnetic Reference Field (IGRF) for the fifth time. This Sixth Generation IGRF now consists of 10 spherical harmonic models of the main geomagnetic field at five year intervals from 1945 through 1990 and a secular variation model extending the main field model of 1990 through 1995. For the interval 1945–1985 the models are definitive (DGRFs), in that it is unlikely that the underlying data sets will be significantly improved so there is no plan for future revision of the models. The present revision consists of adoption of a definitive main field model for 1985, DGRF 1985, a main field model for 1990 with secular variation coefficients for 1990–1995, IGRF 1990, and a provisional model, PGRF 1985, for 1985–1990 defined as the linear interpolation between DGRF 1985 and IGRF 1990. All main field models are of degree and order 10. The secular variation model is of degree and order 8. The models were derived from five candidate main field models at 1985, five at 1990, and three candidate secular variation models at epoch 1992.5. Weighted averages of the candidate models were specified to arrive at the final models. A brief description of the development of the IGRF is given, useful formulae are reviewed, and contour maps of the geomagnetic elements *D*, *I*, *H*, *X*, *Y*, *Z*, and *F* at 1990 are included. The nature of and philosophy behind the IGRF are discussed and a new procedure for deriving the IGRF is proposed.

1. Introduction

The International Association of Geomagnetism and Aeronomy (IAGA), a member of the International Union of Geodesy and Geophysics (IUGG), provides an international forum for geomagnetism. At the 1954 meeting of the IUGG the concept of a World Magnetic Survey (WMS) was formalized in response to a communication by S. K. Runcorn indicating inadequacies in the available descriptions of the magnetic field of the Earth (IAGA, 1958). As part of the WMS, a potential analysis of the main field was to "be made providing spherical harmonic terms up to and including a degree and order useful for adequate representation of the data" (ALLDREDGE, 1971). ZMUDA (1971) described the purpose of the model as being "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". The resulting potential analysis, or field model, and subsequent additions and revisions, is designated the International Geomagnetic Reference Field, or IGRF.

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In deriving these models, the field is assumed to be curl free and so representable by a potential in the form of the usual spherical harmonic series:

$$V = a\sum_{n=1}^{N_{\max}}\sum_{m=0}^{n}(a/r)^{n+1}\left[g_n^m \cos m\phi + h_n^m \sin m\phi\right]P_n^m(\cos\theta) \quad (1)$$

where a is the mean radius of the Earth, taken to be 6371.2 km; r the radial distance from the center of the Earth; ϕ the east longitude measured from Greenwich; θ the geocentric colatitude; and $P_n{}^m(\cos\theta)$ the associated Legendre function of degree n and order m, normalized according to the convention of Schmidt (see, e.g., LANGEL, 1987). Equation (1) represents the potential of a field originating internal to the Earth, i.e., fields of external origin are ignored. The magnetic field is then given by

$$\boldsymbol{B} = -\nabla V. \quad (2)$$

In principle, $N_{\max}$ should be ∞ but in practice it is limited by the ability of the data to resolve the spherical harmonic coefficients. The Working Group has been of the opinion that in practice the available data for most epochs do not justify $N_{\max}$ greater than 10. This value is kept constant between the various IGRF models to maintain consistency. The coefficients are in units of nanotesla (nT).

In the following sections, the history of the development of the IGRF will be sketched briefly, the most recent modifications and additions described in some detail, and some comments made concerning proper use of the IGRF.

2. Previous Generations of the IGRF

The first IGRF model was adopted by the IAGA COMMISSION 2 WORKING GROUP 4 (1969) at the symposium on the Description of the Earth's Magnetic Field, held in Washington, D.C., October 22–25, 1968. A. J. Zmuda was the reporter of the Working Group and B. R. Leaton the chairman of Commission 2. Adoption of this model was a long process, with some dissension, as partly described by ZMUDA (1971).

The model adopted in 1968, designated IGRF 1965, is of degree and order eight in both main field and secular variation terms. Its epoch is 1965 and it was intended to be valid from 1955 to 1972. The main field coefficients are a weighted average of four models submitted by CAIN *et al.* (1967), FOUGERE (1969), MALIN (1968), IZMIRAN (1967a) (main field) and IZMIRAN (1967b) (secular variation). Secular variation coefficients were derived by an unweighted average of these four models and the model of HURWITZ (1968).

As time progressed, IGRF 1965 became very in accurate (e.g. PETKOVIC and WHITWORTH, 1975; DAWSON and NEWITT, 1978; MEAD, 1979). The second IGRF, designated IGRF 1975, was adopted in 1975 (IAGA DIVISION I STUDY GROUP, 1975). As the name implies, its epoch was 1975.0. During the process of adoption, some preference was expressed for a continuous IGRF and, as a result, the adopted main field coefficients were simply IGRF 1965 extrapolated to 1975. A new secular variation model was adopted, again to degree and order eight. Thus, IGRF 1975 was known to be in error by hundreds of nT for some regions at all epochs, although the rate of increase of that error was slowed.

The strategy of IGRF 1975 was reversed in the Third Generation IGRF adopted at the 1981 IAGA Assembly at Edinburgh (IAGA DIVISION I WORKING GROUP 1, 1981; PEDDIE, 1982, 1983; The entire issue of Volume 34, No. 6, 1982, of the *Journal of Geomagnetism and Geoelectricity* was devoted to a discussion of this generation of the IGRF). First, a series of revised models were adopted for epochs 1965, 1970 and 1975 designated Definitive International Geomagnetic Reference Fields: DGRF 1965, DGRF 1970 and DGRF 1975. These are weighted averages of models submitted by the Goddard Space Flight Center (GSFC) of the US National Aeronautics and Space Administration (NASA) (LANGEL *et al.*, 1982), the UK Institute of Geological Sciences (IGS) (BARRACLOUGH *et al.*, 1982) and the US Geological Survey (USGS) (PEDDIE and FABIANO, 1982). The term "definitive" is used because it is unlikely that the data sets utilized will be significantly improved. Secular variation between 1965 and 1975 is specified by linear interpolation between the three models. Second, a model for epoch 1980.0, designated IGRF 1980, was adopted, together with a secular variation model for 1980–1985. The main field model was based mainly on data from the Magsat satellite. Third, for 1975 to 1980 a Provisional Geomagnetic Reference Field, designated PGRF 1975, was defined as the linear interpolation between DGRF 1975 and IGRF 1980. All models discussed in this paragraph are of degree and order ten in main field and eight in secular variation.

At the IAGA General Assembly of 1985 the Fourth Generation of the IGRF was adopted. Detailed documentation is given in a series of papers in the October 1987 issue of *Physics of*

Table 1. Candidate models for the fourth generation IGRF.

Epoch	Model name*	N_{max}	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)
1985–1990	USGSSV87 SV-87	8	Peddie and Zunde (1987)
1985–1990	BGSSV87	8	Barraclough and Kerridge (1987)
1985–1990	IZMSV87	8	Golovkov and Kolomiitseva (1987)

*Where two model names are given, the second is that originally given by the authors.

the Earth and Planetary Interiors, especially the summary article by BARRACLOUGH (1987). Originally it had been planned to select DGRF models for 1945, 1950, 1955, 1960 and 1980, a main field model for 1985 and a secular variation model for 1985–1990. A total of twenty three candidate models were submitted by five groups: The Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN) in the U.S.S.R., NASA/GSFC, the U.S. Naval Oceanographic Office (USNOO), the USGS, and the British Geological Survey (BGS, formerly IGS). These are summarized in Table 1 from BARRACLOUGH (1987).

DGRF 1980 is identical to the GSFC(12/83) model (LANGEL and ESTES, 1985), truncated at degree and order 10. This model is based on data from the Magsat spacecraft. IGRF 1985 was chosen by using what was regarded as the best secular variation model for 1980–1985 to project DGRF 1980 to 1985. The secular variation model for 1985–1990 is a mean of the BGSSV87, IZMSV87 and USGSSV87 models of Table 1, of degree and order 8.

