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International Geomagnetic Reference Field: The Seventh Generation

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A seventh-generation revision of the International Geomagnetic Reference Field (IGRF) was adopted by the International Association of Geomagnetism and Aeronomy (IAGA) at the XXI General Assembly of the International Union of Geodesy and Geophysics in July 1995. The new spherical harmonic models adopted are based on weighted averages of candidate models submitted by NASA's Goddard Space Flight Center, the Russian Institute of Terrestrial Magnetism, Ionospheric, and Radio Wave Propagation—IZMIRAN, and jointly by the US Naval Oceanographic Office and the British Geological Survey. The revised IGRF specifies the Earth's main field from 1900 to 2000 and is declared to be *definitive* from 1945 to 1990. This paper lists the IGRF coefficients, describes the derivation of the new IGRF models, and examines aspects of the IGRF's accuracy, continuity, and behaviour during this century.

1. Introduction

The International Geomagnetic Reference Field (IGRF) is a series of mathematical models of the Earth's main magnetic field (MF) and its secular variation (SV). Each model comprises a set of spherical harmonic (or Gauss) coefficients, g_n^m and h_n^m, in a truncated series expansion of a magnetic scalar potential function of internal origin,

$$V = a\sum_{n=1}^{N}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n+1}\left(g_n^m \cos m\phi + h_n^m \sin m\phi\right)P_n^m(\cos\theta), \tag{1}$$

where a is the mean radius of the Earth (6371.2 km), r is radial distance from the centre of the Earth, ϕ is longitude east of Greenwich, θ is geocentric colatitude, $P_n^m(\cos\theta)$ is the associated Legendre function of degree n and order m, normalized according to the convention of Schmidt (e.g., Chapman and Bartels, 1940; Langel, 1987; Merrill *et al.*, 1996), and N is the maximum spherical harmonic degree of the expansion. If the Gauss coefficients are in units of magnetic field strength (i.e., A m^{-1} in SI units, or oersted in the cgs system), then V in Eq. (1) is the geomagnetic scalar potential as formally defined in physics, and the gradient of V gives the magnetic field ($\boldsymbol{H}$). When IAGA adopted SI units (IAGA, 1974), Eq. (1) was retained but with the Gauss coefficients declared in units of magnetic induction (the induction in nanotesla, nT, being numerically, though not dimensionally, equal to the field in the old cgs unit of gamma). This changes the definition of V. Under this convention, which is used throughout most of the IGRF literature, the potential function in Eq. (1) should really be given a different name, e.g., the magnetic scalar potential for magnetic induction (V_B, say), to emphasize that the gradient of this potential gives the magnetic induction ($\boldsymbol{B}$) not the magnetic field ($\boldsymbol{H}$). For a cartesian coordinate system (X north, Y east, Z down) for a point on a sphere of radius, r,

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$$B_X = -\frac{\partial V_B}{\partial x} = \frac{1}{r}\frac{\partial V_B}{\partial \theta}, \quad B_Y = -\frac{\partial V_B}{\partial y} = \frac{-1}{r\sin\theta}\frac{\partial V_B}{\partial \theta}, \quad B_Z = -\frac{\partial V_B}{\partial z} = \frac{\partial V_B}{\partial r}. \quad (2)$$

Just as $\boldsymbol{B} = \mu \boldsymbol{H}$, so $V_B = \mu V$, where μ is the magnetic permeability (the magnetic permeability of free space, $\mu_0 = 4\pi 10^{-7}$ henry m^{-1}, may be substituted in the present context since the observations are deemed to be made in a magnetic source-free region). These relationships and conventions are discussed in more detail by Merrill *et al.* (1996, Chapter 2 and Appendix B).

2. History of the IGRF

The historical development of the IGRF is summarized in Table 1 and has been described in detail by Langel (1992b). The first version, IGRF 1965, was adopted by IAGA in 1968 and subsequently has been updated six times. Definitive Geomagnetic Reference Field (DGRF) models were introduced in 1981 to provide more accurate models for past epochs. The term *definitive* is used because such models are adopted retrospectively when it has become apparent that the data sets utilized can not be improved significantly, hence any improvement of the models is unlikely. The IGRF-designated models are eventually replaced by definitive models. The name *IGRF* refers collectively to the entire series of spherical harmonic models; if a particular epoch model is intended, the reference must be specific, e.g., IGRF 1995 or DGRF 1990. Production of the IGRF is a world-wide effort coordinated by IAGA, Division V, Working Group V-8: *Analysis of the Global and Regional Geomagnetic Field and its Secular Variation* (WG V-8).

Previous IGRF models are described in the references cited in Table 1 and in: Zmuda (1971); *Journal of Geomagnetism and Geoelectricity*, volume 34, No. 6, 1982 (in particular Peddie, 1982); Peddie (1983);

Table 1. Evolution of the International Geomagnetic Reference Field.

Generation	Main-field models (5-yearly)	SV model interval	Reference
1st	IGRF 1965	1955–1975	IAGA, 1969
2nd	IGRF 1975*	1975–1980	IAGA, 1975
3rd	DGRF 1965–DGRF 1975		IAGA, 1981; Peddie, 1981
	IGRF 1980	1980–1985	
4th	IGRF 1945–IGRF 1960		IAGA, 1985; Barraclough, 1985
	DGRF 1965–DGRF 1980		
	IGRF 1985	1985–1990	
5th	DGRF 1945–DGRF 1980		IAGA, 1987
	IGRF 1985**	1985–1990	
6th	DGRF 1945–DGRF 1985		IAGA, 1991; Langel, 1992a
	IGRF 1990	1990–1995	
7th	IGRF 1900–IGRF 1940		this report
	DGRF 1945–DGRF 1985		unchanged
	DGRF 1990		this report
	IGRF 1995	1995–2000	this report

*Same as IGRF 1965 extended to 1975.0.

**Identical to the 4th generation IGRF 1985.

Langel (1987); *Physics of the Earth and Planetary Interiors*, October issue, 1987 (in particular Barraclough, 1987); and *Journal of Geomagnetism and Geoelectricity*, volume 44, No. 9, 1992 (in particular Langel, 1992b). Charts and tables of gridded values of the IGRF have been published as IAGA Bulletins for IGRF 1965 (Leaton, 1971; Leaton and Barraclough, 1971), IGRF 1975 (Barraclough and Fabiano, 1978), IGRF 1980 (Fabiano *et al.*, 1983), IGRF 1985 (Barraclough and Kerridge, 1986), and DGRF 1985 and IGRF 1990 (Baldwin and Langel, 1993). The demand for tables of gridded values has waned because of the widespread use of desktop computers and the free availability of software for synthesizing IGRF field values.