However, Working Group discussion at that time led to the conclusion that improvements were possible for all of the submitted candidates for 1945, 1950, 1955 and 1960. Accordingly the adoption of DGRF models for these years was postponed until the 1987 meeting of IAGA. Instead, the Fourth Generation IGRF was chosen to include the three models designated GSFCMF B for 1945, 1950 and 1955 and the model designated BGSMF60 for 1960, all non-definitive (BARRACLOUGH, 1987; see also IAGA DIVISION I WORKING GROUP 1, 1985).

The fourth revision, or Fifth Generation IGRF, adopted at the 19th General Assembly of the IUGG in 1987 (IAGA DIVISION I WORKING GROUP 1, 1988) replaced the models for 1945, 1950, 1955 and 1960 with DGRF models derived by a collaborative effort between NASA/GSFC, BGS, and IZMIRAN as described in detail by LANGEL *et al.* (1988).

3. The Sixth Generation IGRF

Working Group 8 (Analysis of the main field and secular variations) of Division V of IAGA (formerly Working Group 1 of Division I) considered the latest revision of the IGRF during the 20th General Assembly of the IUGG in August 1991. It recommended, (1) that IGRF 1985 be replaced by a newly derived DGRF 1985 and (2) that the extension of the IGRF to 1995 be accomplished by adoption of IGRF 1990 comprising a model of the main field at 1990.0 and a predictive model of the secular variation for use in adjusting the main field model to dates between 1990.0 and 1995.0.

Five main field models were submitted for each of the epochs 1985 and 1990. Three of the models for 1990 also included secular variation models for 1990–1995. The models submitted are summarized in Table 2; detailed descriptions are contained in the four papers in this issue that immediately follow this introduction, as referenced in the table. Following those four papers are an additional nine papers assessing the accuracy of some or all of the candidate models.

The main field models selected for DGRF 1985 and IGRF 1990 were weighted means of the candidate models, as summarized in Table 3. Weights were assigned by the entire working group after presentation of model evaluations, including those published in this issue.

The secular variation model for 1990–1995 was determined by an unconventional procedure. The Working Group concluded that the BNS90 candidate secular variation model was suspect for a region in the South Pacific. Otherwise, the (weak) concensus of the working group was that the three candidate models are of equal value. Accordingly, the IGRF secular variation model was determined as follows. An equal-area grid of three-component data points

Table 2. Sixth generation candidate IGRF models.

Model designation	Submitting institute	Submitting authors
	Main field candidates for DGRF 1985	
BN85	BGS/NOO	Barraclough *et al*. (1992)
G85	GSFC	Langel *et al*. (1992)
GD85	GSFC	Langel *et al*. (1992)
IZ85	IZMIRAN	Bondar and Golovkov (1992)
US85	USGS	Peddie (1992a)
	Main field candidates for IGRF 1990	
BN90	BGS/NOO	Barraclough *et al*. (1992)
G90	GSFC	Langel *et al*. (1992)
GD90	GSFC	Langel *et al*. (1992)
IZ90	IZMIRAN	Bondar and Golovkov (1992)
US90	USGS	Peddie (1992a)
	Secular variation candidates for IGRF 1990	
BNS90	BGS/NOO	Barraclough *et al*. (1992)
IZS90	IZMIRAN	Bondar and Golovkov (1992)
USS90	USGS	Peddie (1992a)

BGS/NOO: Joint submission by the British Geological Survey, Edinburgh, Scotland, and the U.S. Naval Oceanographic Office, Stennis Space Center, MS, U.S.A.

GSFC: Goddard Space Flight Center, Greenbelt MD, U.S.A.

IZMIRAN: Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Moscow, USSR.

USGS: United States Geological Survey, Denver, CO, U.S.A.

Table 3. Weights for main field models.

Candidate model	DGRF 1985	IGRF 1990
GD	0.30	0.40
US	0.25	0.30
BN	0.25	0.20
IZ	0.20	0.10

GD = GD85 or GD90. US = US85 or US90. BN = BN85 or BN90. IZ = IZ85 or IZ90. See Table 2.

with spacing equivalent to 3° at the equator was computed from each of the three models. The resulting synthetic data, i.e. values of $\dot{X}$, $\dot{Y}$, and $\dot{Z}$ from the models at the grid points, were used as input to a spherical harmonic analysis to derive the composite IGRF secular variation model for 1990–1995. In order to incorporate the opinion of the Working Group regarding the BNS90 model, the synthetic values from each of the models were assigned appropriate variances, or weights. This was accomplished as follows. Points from BNS90 from 0°N–90°S latitude and 170°E–80°W longitude were skipped, i.e., given zero weight or infinite variance, while the synthetic data for this region from the other two models were each given a weight of 1.5, or

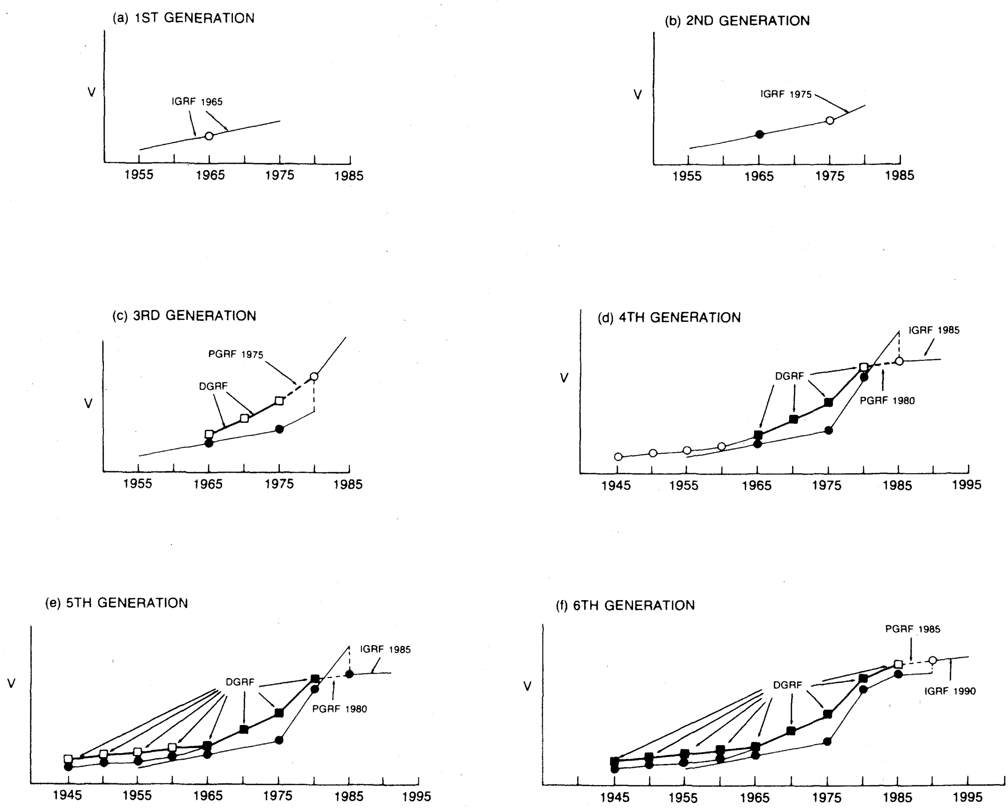

Fig. 1. A hypothetical value *V* associated with the IGRF. *V* can represent one of the field components, *X*, *Y* or *Z* calculated from the IGRF, or alternatively it can represent an IGRF spherical harmonic coefficient of a particular degree and order. Circles or squares represent values derived directly from main field models and the lines indicate values derived by extrapolating between models. Filled circles or squares indicate values from previous generation IGRFs; open circles or squares values from the newest generation IGRF. Circles and thin lines are non-definitive IGRF values; squares and heavy lines are from DGRF models. See text for more information. (Adapted from PEDDIE, 1982.)

a variance of 0.67 nT^2. Over the remainder of the Earth's surface the points computed from each of the models was given a weight of 1.0, or a variance of 1 nT^2.

The IGRF now consists of nine DGRF models spanning the interval 1945.0 to 1985.0; an IGRF for the interval 1990.0 to 1995.0 (IGRF 1990); and a provisional IGRF (PGRF 1985) defined by linear interpolation between the coefficients of DGRF 1985 and IGRF 1990 (main field). For dates between the specified model epochs the IGRF is defined as the linear interpolation of the model coefficients bracketing the time at which the field is to be computed. The present PGRF 1985 will be superseded when DGRF 1990 is adopted. Present plans are that this will take place at the 21st General Assembly of the IUGG in 1995.

Figure 1, adapted from Fig. 1 of PEDDIE (1982, 1983), illustrates the relationship between the various IGRF models. *V* is a hypothetical value which may be a field component (e.g., *X*, *Y*, or *Z*) calculated from the IGRF at a specified location or which may represent a particular

Table 4. IGRF coefficients (units are nT for main field, nT/yr for secular variation).

			DGRF									IGRF	
	n	m	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990	1990-95
g	1	0	-30594	-30554	-30500	-30421	-30334	-30220	-30100	-29992	-29873	-29775	18.0
g	1	1	-2285	-2250	-2215	-2169	-2119	-2068	-2013	-1956	-1905	-1851	10.6
h	1	1	5810	5815	5820	5791	5776	5737	5675	5604	5500	5411	-16.1
g	2	0	-1244	-1341	-1440	-1555	-1662	-1781	-1902	-1997	-2072	-2136	-12.9
g	2	1	2990	2998	3003	3002	2997	3000	3010	3027	3044	3058	2.4
h	2	1	-1702	-1810	-1898	-1967	-2016	-2047	-2067	-2129	-2197	-2278	-15.8
g	2	2	1578	1576	1581	1590	1594	1611	1632	1663	1687	1693	0.0
h	2	2	477	381	291	206	114	25	-68	-200	-306	-380	-13.8
g	3	0	1282	1297	1302	1302	1297	1287	1276	1281	1296	1315	3.3
g	3	1	-1834	-1889	-1944	-1992	-2038	-2091	-2144	-2180	-2208	-2240	-6.7
h	3	1	-499	-476	-462	-414	-404	-366	-333	-336	-310	-287	4.4
g	3	2	1255	1274	1288	1289	1292	1278	1260	1251	1247	1246	0.1
h	3	2	186	206	216	224	240	251	262	271	284	293	1.6
g	3	3	913	896	882	878	856	838	830	833	829	807	-5.9
h	3	3	-11	-46	-83	-130	-165	-196	-223	-252	-297	-348	-10.6

Table 4. (continued).

			DGRF								IGRF	
	n	m	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990	1990-95
g	4	0	944	954	958	957	957	952	946	938	936	939	0.5
g	4	1	776	792	796	800	804	800	791	782	780	782	0.6
h	4	1	144	136	133	135	148	167	191	212	232	248	2.6
g	4	2	544	528	510	504	479	461	438	398	361	324	-7.0
h	4	2	-276	-278	-274	-278	-269	-266	-265	-257	-249	-240	1.8
g	4	3	-421	-408	-397	-394	-390	-395	-405	-419	-424	-423	0.5
h	4	3	-55	-37	-23	3	13	26	39	53	69	87	3.1
g	4	4	304	303	290	269	252	234	216	199	170	142	-5.5
h	4	4	-178	-210	-230	-255	-269	-279	-288	-297	-297	-299	-1.4
g	5	0	-253	-240	-229	-222	-219	-216	-218	-218	-214	-211	0.6
g	5	1	346	349	360	362	358	359	356	357	355	353	-0.1
h	5	1	-12	3	15	16	19	26	31	46	47	47	-0.1
g	5	2	194	211	230	242	254	262	264	261	253	244	-1.6
h	5	2	95	103	110	125	128	139	148	150	150	153	0.5
g	5	3	-20	-20	-23	-26	-31	-42	-59	-74	-93	-111	-3.1
h	5	3	-67	-87	-98	-117	-126	-139	-152	-151	-154	-154	0.4
g	5	4	-142	-147	-152	-156	-157	-160	-159	-162	-164	-166	-0.1
h	5	4	-119	-122	-121	-114	-97	-91	-83	-78	-75	-69	1.7
g	5	5	-82	-76	-69	-63	-62	-56	-49	-48	-46	-37	2.3
h	5	5	82	80	78	81	81	83	88	92	95	98	0.4

Table 4. (continued).

			DGRF									IGRF	
	n	m	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990	1990-95
g	6	0	59	54	47	46	45	43	45	48	53	61	1.3
g	6	1	57	57	57	58	61	64	66	66	65	64	-0.2
h	6	1	6	-1	-9	-10	-11	-12	-13	-15	-16	-16	0.2
g	6	2	6	4	3	1	8	15	28	42	51	60	1.8
h	6	2	100	99	96	99	100	100	99	93	88	83	-1.3
g	6	3	-246	-247	-247	-237	-228	-212	-198	-192	-185	-178	1.3
h	6	3	16	33	48	60	68	72	75	71	69	68	0.0
g	6	4	-25	-16	-8	-1	4	2	1	4	4	2	-0.2
h	6	4	-9	-12	-16	-20	-32	-37	-41	-43	-48	-52	-0.9
g	6	5	21	12	7	-2	1	3	6	14	16	17	0.1
h	6	5	-16	-12	-12	-11	-8	-6	-4	-2	-1	2	0.5
g	6	6	-104	-105	-107	-113	-111	-112	-111	-108	-102	-96	1.2
h	6	6	-39	-30	-24	-17	-7	1	11	17	21	27	1.2

Table 4. (continued).

			DGRF								IGRF	
	n	m	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990	1990-95
g	7	0	70	65	65	67	75	72	71	72	74	77	0.6
g	7	1	-40	-55	-56	-56	-57	-57	-56	-59	-62	-64	-0.5
h	7	1	-45	-35	-50	-55	-61	-70	-77	-82	-83	-81	0.6
g	7	2	0	2	2	5	4	1	1	2	3	4	-0.3
h	7	2	-18	-17	-24	-28	-27	-27	-26	-27	-27	-27	0.2
g	7	3	0	1	10	15	13	14	16	21	24	28	0.6
h	7	3	2	0	-4	-6	-2	-4	-5	-5	-2	1	0.8
g	7	4	-29	-40	-32	-32	-26	-22	-14	-12	-6	1	1.6
h	7	4	6	10	8	7	6	8	10	16	20	20	-0.5
g	7	5	-10	-7	-11	-7	-6	-2	0	1	4	6	0.2
h	7	5	28	36	28	23	26	23	22	18	17	16	-0.2
g	7	6	15	5	9	17	13	13	12	11	10	10	0.2
h	7	6	-17	-18	-20	-18	-23	-23	-23	-23	-23	-23	0.0
g	7	7	29	19	18	8	1	-2	-5	-2	0	0	0.3
h	7	7	-22	-16	-18	-17	-12	-11	-12	-10	-7	-5	0.0

Table 4. (continued).