3. Candidate Models for the 1995 Revision of the IGRF

The call for candidate models put out by WG V-8 requested main-field models at 5-year epochs from 1900 to 1940, inclusive, a DGRF 1990 model to replace IGRF 1990 (MF), and an IGRF 1995 model (MF and SV). The candidate models that were submitted are listed in Table 2. In addition, the 6th generation IGRF may be considered as a candidate for DGRF 1990 and IGRF 1995 (MF). Only one (GSFC) set of models was submitted for the interval 1900 to 1940. All the models submitted were truncated at $N = 10$ for the MF and $N = 8$ for the SV. The set of candidate models was circulated to agencies and individuals around the world for evaluation.

The GSFC models were produced by NASA's Goddard Space Flight Center (Sabaka *et al.*, 1997; Langel *et al.*, 1997). Models GSP-90 and GSP-95 included data from the POGS satellite, but were subsequently withdrawn by the authors in favour of GS-90 and GS-95. Inter-model comparisons show that the differences between the GSFC models with and without POGS data are much smaller than the differences between these and other corresponding candidate models (e.g., Macmillan and Barraclough, 1997). The GSFC candidate model for IGRF 1995 was for the main field only.

Table 2. Candidate models for the 1995 revision of the IGRF.

IGRF model	MF/SV	File name	Agency	Full model name used by authors	Authors of the models (see text for references)
IGRF 1900	MF	GS-00	NASA	GSFC(12/94-s)-1900	Langel, Sabaka, Baldwin
IGRF 1905	MF	GS-05	NASA	GSFC(12/94-s)-1905	Langel, Sabaka, Baldwin
IGRF 1910	MF	GS-10	NASA	GSFC(12/94-s)-1910	Langel, Sabaka, Baldwin
IGRF 1915	MF	GS-15	NASA	GSFC(12/94-s)-1915	Langel, Sabaka, Baldwin
IGRF 1920	MF	GS-20	NASA	GSFC(12/94-s)-1920	Langel, Sabaka, Baldwin
IGRF 1925	MF	GS-25	NASA	GSFC(12/94-s)-1925	Langel, Sabaka, Baldwin
IGRF 1930	MF	GS-30	NASA	GSFC(12/94-s)-1930	Langel, Sabaka, Baldwin
IGRF 1935	MF	GS-35	NASA	GSFC(12/94-s)-1935	Langel, Sabaka, Baldwin
IGRF 1940	MF	GS-40	NASA	GSFC(12/94-s)-1940	Langel, Sabaka, Baldwin
DGRF 1990	MF	GS-90	NASA	GSFC(12/94-s)-1990	Langel, Sabaka, Baldwin
		GSP-90	NASA	GSFC(12/94-sp)-1990	Langel, Sabaka, Baldwin
		IZ-95	IZMIRAN	"DGRF 1990"	Golovkov, Bondar, Burdelnaya, Yakovleva
		UB-95	NOO/BGS	DGRF-90	Quinn, Macmillan, Barraclough
IGRF 1995	MF	GS-95	NASA	GSFC(12/94-s)-1995	Langel, Sabaka, Baldwin
		GSP-95	NASA	GSFC(12/94-sp)-1995	Langel, Sabaka, Baldwin
		IZ-95	IZMIRAN	"IGRF 1995"	Golovkov, Bondar, Burdelnaya, Yakovleva
		UB-95	NOO/BGS	IGRF-95	Quinn, Coleman, Macmillan, Barraclough
	SV	IZ-SV	IZMIRAN	"IGRF 1995"	Golovkov, Bondar, Burdelnaya, Yakovleva
		UB-SV	NOO/BGS	IGRF-95	Quinn, Macmillan, Barraclough

Table 3. Ranges of the rms differences between all combinations of pairs of candidate models.

IGRF model	X	Y	Z	F
DGRF 1990 (nT)	30–37	29–37	40–57	62–78
IGRF 1995 (MF) (nT)	51–67	63–85	91–132	122–165
IGRF 1995 (SV) (nT/yr)	7	8	12	16

The IZ series of models was produced by the Russian Institute of Terrestrial Magnetism, Ionospheric, and Radio Wave Propagation—IZMIRAN (Golovkov *et al.*, 1997a, 1997b) based on a continuous space-time model of the field for the interval 1970–1994, IZMST. Time-dependence was modelled by the method of natural orthogonal components (NOCs) using observatory annual means, and then expanded spatially with satellite data using spherical harmonics up to $N = 10$. IZ-90 and IZ-95 were obtained by selecting the coefficients for 1990 and 1995 from ISMST.

The UB series of models was produced jointly by the US Navy Oceanographic Office (NOO) and the British Geological Survey (BGS) (Quinn *et al.*, 1997; Macmillan *et al.*, 1997). UB-95 was obtained from World Magnetic Model WMM95 by truncation at $N = 10$; UB-SV is identical to the secular-variation model of WMM95.

4. Comparisons between Candidate Models

Comparisons between candidate models and evaluations against global observatory and survey data sets are presented by Cohen *et al.* (1997), Golovkov *et al.* (1997b), and Macmillan and Barraclough (1997). Ranges of the rms differences between all combinations of pairs of candidate models, GSP models excluded, are given in Table 3 (figures are derived from tables in Macmillan and Barraclough (1997) and Golovkov *et al.* (1997b)). Table 3 provides a simple summary of how well the various candidate models agree.

The rms fits of the candidate models to the 1985–1994 observational data are typified by the results of Macmillan and Barraclough, namely 167 nT for observatory annual means, 104 nT for magnetic survey and repeat station data, 143 nT for Project MAGNET data, and 63 nT for marine data. For any particular data type and year, the differences between the rms residuals of the different candidates amount to no more than several nanoteslas (though Langel *et al.*, 1982, point out that rms residuals are insensitive as a test of model quality).

Macmillan and Barraclough (1997) have undertaken the most exhaustive comparisons with different types of observational data. They conclude (i) there is not enough evidence to recommend one model in favour of another, (ii) some large differences occur between the candidate models, especially in areas where there is poor coverage of data, and (iii) the overall fit of each candidate model to the observational data over-all is marginally better than given by the sixth generation IGRF. From a comparison with the most recent observatory data, Cohen *et al.* (1997) conclude that the main-field candidates for 1995 do "a very comparable job", though UB-95 fits the observations marginally better. Golovkov *et al.* (1997b) conclude that IZ-90 and IZ-95 give the best fits to the observational data, but IZ-SV and UB-SV are comparable. Evaluations of the candidate models for particular regions of the globe (see other papers in this special issue) bear out the general view that no particular candidates stand out as being significantly better or worse than the others.