			DGRF								IGRF	
	n	m	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990	1990-95
g	8	0	13	22	11	15	13	14	14	18	21	22	0.2
g	8	1	7	15	9	6	5	6	6	6	6	5	-0.7
h	8	1	12	5	10	11	7	7	6	7	8	10	0.5
g	8	2	-8	-4	-6	-4	-4	-2	-1	0	0	-1	-0.2
h	8	2	-21	-22	-15	-14	-12	-15	-16	-18	-19	-20	-0.2
g	8	3	-5	-1	-14	-11	-14	-13	-12	-11	-11	-11	0.1
h	8	3	-12	0	5	7	9	6	4	4	5	7	0.3
g	8	4	9	11	6	2	0	-3	-8	-7	-9	-12	-1.1
h	8	4	-7	-21	-23	-18	-16	-17	-19	-22	-23	-22	0.3
g	8	5	7	15	10	10	8	5	4	4	4	4	0.0
h	8	5	2	-8	3	4	4	6	6	9	11	12	0.4
g	8	6	-10	-13	-7	-5	-1	0	0	3	4	4	-0.1
h	8	6	18	17	23	23	24	21	18	16	14	11	-0.5
g	8	7	7	5	6	10	11	11	10	6	4	3	-0.5
h	8	7	3	-4	-4	1	-3	-6	-10	-13	-15	-16	-0.3
g	8	8	2	-1	9	8	4	3	1	-1	-4	-6	-0.6
h	8	8	-11	-17	-13	-20	-17	-16	-17	-15	-11	-11	0.6

Table 4. (continued).

	n	m	DGRF 1945	DGRF 1950	DGRF 1955	DGRF 1960	DGRF 1965	DGRF 1970	DGRF 1975	DGRF 1980	DGRF 1985	IGRF 1990	IGRF 1990-95
g	9	0	5	3	4	4	8	8	7	5	5	4	0.0
g	9	1	-21	-7	9	6	10	10	10	10	10	10	0.0
h	9	1	-27	-24	-11	-18	-22	-21	-21	-21	-21	-21	0.0
g	9	2	1	-1	-4	0	2	2	2	1	1	1	0.0
h	9	2	17	19	12	12	15	16	16	16	15	15	0.0
g	9	3	-11	-25	-5	-9	-13	-12	-12	-12	-12	-12	0.0
h	9	3	29	12	7	2	7	6	7	9	9	10	0.0
g	9	4	3	10	2	1	10	10	10	9	9	9	0.0
h	9	4	-9	2	6	0	-4	-4	-4	-5	-6	-6	0.0
g	9	5	16	5	4	4	-1	-1	-1	-3	-3	-4	0.0
h	9	5	4	2	-2	-3	-5	-5	-5	-6	-6	-6	0.0
g	9	6	-3	-5	1	-1	-1	0	-1	-1	-1	-1	0.0
h	9	6	9	8	10	9	10	10	10	9	9	9	0.0
g	9	7	-4	-2	2	-2	5	3	4	7	7	7	0.0
h	9	7	6	8	7	8	10	11	11	10	9	9	0.0
g	9	8	-3	3	2	3	1	1	1	2	1	2	0.0
h	9	8	1	-11	-6	0	-4	-2	-3	-6	-7	-7	0.0
g	9	9	-4	8	5	-1	-2	-1	-2	-5	-5	-6	0.0
h	9	9	8	-7	5	5	1	1	1	2	2	2	0.0

Table 4. (continued).

			DGRF									IGRF	
	n	m	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990	1990-95
g	10	0	-3	-8	-3	1	-2	-3	-3	-4	-4	-4	0.0
g	10	1	11	4	-5	-3	-3	-3	-3	-4	-4	-4	0.0
h	10	1	5	13	-4	4	2	1	1	1	1	1	0.0
g	10	2	1	-1	-1	4	2	2	2	2	3	2	0.0
h	10	2	1	-2	0	1	1	1	1	0	0	0	0.0
g	10	3	2	13	2	0	-5	-5	-5	-5	-5	-5	0.0
h	10	3	-20	-10	-8	0	2	3	3	3	3	3	0.0
g	10	4	-5	-4	-3	-1	-2	-1	-2	-2	-2	-2	0.0
h	10	4	-1	2	-2	2	6	4	4	6	6	6	0.0
g	10	5	-1	4	7	4	4	6	5	5	5	4	0.0
h	10	5	-6	-3	-4	-5	-4	-4	-4	-4	-4	-4	0.0
g	10	6	8	12	4	6	4	4	4	3	3	3	0.0
h	10	6	6	6	1	1	0	0	-1	0	0	0	0.0
g	10	7	-1	3	-2	1	0	1	1	1	1	1	0.0
h	10	7	-4	-3	-3	-1	-2	-1	-1	-1	-1	-1	0.0
g	10	8	-3	2	6	-1	2	0	0	2	2	2	0.0
h	10	8	-2	6	7	6	3	3	3	4	4	4	0.0
g	10	9	5	10	-2	2	2	3	3	3	3	3	0.0
h	10	9	0	11	-1	0	0	1	1	0	0	0	0.0
g	10	10	-2	3	0	0	0	-1	-1	0	0	0	0.0
h	10	10	-2	8	-3	-7	-6	-4	-5	-6	-6	-6	0.0

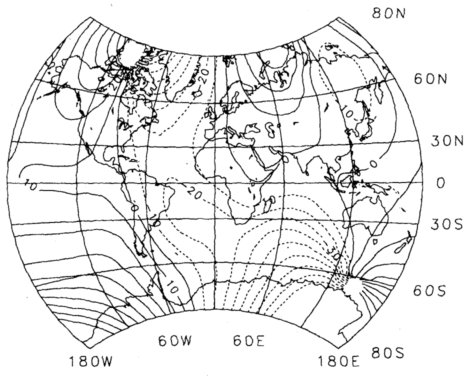

Fig. 2. Declination (D) at 1990. Solid lines are positive values, dashed lines negative values. Units are degrees; CI = 10°. Van der Grinten projection.

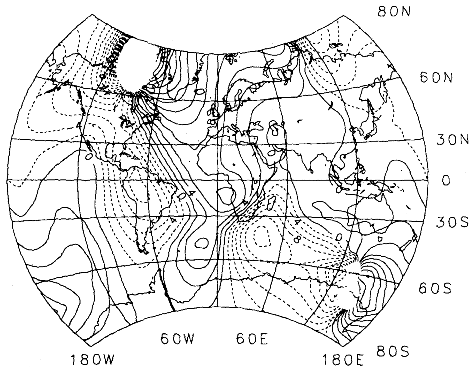

Fig. 3. Annual change of declination ($\dot{D}$) at 1990. Solid lines are positive values, dashed lines negative values. Units are minutes/yr; CI = 2 min/yr. Van der Grinten projection.

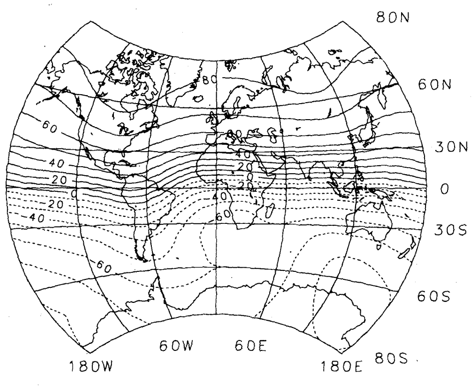

Fig. 4. Inclination (I) at 1990. Solid lines are positive values, dashed lines negative values. Units are degrees; CI = 10°. Van der Grinten projection.

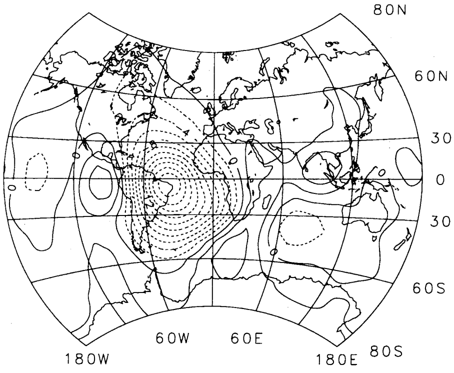

Fig. 5. Annual change of inclination ($\dot{I}$) at 1990. Solid lines are positive values, dashed lines negative values. Units are minutes/yr; CI = 2 min/yr. Van der Grinten projection.

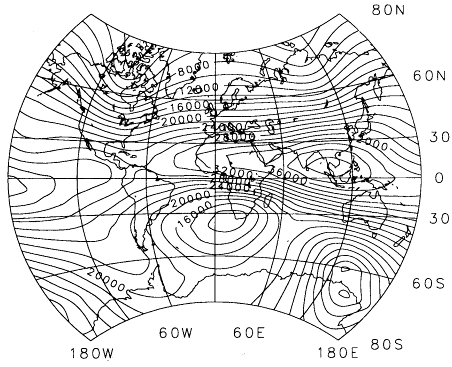

Fig. 6. Horizontal intensity (*H*) at 1990. Units are nT, CI = 2000 nT. Van der Grinten projection.

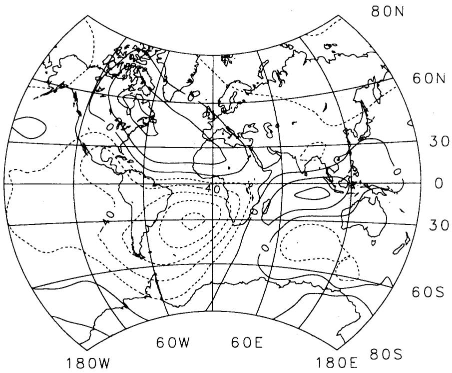

Fig. 7. Annual change of horizontal intensity ($\dot{H}$) at 1990. Solid lines are positive values, dashed lines negative values. Units are nT/yr; CI = 20 nT/yr. Van der Grinten projection.

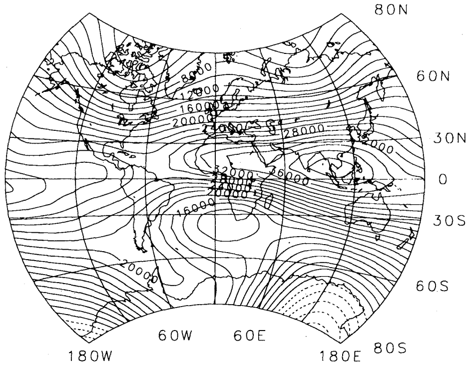

Fig. 8. North component (X) at 1990. Units are nT, CI = 2000 nT. Van der Grinten projection.

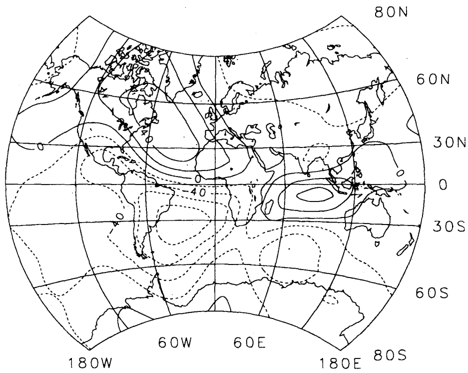

Fig. 9. Annual change of north component ($\dot{X}$) at 1990. Solid lines are positive values, dashed lines negative values. Units are nT/yr; CI = 20 nT/yr. Van der Grinten projection.

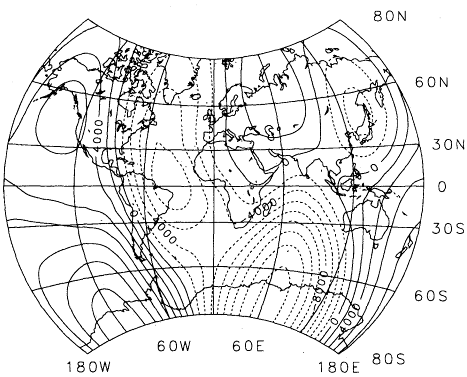

Fig. 10. East component (Y) at 1990. Solid lines are positive values, dashed lines negative values. Units are nT, CI = 2000 nT. Van der Grinten projection.

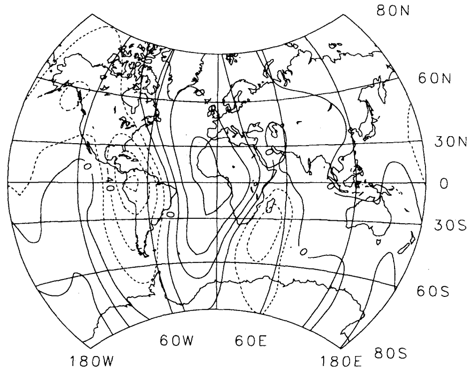

Fig. 11. Annual change of east component ($\dot{Y}$) at 1990. Solid lines are positive values, dashed lines negative values. Units are nT/yr; CI = 20 nT/yr. Van der Grinten projection.

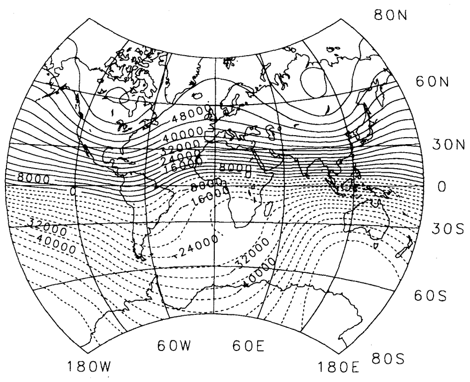

Fig. 12. Vertical intensity (Z) at 1990. Solid lines are positive values, dashed lines negative values. Units are nT, CI = 4000 nT. Van der Grinten projection.

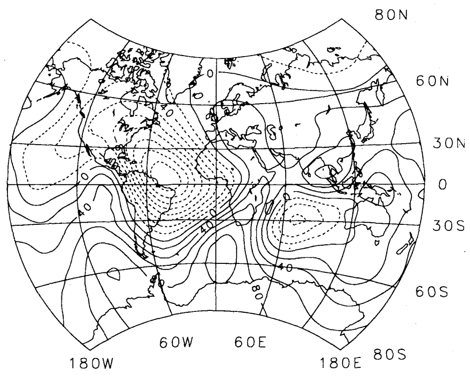

Fig. 13. Annual change of vertical intensity ($\dot{Z}$) at 1990. Solid lines are positive values, dashed lines negative values. Units are nT/yr; CI = 20 nT/yr. Van der Grinten projection.

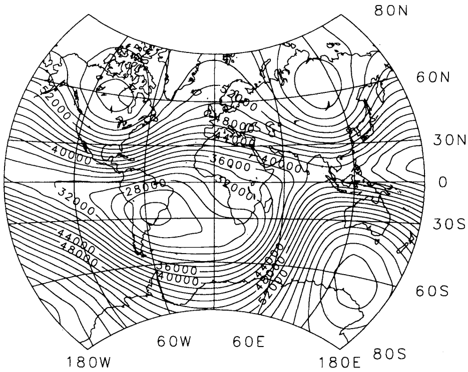

Fig. 14. Total intensity (F) at 1990. Units are nT, CI = 2000 nT. Van der Grinten projection.

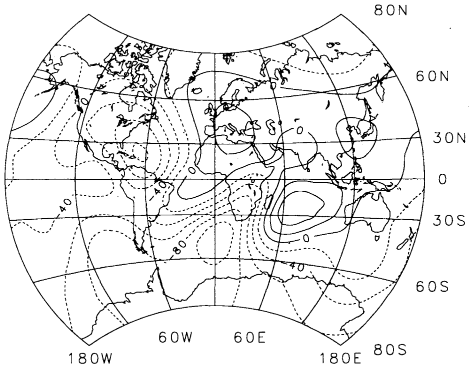

Fig. 15. Annual change of total intensity ($\dot{F}$) at 1990. Solid lines are positive values, dashed lines negative values. Units are nT/yr; CI = 20 nT/yr. Van der Grinten projection.

spherical harmonic coefficient. Circles or squares represent values derived directly from main field models and the lines indicate values derived either by extrapolating between main field models via a secular variation model or, in the case of the DGRF and PGRF, by direct interpolation. Filled circles or squares indicate values from previous generation IGRFs; open circles or squares indicate values from the newest generation IGRF. Figure 1(a) shows IGRF 1965, including the secular variation model; Fig. 1(b) shows how IGRF 1975 is continuous with IGRF 1965 but with a new rate of secular variation. The Third Generation IGRF, Fig. 1(c), shows IGRF 1980 as discontinuous with IGRF 1975, again with a new rate of secular change. It also shows that the DGRF models differ from the IGRF 1965 and IGRF 1975 models. The difference supposedly represents the error in the older models. Taken together, the DGRF models, the PGRF, and the IGRF are continuous. Figure 1(d) represents the Fourth Generation IGRF in which DGRF 1980 and IGRF 1985 were adopted. Here, PGRF 1980 is the linear interpolation between the two. The figure also shows the addition of IGRF models for 1945, 1950, 1955, and 1960. The only change between the Fourth and Fifth Generation, shown in Fig.