5. The 1995 Revision of the IGRF

Descriptions of the candidate models and the data sets used, assessments of the models, and evaluations of the models for different parts of the world were presented at the XXI General Assembly

Table 4. New models and weights adopted for the seventh generation of the IGRF.

IGRF model	Adoption	Weight
IGRF 1900	GS-00	1.00
IGRF 1905	GS-05	1.00
IGRF 1910	GS-10	1.00
IGRF 1915	GS-15	1.00
IGRF 1920	GS-20	1.00
IGRF 1925	GS-25	1.00
IGRF 1930	GS-30	1.00
IGRF 1935	GS-35	1.00
IGRF 1940	GS-40	1.00
DGRF 1990	GS-90	0.33
	IZ-90	0.33
	UB-90	0.33
IGRF 1995 (MF)	GS-95	0.33
	IZ-95	0.33
	UB-95	0.33
IGRF 1995 (SV)	UB-SV	0.60
	IZ-SV	0.40

of the International Union of Geodesy and Geophysics, Boulder, USA in July 1995. WG V-8 agreed to adopt the GSFC models for IGRF 1900 through 1940. It was deemed premature to adopt definitive models back to 1900, so the new models for the earlier epochs carry the "IGRF" designation. This leaves open the option of adopting definitive models at a later date. For the remaining new models, weighted combinations of the candidates were adopted, as listed in Table 4 (weighting is achieved by applying a weighted average of corresponding coefficients).

Thus, spherical harmonic models of the main field are now defined at discrete 5-year epochs from 1900 to 1995, truncated at $N = 10$, and a secular change model is introduced for 1995 to 2000 (as part of IGRF 1995), truncated at $N = 8$. Coefficients for dates between the 5-year epochs are obtained by linear interpolation between corresponding coefficients for neighbouring 5-year epochs. The field definition has "IGRF" status from 1900 to 1940 and at 1995, is deemed to be definitive between 1945 and 1990, inclusive, and is declared "provisional" for the intervening intervals (1940 to 1945, and 1990 to 1995). Spherical harmonic coefficients for the complete seventh generation IGRF are given in Table 5. MF coefficients are in nT and SV coefficients in nT/yr.

6. How Well-Determined are the Coefficients?

IGRF main-field models are truncated at $N = 10$ (120 coefficients), which is considered to be the practical compromise adopted for producing well-determined main-field models while avoiding most of the contamination from crustal fields (the now-obsolete IGRF 1965 and IGRF 1975 models were exceptions, being truncated at $N = 8$). Main-field coefficients are rounded to the nearest nT to reflect the limit of resolution of the observational data. The spectrum of main-field variations certainly extends beyond $N = 10$ and is considered by most to dominate the crustal spectrum up to degree 12 or 13 (some would claim to degree 14). However, achieving a practical separation of the core and crustal fields in this overlapping part of the spectrum is challenging. The prospective secular-variation model is truncated at $N = 8$ (80 coefficients) and rounded to the nearest 0.1 nT/yr, which is necessary to avoid rounding errors when extending the main field coefficients and also reflects the resolution of the available data (see Fig. 1 below).

Table 5. Spherical harmonic (Gauss) coefficients* of the 1995 revision of the IGRF.

	g/h	n	m	IGRF	IGRF	IGRF	IGRF	IGRF	IGRF	IGRF	IGRF	IGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	IGRF	
				1900	1905	1910	1915	1920	1925	1930	1935	1940	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990	1995	SV
001	g	1	0	-31543	-31464	-31354	-31212	-31060	-30926	-30805	-30715	-30654	-30594	-30554	-30500	-30421	-30334	-30220	-30100	-29992	-29873	-29775	-29682	17.6
002	g	1	1	-2298	-2298	-2297	-2306	-2317	-2318	-2316	-2306	-2292	-2285	-2250	-2215	-2169	-2119	-2068	-2013	-1956	-1905	-1848	-1789	13.0
003	h	1	1	5922	5909	5898	5875	5845	5817	5808	5812	5821	5810	5815	5820	5791	5776	5737	5675	5604	5500	5406	5318	-18.3
004	g	2	0	-677	-728	-769	-802	-839	-893	-951	-1018	-1106	-1244	-1341	-1440	-1555	-1662	-1781	-1902	-1997	-2072	-2131	-2197	-13.2
005	g	2	1	2905	2928	2948	2956	2959	2969	2980	2984	2981	2990	2998	3003	3002	2997	3000	3010	3027	3044	3059	3074	3.7
006	h	2	1	-1061	-1086	-1128	-1191	-1259	-1334	-1424	-1520	-1614	-1702	-1810	-1898	-1967	-2016	-2047	-2067	-2129	-2197	-2279	-2356	-15.0
007	g	2	2	924	1041	1176	1309	1407	1471	1517	1550	1566	1578	1576	1581	1590	1594	1611	1632	1663	1687	1686	1685	-0.8
008	h	2	2	1121	1065	1000	917	823	728	644	586	528	477	381	291	206	114	25	-68	-200	-306	-373	-425	-8.8
009	g	3	0	1022	1037	1058	1084	1111	1140	1172	1206	1240	1282	1297	1302	1302	1297	1287	1276	1281	1296	1314	1329	1.5
010	g	3	1	-1469	-1494	-1524	-1559	-1600	-1645	-1692	-1740	-1790	-1834	-1889	-1944	-1992	-2038	-2091	-2144	-2180	-2208	-2239	-2268	-6.4
011	h	3	1	-330	-357	-389	-421	-445	-462	-480	-494	-499	-499	-476	-462	-414	-404	-366	-333	-336	-310	-284	-263	4.1
012	g	3	2	1256	1239	1223	1212	1205	1202	1205	1215	1232	1255	1274	1288	1289	1292	1278	1260	1251	1247	1248	1249	-0.2
013	h	3	2	3	34	62	84	103	119	133	146	163	186	206	216	224	240	251	262	271	284	293	302	2.2
014	g	3	3	572	635	705	778	839	881	907	918	916	913	896	882	878	856	838	830	833	829	802	769	-8.1
015	h	3	3	523	480	425	360	293	229	166	101	43	-11	-46	-83	-130	-165	-196	-223	-252	-297	-352	-406	-12.1
016	g	4	0	876	880	884	887	889	891	896	903	914	944	954	958	957	957	952	946	938	936	939	941	0.8
017	g	4	1	628	643	660	678	695	711	727	744	762	776	792	796	800	804	800	791	782	780	780	782	0.9
018	h	4	1	195	203	211	218	220	216	205	188	169	144	136	133	135	148	167	191	212	232	247	262	1.8
019	g	4	2	660	653	644	631	616	601	584	565	550	544	528	510	504	479	461	438	398	361	325	291	-6.9
020	h	4	2	-69	-77	-90	-109	-134	-163	-195	-226	-252	-276	-278	-274	-278	-269	-266	-265	-257	-249	-240	-232	1.2
021	g	4	3	-361	-380	-400	-416	-424	-426	-422	-415	-405	-421	-408	-397	-394	-390	-395	-405	-419	-424	-423	-421	0.5
022	h	4	3	-210	-201	-189	-173	-153	-130	-109	-90	-72	-55	-37	-23	3	13	26	39	53	69	84	98	2.7
023	g	4	4	134	146	160	178	199	217	234	249	265	304	303	290	269	252	234	216	199	170	141	116	-4.6
024	h	4	4	-75	-65	-55	-51	-57	-70	-90	-114	-141	-178	-210	-230	-255	-269	-279	-288	-297	-297	-299	-301	-1.0
025	g	5	0	-184	-192	-201	-211	-221	-230	-237	-241	-241	-253	-240	-229	-222	-219	-216	-218	-218	-214	-214	-210	0.8
026	g	5	1	328	328	327	327	326	326	327	329	334	346	349	360	362	358	359	356	357	355	353	352	0.1
027	h	5	1	-210	-193	-172	-148	-122	-96	-72	-51	-33	-12	3	15	16	19	26	31	46	47	46	44	0.2
028	g	5	2	264	259	253	245	236	226	218	211	208	194	211	230	242	254	262	264	261	253	245	237	-1.5
029	h	5	2	53	56	57	58	58	58	60	64	71	95	103	110	125	128	139	148	150	150	154	157	1.2
030	g	5	3	5	-1	-9	-16	-23	-28	-32	-33	-33	-20	-20	-23	-26	-31	-42	-59	-74	-93	-109	-122	-2.0
031	h	5	3	-33	-32	-33	-34	-38	-44	-53	-64	-75	-67	-87	-98	-117	-126	-139	-152	-151	-154	-153	-152	0.3
032	g	5	4	-86	-93	-102	-111	-119	-125	-131	-136	-141	-142	-147	-152	-156	-157	-160	-159	-162	-164	-165	-167	-0.1
033	h	5	4	-124	-125	-126	-126	-125	-122	-118	-115	-113	-119	-122	-121	-114	-97	-91	-83	-78	-75	-69	-64	1.8
034	g	5	5	-16	-26	-38	-51	-62	-69	-74	-76	-76	-82	-76	-69	-63	-62	-56	-49	-48	-46	-36	-26	2.3
035	h	5	5	3	11	21	32	43	51	58	64	69	82	80	78	81	81	83	88	92	95	97	99	0.9
036	g	6	0	63	62	62	61	61	61	60	59	57	59	54	47	46	45	43	45	48	53	61	66	0.5
037	g	6	1	61	60	58	57	55	54	53	53	54	57	57	57	58	61	64	66	66	65	65	64	-0.4
038	h	6	1	-9	-7	-5	-2	0	3	4	4	4	6	-1	-9	-10	-11	-12	-13	-15	-16	-16	-16	0.3
039	g	6	2	-11	-11	-11	-10	-10	-9	-9	-8	-7	6	4	3	1	8	15	28	42	51	59	65	0.6
040	h	6	2	83	86	89	93	96	99	102	104	105	100	99	96	99	100	100	99	93	88	82	77	-1.6

Table 5. (continued).

	g/h	n	m	IGRF 1900	IGRF 1905	IGRF 1910	IGRF 1915	IGRF 1920	IGRF 1925	IGRF 1930	IGRF 1935	IGRF 1940	DGRF 1945	DGRF 1950	DGRF 1955	DGRF 1960	DGRF 1965	DGRF 1970	DGRF 1975	DGRF 1980	DGRF 1985	DGRF 1990	IGRF 1995	IGRF SV
041	g	6	3	−217	−221	−224	−228	−233	−238	−242	−246	−249	−246	−247	−247	−237	−228	−212	−198	−192	−185	−178	−172	1.9
042	h	6	3	2	4	5	8	11	14	19	25	33	16	33	48	60	68	72	75	71	69	69	67	−0.2
043	g	6	4	−58	−57	−54	−51	−46	−40	−32	−25	−18	−25	−16	−8	−1	4	2	1	4	4	3	2	−0.2
044	h	6	4	−35	−32	−29	−26	−22	−18	−16	−15	−15	−9	−12	−16	−20	−32	−37	−41	−43	−48	−52	−57	−0.9
045	g	6	5	59	57	54	49	44	39	32	25	18	21	12	7	−2	1	3	6	14	16	18	17	−0.2
046	h	6	5	36	32	28	23	18	13	8	4	0	−16	−12	−12	−11	−8	−6	−4	−2	−1	1	4	1.0
047	g	6	6	−90	−92	−95	−98	−101	−103	−104	−106	−107	−104	−105	−107	−113	−111	−112	−111	−108	−102	−96	−94	0.0
048	h	6	6	−69	−67	−65	−62	−57	−52	−46	−40	−33	−39	−30	−24	−17	−7	1	11	17	21	24	28	2.2
049	g	7	0	70	70	71	72	73	73	74	74	74	70	65	65	67	75	72	71	72	74	77	78	−0.2
050	g	7	1	−55	−54	−54	−54	−54	−54	−54	−53	−53	−40	−55	−56	−56	−57	−57	−56	−59	−62	−64	−67	−0.8
051	h	7	1	−45	−46	−47	−48	−49	−50	−51	−52	−52	−45	−35	−50	−55	−61	−70	−77	−82	−83	−80	−77	0.8
052	g	7	2	0	0	1	2	2	3	4	4	4	0	2	2	5	4	1	1	2	3	2	1	−0.6
053	h	7	2	−13	−14	−14	−14	−14	−14	−15	−17	−18	−18	−17	−24	−28	−27	−27	−26	−27	−27	−26	−25	0.2
054	g	7	3	34	33	32	31	29	27	25	23	20	0	1	10	15	13	14	16	21	24	26	29	0.6
055	h	7	3	−10	−11	−12	−12	−13	−14	−14	−14	−14	2	0	−4	−6	−2	−4	−5	−5	−2	0	3	0.6
056	g	7	4	−41	−41	−40	−38	−37	−35	−34	−33	−31	−29	−40	−32	−32	−26	−22	−14	−12	−6	−1	4	1.2
057	h	7	4	−1	0	1	2	4	5	6	7	7	6	10	8	7	6	8	10	16	20	21	22	−0.4
058	g	7	5	−21	−20	−19	−18	−16	−14	−12	−11	−9	−10	−7	−11	−7	−6	−2	0	1	4	5	8	0.1
059	h	7	5	28	28	28	28	28	29	29	29	29	28	36	28	23	26	23	22	18	17	17	16	0.0
060	g	7	6	18	18	18	19	19	19	18	18	17	15	5	9	17	13	13	12	11	10	9	10	0.2
061	h	7	6	−12	−12	−13	−15	−16	−17	−18	−19	−20	−17	−18	−20	−18	−23	−23	−23	−23	−23	−23	−23	−0.3
062	g	7	7	6	6	6	6	6	6	6	6	5	29	19	18	8	1	−2	−5	−2	0	0	−2	−0.6
063	h	7	7	−22	−22	−22	−22	−22	−21	−20	−19	−19	−22	−16	−18	−17	−12	−11	−12	−10	−7	−4	−3	0.0
064	g	8	0	11	11	11	11	11	11	11	11	11	13	22	11	15	13	14	14	18	21	23	24	0.3
065	g	8	1	8	8	8	8	7	7	7	7	7	7	15	9	6	5	6	6	6	6	5	4	−0.2
066	h	8	1	8	8	8	8	8	8	8	8	8	12	5	10	11	7	7	6	7	8	10	12	0.4
067	g	8	2	−4	−4	−4	−4	−3	−3	−3	−3	−3	−8	−4	−6	−4	−4	−2	−1	0	0	−1	−1	0.1
068	h	8	2	−14	−15	−15	−15	−15	−15	−15	−15	−14	−21	−22	−15	−14	−12	−15	−16	−18	−19	−19	−20	−0.2
069	g	8	3	−9	−9	−9	−9	−9	−9	−9	−9	−10	−5	−1	−14	−11	−14	−13	−12	−11	−11	−10	−9	0.4
070	h	8	3	7	7	6	6	6	6	5	5	5	−12	0	5	7	9	6	4	4	5	6	7	0.2
071	g	8	4	1	1	1	2	2	2	2	1	1	9	11	6	2	0	−3	−8	−7	−9	−12	−14	−1.1
072	h	8	4	−13	−13	−13	−13	−14	−14	−14	−15	−15	−7	−21	−23	−18	−16	−17	−19	−22	−23	−22	−21	0.7
073	g	8	5	2	2	2	3	4	4	5	6	6	7	15	10	10	8	5	4	4	4	3	4	0.3
074	h	8	5	5	5	5	5	5	5	5	5	5	2	−8	3	4	4	6	6	9	11	12	12	0.0
075	g	8	6	−9	−8	−8	−8	−7	−7	−6	−6	−5	−10	−13	−7	−5	−1	0	0	3	4	4	5	0.2
076	h	8	6	16	16	16	16	17	17	18	18	19	18	17	23	23	24	21	18	16	14	12	10	−1.2
077	g	8	7	5	5	5	6	6	7	8	8	9	7	5	6	10	11	11	10	6	4	2	0	−0.9