1(e), is the replacement of IGRFs by DGRFs at 1945, 1950, 1955, and 1960. Finally, Fig. 1(f) illustrates the present, or Sixth, Generation. DGRF 1985 is shown by an open square and IGRF 1990 by the open circle and line indicating the secular variation model. PGRF 1985 is the interpolation between these two models. The discontinuity between IGRF 1985 and IGRF 1990 is shown by the dotted line.

The spherical harmonic coefficients of all DGRF models and IGRF 1990 are given in Table 4. The ten main field models each have 120 coefficients and extend to degree and order 10. The secular variation model has 80 coefficients and extends only to degree and order 8.

Figures 2 through 15 show contour maps of the values of D, I, H, X, Y, Z, and F, and their first derivatives with respect to time (the annual change) at the surface of the Earth at 1990.0 as computed from IGRF 1990.

4. Accuracy of the IGRF

There are various approaches to considering the accuracy of a geomagnetic field model. Error estimates for the coefficients can be derived from the covariance matrix of the least squares solution for those coefficients. Of the four candidate main field models contributing to the DGRF or IGRF at each epoch, only GD85 and GD90 were submitted with coefficient error estimates. These estimates, given in tabular form in LANGEL *et al.* (1992) and plotted along with the scatter in the coefficients of the candidate models in LANGEL and BALDWIN (1992), may be taken as a lower bound for the error of the combined model. In general, the scatter in the coefficients of the candidate models is less than the corresponding error estimate (LANGEL and BALDWIN, 1992).

From the solution covariance matrix, an error estimate can be made for the computed field at any location by using equation (173) from LANGEL (1987). Such errors were calculated on a 5° grid spacing for the G90 model, from which the maximum and minimum values of Table 5 were computed. The maximum error listed in Table 5 for declination is misleading. In the polar regions, where the field is mainly vertical, the declination may vary considerably in a short distance and accuracy in representation is difficult to achieve. Away from these regions, the maximum error in D is on the order of 0.12°.

When projecting a spherical harmonic model to the core-mantle boundary (CMB) particular attention must be paid to proper error analysis. The high degree fields, in this case above degree 10, which are small at the Earth's surface, become very large at the CMB. The issues involved are reviewed by LANGEL (1991).

Another consideration is the degree and order of the model. In the ideal situation the field model represents only, and all of, that field believed to originate in the core of the Earth. In practice this is not true. At the Earth's surface, for the degree and order 10 IGRF fields not all of the field from the core is represented by the model. The magnitude of the omitted field, at the Earth's surface, is estimated to have an rms of about 20–30 nT (LANGEL and ESTES, 1982).

Another measure of the accuracy of the new IGRF models, in their representation of the first 10 degrees of the field, is the statistics of the differences between the candidate models. One might expect that the accuracy of the final model, which is a combination of the candidate models, would be of the same order of magnitude as these differences. Tables 6 and 7, reproduced from LANGEL and BALDWIN (1992), summarize the rms differences between the candidate models at the Earth's surface. LANGEL and BALDWIN (1992) also plot the model differences at the Earth's surface. For 1985, the maximum plotted difference is about 200 nT,

Table 5. Minimum and maximum estimated error by element, in degrees and nT.

Element	Minimum	Maximum
D	0.0422	4.2038
I	0.0261	0.1114
H	29.5	33.5
X	29.5	33.4
Y	29.5	33.6
Z	44.3	52.3
B	30.4	48.2

Table 6. RMS differences between candidate IGRF 1985 models. Units are nT.

Model pairs	*X*	*Y*	*Z*	*F*
G85-GD85	12.3	10.7	19.4	15.2
G85-US85	16.0	16.6	25.5	19.9
G85-BN85	22.9	21.7	33.0	29.9
G85-IZ85	22.6	26.2	40.0	28.6
BN85-US85	25.6	22.3	38.2	35.5
IZ85-US85	24.5	29.8	45.4	29.9
BN85-IZ85	29.0	33.5	48.0	33.9
GD85-US85	18.8	19.7	29.6	24.4
GD85-BN85	23.3	25.8	36.1	30.0
GD85-IZ85	24.2	25.3	41.2	28.4

Table 7. RMS differences between candidate IGRF 1990 models. Units are nT.

Model pairs	*X*	*Y*	*Z*	*F*
G90-GD90	18.5	21.1	33.5	24.3
G90-US90	34.8	29.9	52.1	45.3
G90-BN90	41.7	37.4	61.8	56.7
G90-IZ90	38.3	36.2	60.9	51.0
BN90-US90	35.6	31.1	55.9	50.4
IZ90-US90	39.0	39.2	62.0	52.8
BN90-IZ90	37.7	44.0	60.0	51.0
GD90-US90	35.6	32.9	52.0	46.9
GD90-BN90	40.1	40.5	60.1	54.3
GD90-IZ90	36.9	35.7	56.9	45.1

and differences of 60–80 nT are not uncommon, but generally the differences are less than 50 nT. For 1990, the maximum plotted difference is about 300 nT, and differences of 100–200 nT are not uncommon, but generally the differences are less than 70–80 nT.

5. Use of the IGRF

Equation (1) gives the geomagnetic potential in geocentric spherical coordinates. In these coordinates the components of $\boldsymbol{B}$ from Eq. (2) are the usual B_r, B_θ, B_ϕ. On the surface of the Earth, observations are often taken with respect to the usual latitude, say α, and longitude which are geodetic, as opposed to geocentric, coordinates. Geodetic and geocentric longitude are identical; the corresponding latitudes are not. The Earth is better approximated by an ellipsoid of revolution than by a sphere. Suppose the ellipsoid has equatorial radius A and polar radius B, $B < A$. The eccentricity e of the ellipsoid is defined by

$$e^2 = \left(A^2 - B^2\right)/A^2 \tag{3}$$

and the flattening, f, by

$$f = (A - B)/A. \tag{4}$$

Geodetic coordinates are usually specified by latitude, i.e. α (or colatitude, $u = 90° - \alpha$) and altitude above the geoid, h. These are transformed to the geocentric system by

$$\cot\theta = \frac{h\left(A^2\cos^2\alpha + B^2\sin^2\alpha\right)^{1/2} + B^2}{h\left(A^2\cos^2\alpha + B^2\sin^2\alpha\right)^{1/2} + A^2}\tan\alpha, \tag{5}$$

which reduces to

$$\cot\theta = \left(B^2/A^2\right)\tan\alpha \tag{6}$$

at the surface of the ellipsoid where $h = 0$, and by

$$r^2 = h^2 + 2h\left(A^2\cos^2\alpha + B^2\sin^2\alpha\right)^{1/2} + \frac{A^4 - \left(A^4 - B^4\right)\sin^2\alpha}{A^2 - \left(A^2 - B^2\right)\sin^2\alpha} \tag{7}$$

which can be approximated by

$$r^2 = r_0^2/\left(1 + e^2\cos^2 u\right), \tag{8}$$

where r_0 is the equatorial radius of the ellipsoid, equal to A at the surface of the Earth.

Table 8. Benchmark points or test calculations DGRF 1985.