078	h	8	7	−5	−5	−5	−5	−5	−5	−5	−5	−5	3	−4	−4	1	−3	−6	−10	−13	−15	−16	−17	−0.7
079	g	8	8	8	8	8	8	8	8	8	7	7	2	−1	9	8	4	3	1	−1	−4	−6	−7	−0.3
080	h	8	8	−18	−18	−18	−18	−19	−19	−19	−19	−19	−11	−17	−13	−20	−17	−16	−17	−15	−11	−10	−10	−0.6

Table 5. (continued).

	g/h	n	m	IGRF	IGRF	IGRF	IGRF	IGRF	IGRF	IGRF	IGRF	IGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	IGRF	
				1900	1905	1910	1915	1920	1925	1930	1935	1940	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990	1995	SV
081	g	9	0	8	8	8	8	8	8	8	8	8	5	3	4	4	8	8	7	5	5	4	4	0.0
082	g	9	1	10	10	10	10	10	10	10	10	10	−21	−7	9	6	10	10	10	10	10	9	9	0.0
083	h	9	1	−20	−20	−20	−20	−20	−20	−20	−20	−21	−27	−24	−11	−18	−22	−21	−21	−21	−21	−20	−19	0.0
084	g	9	2	1	1	1	1	1	1	1	1	1	1	−1	−4	0	2	2	2	1	1	1	1	0.0
085	h	9	2	14	14	14	14	14	14	14	15	15	17	19	12	12	15	16	16	16	15	15	15	0.0
086	g	9	3	−11	−11	−11	−11	−11	−11	−12	−12	−12	−11	−25	−5	−9	−13	−12	−12	−12	−12	−12	−12	0.0
087	h	9	3	5	5	5	5	5	5	5	5	5	29	12	7	2	7	6	7	9	9	11	11	0.0
088	g	9	4	12	12	12	12	12	12	12	11	11	3	10	2	1	10	10	10	9	9	9	9	0.0
089	h	9	4	−3	−3	−3	−3	−3	−3	−3	−3	−3	−9	2	6	0	−4	−4	−4	−5	−6	−7	−7	0.0
090	g	9	5	1	1	1	1	1	1	1	1	1	16	5	4	4	−1	−1	−1	−3	−3	−4	−4	0.0
091	h	9	5	−2	−2	−2	−2	−2	−2	−2	−3	−3	4	2	−2	−3	−5	−5	−5	−6	−6	−7	−7	0.0
092	g	9	6	−2	−2	−2	−2	−2	−2	−2	−2	−2	−3	−5	1	−1	−1	0	−1	−1	−1	−2	−2	0.0
093	h	9	6	8	8	8	8	9	9	9	9	9	9	8	10	9	10	10	10	9	9	9	9	0.0
094	g	9	7	2	2	2	2	2	2	3	3	3	−4	−2	2	−2	5	3	4	7	7	7	7	0.0
095	h	9	7	10	10	10	10	10	10	10	11	11	6	8	7	8	10	11	11	10	9	8	7	0.0
096	g	9	8	−1	0	0	0	0	0	0	0	1	−3	3	2	3	1	1	1	2	1	1	0	0.0
097	h	9	8	−2	−2	−2	−2	−2	−2	−2	−2	−2	1	−11	−6	0	−4	−2	−3	−6	−7	−7	−8	0.0
098	g	9	9	−1	−1	−1	−1	−1	−1	−2	−2	−2	−4	8	5	−1	−2	−1	−2	−5	−5	−6	−6	0.0
099	h	9	9	2	2	2	2	2	2	2	2	2	8	−7	5	5	1	1	1	2	2	2	1	0.0
100	g	10	0	−3	−3	−3	−3	−3	−3	−3	−3	−3	−3	−8	−3	1	−2	−3	−3	−4	−4	−3	−3	0.0
101	g	10	1	−4	−4	−4	−4	−4	−4	−4	−4	−4	11	4	−5	−3	−3	−3	−3	−4	−4	−4	−4	0.0
102	h	10	1	2	2	2	2	2	2	2	2	2	5	13	−4	4	2	1	1	1	1	2	2	0.0
103	g	10	2	2	2	2	2	2	2	2	2	2	1	−1	−1	4	2	2	2	2	3	2	2	0.0
104	h	10	2	1	1	1	1	1	1	1	1	1	1	−2	0	1	1	1	1	0	0	1	1	0.0
105	g	10	3	−5	−5	−5	−5	−5	−5	−5	−5	−5	2	13	2	0	−5	−5	−5	−5	−5	−5	−5	0.0
106	h	10	3	2	2	2	2	2	2	2	2	2	−20	−10	−8	0	2	3	3	3	3	3	3	0.0
107	g	10	4	−2	−2	−2	−2	−2	−2	−2	−2	−2	−5	−4	−3	−1	−2	−1	−2	−2	−2	−2	−2	0.0
108	h	10	4	6	6	6	6	6	6	6	6	6	−1	2	−2	2	6	4	4	6	6	6	6	0.0
109	g	10	5	6	6	6	6	6	6	6	6	6	−1	4	7	4	4	6	5	5	5	4	4	0.0
110	h	10	5	−4	−4	−4	−4	−4	−4	−4	−4	−4	−6	−3	−4	−5	−4	−4	−4	−4	−4	−4	−4	0.0
111	g	10	6	4	4	4	4	4	4	4	4	4	8	12	4	6	4	4	4	3	3	3	3	0.0
112	h	10	6	0	0	0	0	0	0	0	0	0	6	6	1	1	0	0	−1	0	0	0	0	0.0
113	g	10	7	0	0	0	0	0	0	0	0	0	−1	3	−2	1	0	1	1	1	1	1	1	0.0
114	h	10	7	−2	−2	−2	−2	−2	−2	−2	−1	−1	−4	−3	−3	−1	−2	−1	−1	−1	−1	−2	−2	0.0
115	g	10	8	2	2	2	1	1	1	1	2	2	−3	2	6	−1	2	0	0	2	2	3	3	0.0
116	h	10	8	4	4	4	4	4	4	4	4	4	−2	6	7	6	3	3	3	4	4	3	3	0.0
117	g	10	9	2	2	2	2	3	3	3	3	3	5	10	−2	2	2	3	3	3	3	3	3	0.0
118	h	10	9	0	0	0	0	0	0	0	0	0	0	11	−1	0	0	1	1	0	0	−1	−1	0.0
119	g	10	10	0	0	0	0	0	0	0	0	0	−2	3	0	0	0	−1	−1	0	0	0	0	0.0
120	h	10	10	−6	−6	−6	−6	−6	−6	−6	−6	−6	−2	8	−3	−7	−6	−4	−5	−6	−6	−6	−6	0.0