Geodetic positions			Field values (nT)			Secular variation (nT/yr)		
colat (°)	long. (°)	alt (km)	X	Y	Z	$\dot{X}$	$\dot{Y}$	$\dot{Z}$
30.0	240.0	0.0	9755.2	5385.5	58899.4	16.64	–35.90	–38.97
90.0	240.0	0.0	31134.8	4794.0	5072.0	–40.92	9.76	2.32
150.0	240.0	0.0	16527.7	13115.4	–48072.7	–15.84	13.31	91.96
30.0	0.0	0.0	15055.1	–1886.8	47828.8	–4.26	33.66	18.76
90.0	0.0	0.0	27552.3	–4435.3	–13972.4	–13.91	62.03	–72.19
150.0	0.0	0.0	15405.6	–5529.4	–28512.5	–20.67	21.11	109.89
30.0	120.0	0.0	14443.2	–3042.6	58927.0	–38.52	–2.73	1.20
90.0	120.0	0.0	39167.3	895.4	–12990.9	24.63	–20.59	4.07
150.0	120.0	0.0	2878.6	–5075.0	–66062.8	–35.88	–0.91	28.46
Geocentric positions			Field values (nT)			Secular variation (nT/yr)		
colat (°)	long. (°)	r (km)	$-B_\theta$	B_ϕ	$-B_r$	$-\dot{B}_\theta$	$\dot{B}_\phi$	$-\dot{B}_r$
30.0	240.0	6371.2	9445.4	5329.3	58691.0	16.62	–35.66	–38.60
90.0	240.0	6371.2	31239.9	4805.7	5080.5	–41.07	9.88	2.34
150.0	240.0	6371.2	16241.3	13069.6	–48003.1	–15.30	13.12	91.54
30.0	0.0	6371.2	14789.3	–1884.8	47748.8	–4.48	33.45	18.38
90.0	0.0	6371.2	27647.6	–4448.0	–14052.9	–13.92	62.26	–72.57
150.0	0.0	6371.2	15306.6	–5523.4	–28571.5	–20.07	20.75	109.20
30.0	120.0	6371.2	14105.7	–2998.3	58735.2	–38.32	–2.78	0.71
90.0	120.0	6371.2	39308.9	901.5	–13032.9	24.80	–20.74	4.00
150.0	120.0	6371.2	2567.2	–5074.6	–65757.5	–35.66	–0.92	28.80

At and near the Earth's surface, e.g., at magnetic observatories, measurements are typically made in the geodetic coordinate system. In particular the usual X, Y, and Z components are defined in the geodetic system where X is horizontal to the ellipsoid in the meridian towards the north, Y is horizontal towards the east, perpendicular to the meridian, and Z is downwards perpendicular to the surface of the ellipsoid. If

$$\psi = \theta - u, \tag{9}$$

the angle between geodetic and geocentric latitude or colatitude, then

$$\begin{aligned} X &= -B_\theta \cos\psi - B_r \sin\psi, \\ Y &= B_\phi, \\ Z &= B_\theta \sin\psi - B_r \cos\psi. \end{aligned} \tag{10}$$

The angle ψ can be computed from

$$\sin\psi = \sin\alpha \sin\theta - \cos\alpha \cos\theta. \tag{11}$$

Table 9. Benchmark points or test calculations IGRF 1990.

Geodetic positions			Field values (nT)			Secular variation (nT/yr)		
colat (°)	long. (°)	alt (km)	X	Y	Z	$\dot{X}$	$\dot{Y}$	$\dot{Z}$
30.0	240.0	0.0	9837.4	5205.4	58701.2	17.82	−36.81	−39.12
90.0	240.0	0.0	30927.6	4847.4	5082.5	−38.13	10.75	0.03
150.0	240.0	0.0	16448.0	13179.2	−47612.8	−16.98	13.56	91.78
30.0	0.0	0.0	15033.7	−1714.8	47924.6	−1.73	33.49	20.80
90.0	0.0	0.0	27485.4	−4127.9	−14326.4	−13.64	61.41	−64.37
150.0	0.0	0.0	15302.1	−5422.3	−27960.1	−14.32	15.69	110.22
30.0	120.0	0.0	14249.7	−3056.8	58934.4	−37.48	−5.02	4.78
90.0	120.0	0.0	39287.7	794.8	−12975.0	17.73	−16.74	13.91
150.0	120.0	0.0	2699.9	−5082.3	−65920.1	−36.25	−4.43	18.48
Geocentric positions			**Field values (nT)**			**Secular variation (nT/yr)**		
colat (°)	long. (°)	r (km)	$-B_\theta$	B_ϕ	$-B_r$	$-\dot{B}_\theta$	$\dot{B}_\phi$	$-\dot{B}_r$
30.0	240.0	6371.2	9527.6	5150.3	58494.7	17.82	−36.53	−38.69
90.0	240.0	6371.2	31031.9	4859.8	5091.2	−38.28	10.87	0.01
150.0	240.0	6371.2	16164.4	13132.4	−47545.3	−16.42	13.36	91.39
30.0	0.0	6371.2	14766.9	−1714.0	47842.6	−1.94	33.26	20.48
90.0	0.0	6371.2	27580.8	−4139.5	−14408.8	−13.65	61.64	−64.71
150.0	0.0	6371.2	15206.2	−5418.2	−28022.6	−13.77	15.40	109.37
30.0	120.0	6371.2	13913.2	−3012.8	58740.1	−37.29	−5.02	4.22
90.0	120.0	6371.2	39430.1	800.2	−13017.4	17.84	−16.87	13.93
150.0	120.0	6371.2	2389.6	−5082.0	−65613.1	−36.12	−4.39	18.95

When converting between geodetic and geocentric coordinates, use of the IAU ellipsoid (INTERNATIONAL ASTRONOMICAL UNION, 1966) is recommended; it has an equatorial radius of 6378.160 km and a flattening of 1/298.25.

The geomagnetic elements H (horizontal intensity), F or B or T (total intensity), D (declination), and I (inclination) are defined as:

$$\begin{aligned} H &= \left(X^2 + Y^2\right)^{1/2}, \\ F &= \left(H^2 + Z^2\right)^{1/2}, \\ D &= \tan^{-1}(Y/X), \\ I &= \tan^{-1}(Z/H). \end{aligned} \qquad (12)$$

When computing the field elements at some time other than the epoch of one of the IGRF models, the correct procedure is to first interpolate in time on the spherical harmonic coefficients and then compute the desired elements. Correct answers may also be obtained by interpolating on those elements (X, Y, and Z) which are linear in the coefficients. It is not proper to interpolate in time on the non-linear elements D, I, H or F.

For users who wish to verify their software, Tables 8 and 9 contain benchmark, or test, calculations at a small number of locations, both in geocentric and in geodetic coordinates.

6. What is an IGRF?

As indicated in the introduction, the initial IGRF was derived as part of the World Magnetic Survey (WMS) to redress inadequacies in available models of the Earth's magnetic field. In my judgement, the WMS, during which spaceborne magnetic field measurements began, initiated a resurgence in geomagnetic studies which had its high point in the Magsat mission and associated studies. As one result, at the present time there are many field models in the literature besides the IGRF. The candidate models themselves are high quality models. What makes the IGRF special?

The distinguishing feature of the IGRF is that, according to ZMUDA (1971), it forms "an agreed basis for main field calculations and to unify studies ...". In other words, the IGRF is an agreed upon standard of comparison, a standard which is easily available in the literature, whose characteristics, including shortcomings, are well known. So that if two researchers wish to compare results they will have a common basis on which to make that comparison, at least as far as their geomagnetic model is concerned.

Is the IGRF or, better, DGRF the most accurate model for its epoch? It may or may not be. For epochs where no satellite data are available, there is a good chance that it is indeed the most accurate model available, though that is not certain. Modelers submitting candidate IGRF models often retain the opinion that their submission is better than the resulting IGRF. For epochs where high quality satellite data are available permitting solution to higher degree than ten, it is probable that such models are more accurate. More to the point, the most recent IGRF is always a predictive model, i.e., the data used in the model predate the epoch of the model by one to two years and predate the extended projection of the model by six to seven years. This means that models which are derived after the latest IGRF and prior to the next IGRF, and which incorporate later data than the latest IGRF, are likely to be more accurate than the current IGRF.

For many applications, the IGRF is perfectly adequate whether it is the most accurate model of its epoch or not. This is true for most magnetospheric studies, for charts, for most navigation purposes (localized crustal fields are not well represented in many, if any, spherical harmonic models), and for many surface, shipborne, and aircraft magnetic surveys. In the case of surveys where a regional field is removed in addition to the IGRF, the IGRF is sufficient and appropriate to use so that future reconstruction of the measured field is easily possible. In the case of surveys in which it is important to preserve long wavelength crustal fields, the IGRF is the only appropriate model to use.