*In units of nT for the main field and nT/yr for the secular variation.

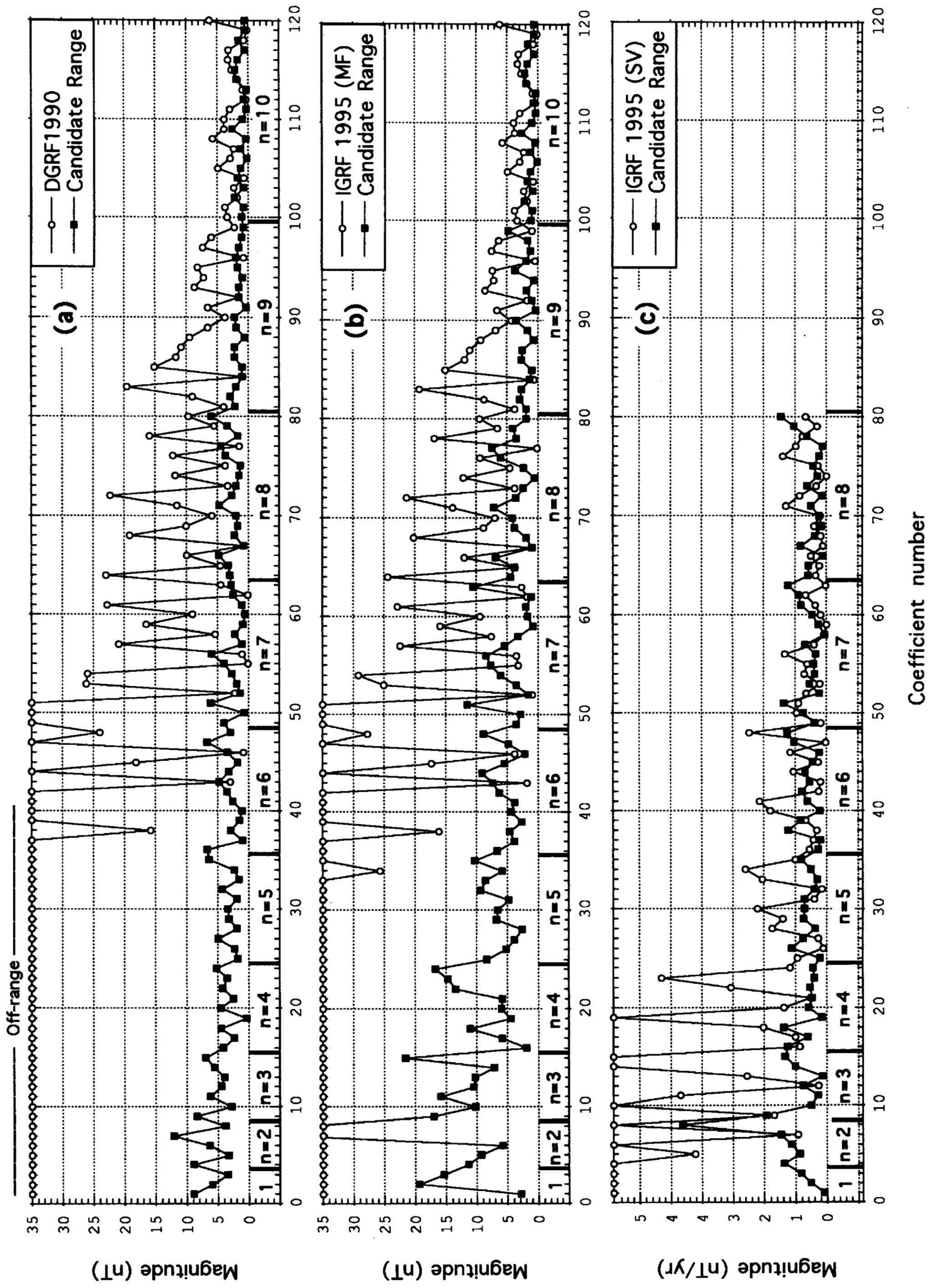

Fig. 1. Ranges of corresponding coefficients for IGRF candidate models for (a) DGRF 1990, (b) IGRF 1995 (MF), and (c) IGRF 1995 (SV), plotted as squares. The adopted IGRF coefficients are plotted as circles for comparison, with cutoffs at 35 nT and 6 nT/yr.

Table 6(a). Differences in F (coefficients rounded-unrounded) for IGRF 1995, in nT.

Lon. (°E) Lat. (°N)	000	015	030	045	060	075	090	105	120	135	150	165	180	195	210	225	240	255	270	285	300	315	330	345
80	−3	−5	−6	−7	−7	−7	−5	−3	−2	−1	−1	−1	−1	−2	−2	−2	−1	−1	0	0	0	0	−1	−2
70	−1	−2	−4	−5	−5	−3	1	5	8	9	8	5	1	−2	−2	−1	1	0	−1	−2	−1	1	1	1
60	−4	−2	1	−1	−4	−4	2	9	9	7	8	6	−1	−8	−5	1	2	−2	−5	−7	−7	−5	−3	−4
50	−7	−1	3	1	−8	−13	−3	7	3	−4	2	7	−1	−9	−3	7	5	−3	−3	−3	−6	−6	−4	−6
40	−7	−1	1	0	−9	−18	−7	7	1	−8	1	9	2	−4	5	13	5	−5	3	7	−1	−1	1	−6
30	−9	−3	−3	0	−3	−14	−6	6	1	−4	2	4	−2	−1	10	13	1	−8	5	11	−1	2	5	−8
20	−10	−5	−5	0	3	−5	−3	1	−1	−1	0	−6	−9	−2	6	5	−3	−8	5	8	−4	2	5	−9
10	−9	−4	−3	1	2	0	−1	−4	−4	−1	−2	−9	−8	−2	2	−1	−4	−4	6	7	−2	5	5	−7
0	−3	0	−1	0	−3	2	2	−6	−4	−1	0	−2	0	4	3	−1	−2	0	7	8	3	8	9	−1
−10	4	2	0	0	−7	5	9	−4	−1	3	4	5	8	11	7	3	2	1	4	5	3	7	9	4
−20	4	−1	−1	1	−6	8	12	−4	2	8	3	2	7	8	7	7	3	−3	−2	0	−1	2	2	1
−30	−2	−4	−1	3	0	8	4	−8	3	9	−4	−9	−4	−1	2	5	1	−8	−8	−4	−2	−2	−6	−6
−40	1	2	2	1	0	2	−5	−11	1	5	−9	−16	−9	−3	0	1	−4	−11	−9	−3	2	1	−5	−5
−50	8	8	2	−4	−4	−3	−4	−4	2	1	−8	−11	−3	5	7	3	−3	−6	−3	2	4	2	−1	2
−60	2	2	−2	−5	−3	0	3	3	2	−3	−9	−7	1	10	12	9	5	3	3	3	1	−3	−5	−2
−70	−6	−4	−3	−2	0	3	4	2	−2	−7	−10	−8	−3	4	8	10	9	8	6	2	−2	−6	−8	−8
−80	−4	−3	−2	−1	−1	−1	−1	−3	−5	−6	−7	−6	−4	−2	1	3	4	4	3	1	−1	−3	−4	−4

Table 6(b). Differences in Z (coefficients rounded-unrounded) for IGRF 1995, in nT.

Lon. (°E) Lat. (°N)	000	015	030	045	060	075	090	105	120	135	150	165	180	195	210	225	240	255	270	285	300	315	330	345
80	−3	−5	−6	−7	−8	−7	−5	−3	−2	0	0	0	−1	−2	−2	−2	−1	−1	−1	0	0	0	−1	−2
70	−1	−2	−3	−5	−5	−3	1	6	8	9	9	6	1	−2	−3	−1	1	0	−1	−2	−1	0	1	0
60	−5	−2	1	0	−5	−6	1	9	8	5	7	6	−1	−9	−6	2	3	−1	−5	−7	−8	−6	−4	−5
50	−8	−1	3	2	−9	−16	−5	7	1	−7	1	8	−1	−10	−2	10	7	−3	−2	−1	−6	−5	−4	−8
40	−8	−1	0	1	−7	−19	−8	8	−1	−9	0	7	0	−5	8	17	6	−6	4	10	−1	1	3	−8
30	−8	−1	−6	1	3	−10	−4	6	−3	−2	1	−5	−8	−3	10	14	0	−10	7	12	−3	5	6	−13
20	1	5	−7	1	9	−1	3	0	−11	3	−1	−15	−9	−3	4	5	−3	−8	7	9	−5	7	4	−12
10	14	11	−3	0	5	−1	7	0	−14	6	−1	−7	6	0	1	5	2	−2	6	9	1	8	1	−3
0	15	8	0	−2	3	−3	5	7	−5	7	0	3	16	−1	2	13	9	1	0	4	5	4	−7	2
−10	2	1	0	−1	9	−4	−6	8	1	2	−3	−1	3	−12	−1	12	8	−1	−9	−5	2	−5	−15	−4
−20	−5	1	1	−1	10	−7	−14	5	−2	−8	−5	−6	−10	−16	−5	1	1	0	−9	−7	1	−5	−11	−6
−30	1	5	3	−3	2	−8	−9	7	−3	−11	2	5	−2	−5	−4	−6	−1	6	1	0	3	0	2	4
−40	0	0	−1	−2	−1	−4	3	11	−2	−7	9	15	8	2	0	−2	5	13	9	3	0	−1	5	6
−50	−7	−9	−4	2	4	2	4	5	−2	−2	9	12	3	−5	−5	0	7	11	6	−1	−5	−4	1	0
−60	−4	−6	−1	4	4	1	−2	−3	−2	3	9	7	−3	−11	−12	−7	−2	0	−2	−4	−3	1	4	1
−70	5	3	3	2	1	−2	−4	−2	2	7	10	8	1	−5	−9	−10	−9	−7	−5	−2	2	7	9	8
−80	5	4	3	2	1	1	1	2	4	6	6	6	3	1	−2	−4	−4	−4	−2	0	2	4	6	6

Table 7. Some reference ellipsoids.