Field models provide an effective means for removing the background, or main field, from magnetic survey data. When using the IGRF to remove the background field from survey data it is important that the epoch of the IGRF be the same as the epoch of the survey data, otherwise the secular variation of the main field will introduce errors in the resulting residuals. Thus, when comparing adjacent surveys from different epochs the IGRF epoch for background removal will be different for each survey. It is also important, when comparing surveys of anomaly fields, that the reference fields used be of the same degree and order. This is one reason why the degree and order of the IGRF models is uniform.

7. Discussion

As outgoing chairman of IAGA Working Group V-8, I would like to take this opportunity to comment on the process of deriving and evaluating IGRF models. The present special issue is representative of the general process involved. (1) A call is made for candidate models. (2) Various modeling groups gather the best data set possible given the constraints they have in terms of finances, time, management support, etc. (3) The models are submitted to the Working Group chairman who distributes them for evaluation. (4) Evaluations are submitted and distributed to members of the Working Group and interested parties. (5) At the next IAGA assembly, the Working Group meets, listens to presentations of the candidate models and evaluations of those models, and decides how to weight the candidate models. Although the process is as much political as it is scientific, it has worked remarkably well. In spite of grumbling by myself and others, in hindsight the weighted models generally turn out to be better than most or all the candidate models. At the same time the process is cumbersome and, I believe, sub-optimal.

Consider the evaluations. In the present issue there are nine papers presenting model evaluations. Six of these deal with specific regions of the Earth: Southern Africa (KOTZÉ, 1992); Australia (BARTON *et al.*, 1992); India (SINGH *et al.*, 1992); New Zealand and Antarctica (MCKNIGHT, 1992); Canada (NEWITT and HAINES, 1992); and the North Atlantic Ocean (SRIVASTAVA and SHIH, 1992). In each case the conclusion is the same: most or all models are very nearly the same in the way they fit the regional data; there is usually no single outstanding model and there is rarely a model which is obviously very poor. Such a result should not be surprising. Five of these evaluations were for continental or coastal regions where data are generally readily available. Most, if not all, the data used in the evaluations were also part of the data available for the derivation of the models. Of course the models all fit the data acceptably. This is not to minimize the importance of such data or of such evaluations. Both are crucial to the process and have aided greatly in deciding on model weighting. But the real model problems occur in regions where the data are sparse or non-existent, where such evaluations are not even possible.

Three other evaluations are included in this issue (PEDDIE, 1992b; QUINN *et al.*, 1992; LANGEL and BALDWIN, 1992). Each of these compares the candidate models to observatory data with the conclusion that the differences in the way the models fit these data are negligible. PEDDIE (1992b) compared the candidate models with Project MAGNET data and found the IZMIRAN models, which did not use this data, somewhat less representative than the other models, although the main differences occurred in years other than the epoch of the model. LANGEL and BALDWIN (1992) also compared the models to other survey data again with the conclusion that the differences between the way the models fit the data is small. The only paper which brought new data to the evaluation was that of QUINN *et al.* (1992) which compared the 1990 models to newly acquired data from the POGS satellite. This comparison was crucial in determining the final weighting of the models for IGRF 1990 and of the 1990–1995 secular variation model. It should be noted, however, that in the normal course of events, if this data had been available during the time when the models were being derived, it would have been included in all of the candidate models.

Another point which must be taken into account is what happens if one model, say, introduces a new set of data which contributes significantly to the model solution, but does not dominate it. For example, suppose one candidate model included data from a recently completed aeromagnetic survey in the south Pacific. Note that the effect on the model of including that data is likely to be to worsen its fit to the other data while at the same time making the resulting model more accurate than the other candidates in the south Pacific.

With the present state of data availability, candidate models from competent researchers will be difficult to distinguish by comparing those models to data.

How else can we compare models? PEDDIE (1992b) and LANGEL and BALDWIN (1992) examined the scatter between candidate model coefficients on a coefficient-by-coefficient basis. This reveals deviations between models and shows if any one model is consistently different from the others. Two of the evaluation papers (QUINN *et al.*, 1992; LANGEL and BALDWIN, 1992) compared the candidate models amongst themselves by contouring differences, by component (LANGEL and BALDWIN, 1992) or by field magnitude (QUINN *et al.*, 1992). These differences were then discussed, compared with the data distributions and methods of determining secular variation, and evaluated. Aside from the data from POGS, these two provided the only "tests" which found substantial distinctions between models. They provided much of the basis for the final weighting. However, they remain a subjective tests because if two models differ there is no proof positive to indicate which is correct. At its most effective the method highlights coefficients or geographic regions where, say, one out of four candidate models is in disagreement with the others.

I believe that the modeling community can arrive at IGRF models in a manner which is less time consuming, more accurate, and more enjoyable than the way we are going about it. The prototype for my proposed method is found in the derivation of the DGRF models for 1945, 1950, 1955, and 1960 (LANGEL *et al.*, 1988). In that case three different groups cooperated in deriving the models: IZMIRAN, BGS, and GSFC. First, each group contributed its unique input into forming the best possible data set. Then, a proposed method of data fitting was agreed upon and the necessary software prepared at a host institution, in this case GSFC. Finally, one of the scientists from BGS visited GSFC and participated in the final fitting processes and evaluation. The cooperation worked well, the results were agreed upon as the best possible, and the experience of producing the model was enjoyed by all concerned.

A similar process could be followed each time an IGRF update is needed. The working group chair could serve as the focal point. All institutions with relevant data, strongly encouraged by Working Group members, would forward that data to him; the various modeling groups would correspond or meet to decide on the details of the fitting procedure; and it would be carried out at a host institution with scientists from the various groups participating as possible. There would then be only one candidate model. It would be based on a data set contributed from researchers around the world and would be as good as that data permitted. With community cooperation, such a data set should, in principle, be more complete than any data set assembled by an individual modeler. If useful, the Working Group chairman could distribute all or subsets of the data to other modelers or Working Group members for evaluation and processing. The resulting model would be based on an agreed upon fitting procedure. Evaluation would still be in order, but now the evaluations would not be of competing models but would be aimed at assuring that the product model was not deficient in some way not apparent in the fitting procedure. The keys to this process are total community cooperation and redirection of some of the effort put into the present models. Some of the resources now committed to making and evaluating separate models would be used instead for seeking, collecting and evaluating data. Some of the energy now used in deciding between candidate models would instead be used for productive debate on fitting methodology and strategy. It is my contention that such a process would benefit the entire community and result in a better product.

Finally, it is important to note that the quality and, therefore, usefulness, of the IGRF is only as good as the data used in its derivation. One measure of this is that the degree and order of the models is maintained at 10. If Magsat quality data were available for all IGRF models it would be possible to extend this to 12 or 13 and still be confident of modeling the field from the core. In the absence of satellite data, modelers are dependent upon observatories, repeat stations and surveys on land, sea and air. No modeler has time to scour the world to be sure he has all the key data. We rely on the transmittal of all available data to the World Data Centers. It does the community no good if data is withheld from the data center, for whatever reason, and then later used to evaluate the IGRF model. Depositing all data in the Data Centers as soon as humanly possible, national interests notwithstanding, should be a top priority. In the case of proprietary surveys taken for resource exploration, a suitably decimated or filtered version would be preferable (see, e.g., LANGEL *et al.*, 1990). This is becoming increasingly important as some of the usual sources of data, e.g., some observatories, Project MAGNET, are losing support and may not be available in the future.

8. Obtaining Coefficients and Software

The coefficients of the IGRF models and computer programs for synthesizing field component values are available from the following sources:

World Data Centre C1 for Geomagnetism, British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, United Kingdom

World Data Center A for Solid Earth Geophysics, National Geophysical Data Center, NOAA, Code E/GCI, 325 Broadway, Boulder, CO 80303, U.S.A.

World Data Center A for Rockets and Satellites,
National Space Science Data Center (Code 930.2),
NASA Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.

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