Ellipsoid	a (km)	$1/f$
Clarke, 1866	6378.206	294.98
International, IAG, 1924	6378.388	297.00
Krassovsky, 1942	6378.245	298.30
International Astronomical Union (IAU), 1966	6378.160	298.25
Geodetic Reference System (GRS), 1967	6378.160	298.247167427
Geodetic Reference System (GRS), 1980	6378.137	298.257222101
WGS, 1972	6378.135	298.26
WGS, 1984	6378.137	298.257223563

The justification for these choices of truncation and rounding is illustrated by the range of corresponding coefficients of the candidate models (all of which were deemed to be acceptable models). The magnitudes of these ranges are shown in Figs. 1(a), (b), and (c) (squares) for the candidate models for each of DGRF 1990, IGRF 1995 (MF), and IGRF 1995 (SV). The adopted coefficients are also plotted for comparison (circles; large coefficients are plotted at cutoffs of 35 nT for the MF and 6 nT/yr for the SV). The coefficient number is the sequence number as it appears in Table 5. With only two candidate models, the SV results should be treated with caution. A coefficient is essentially unresolved when the range is comparable to the value of the coefficient. This condition is common at about $N = 10$ for the main field and about $N = 8$ for the secular variation. Since all the candidate models contribute substantially to the adopted values (equal weights for DGRF 1990 and IGRF 1995-MF, and 40/60 weights for the SV model), it is clear that truncation levels beyond $N = 10$ (MF) and $N = 8$ (SV) are not meaningful.

It is also clear that it is meaningless to quote the MF coefficients to a precision greater than the nearest nT and the SV coefficients to better than the nearest 0.1 nT. The effect of rounding to these levels is illustrated in Table 6, which shows grid-point differences of total field (F) and vertical field (Z) computed for IGRF 1995 before and after rounding the coefficients. The differences are typically several nT, with peak magnitudes of 18 and 19 nT, respectively. These differences are significant for certain applications but are, nevertheless, small compared to the scatter in F- and Z-values given by the different candidate models.

7. Effect of Different Reference Ellipsoids

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 flattening 1/298.25. Some commonly-used ellipsoids are listed in Table 7. Given the semi-major axis (a) and the flattening (f), the semi-minor axis (b) can be derived from $b = a(1 - f)$. Many users of IGRF will be blissfully unaware of what reference ellipsoid was used to produce their site coordinates, and, indeed, the reference ellipsoid of some of the data used in the production of the IGRF is ignored. An approximate idea of the magnitude of the field differences caused by the use of different ellipsoids is given by Table 8. The values tabulated are differences between computations, using the Clark 1866 ellipsoid and the IAU 1966 ellipsoid, of the total field (F) and vertical field (Z) in nT at 10° grid-points for DGRF 1990. The magnitudes of the differences range up to 6 nT toward the polar regions and are no more than a few nT at middle and low latitudes. Such differences are very small compared to the accuracy of the IGRF.

8. One Hundred Years in the Life of the Main Field

Between 1900 and 1940, the IGRF varies smoothly, being based on the single time-dependent GSFC (S95-sc) model (the secular variation in this model is represented by cubic B-splines over time, the splines

Table 8(a). Differences in F (Clark, 1866–IAU, 1966) using different ellipsoids for DGRF 1990, in nT.

Lon. (°E) Lat. (°N)	000	015	030	045	060	075	090	105	120	135	150	165	180	195	210	225	240	255	270	285	300	315	330	345
80	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	4	4
70	3	3	3	4	4	5	5	5	5	5	4	4	4	4	4	4	5	5	5	5	4	4	4	3
60	2	2	3	3	3	4	4	4	4	3	3	2	2	2	3	3	4	4	4	4	3	3	3	2
50	1	1	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2	2	2	2	2	1	1
40	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	–1	0	–1	0	–1	–1	–1	–1	–1	–1	–1	–1	0	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1
20	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1
10	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1
0	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1
–10	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	0	0	0	0	0	–1
–20	0	0	0	0	0	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	0	0	0	0	0	0
–30	0	1	0	0	0	0	0	0	–1	–1	–1	–1	–1	–1	–1	–1	–1	0	0	0	0	0	0	0
–40	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
–50	0	0	0	0	1	2	2	3	3	3	2	2	2	2	1	1	1	1	0	0	0	0	0	0
–60	0	0	0	1	2	3	4	4	5	5	4	4	4	3	3	3	3	2	1	1	1	0	0	0
–70	1	2	2	2	3	4	5	5	6	6	6	6	5	5	5	5	4	4	3	3	2	2	2	2
–80	3	3	4	4	4	5	5	6	6	6	6	6	6	6	6	6	5	5	5	4	4	4	4	3

Table 8(b). Differences in Z (Clark, 1866–IAU, 1966) using different ellipsoids for DGRF 1990, in nT.

Lon. (°E) Lat. (°N)	000	015	030	045	060	075	090	105	120	135	150	165	180	195	210	225	240	255	270	285	300	315	330	345
80	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	4	4
70	3	3	3	3	4	4	5	5	5	4	4	3	3	3	4	4	5	5	5	4	4	4	3	3
60	2	2	2	2	2	3	3	3	3	2	2	1	1	1	2	3	3	4	4	3	3	2	2	2
50	0	0	0	0	0	1	1	1	1	0	–1	–1	–1	–1	0	0	1	1	2	1	1	0	0	0
40	–2	–2	–2	–1	–2	–2	–2	–2	–2	–2	–2	–2	–2	–2	–2	–2	–1	–1	–1	–1	–1	–1	–2	–2
30	–3	–3	–3	–3	–3	–3	–3	–3	–3	–3	–3	–2	–2	–2	–2	–2	–2	–2	–2	–2	–2	–2	–3	–3
20	–3	–3	–3	–3	–3	–3	–3	–3	–3	–3	–2	–2	–2	–2	–2	–2	–2	–3	–2	–2	–2	–2	–2	–3
10	–1	–1	–2	–2	–2	–2	–2	–2	–2	–2	–1	–1	–1	–1	–1	–1	–1	–2	–2	–2	–1	–1	–1	–1
0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
–10	1	1	1	1	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1
–20	1	1	1	1	1	2	2	3	3	3	3	3	3	3	2	2	2	2	2	2	1	1	1	1
–30	0	0	0	0	1	1	1	2	2	2	2	2	2	3	3	2	2	2	2	2	1	1	1	0
–40	0	0	0	0	0	0	0	0	0	1	1	1	1	1	2	2	2	2	2	2	1	1	0	0
–50	0	0	1	0	0	–1	–2	–2	–2	–2	–1	–1	–1	0	0	0	0	1	1	2	2	1	1	0
–60	0	0	0	0	–1	–2	–3	–4	–4	–4	–4	–4	–3	–3	–2	–2	–1	–1	0	1	1	1	1	0
–70	0	0	–1	–1	–2	–3	–4	–5	–6	–6	–6	–6	–5	–5	–5	–4	–4	–3	–2	–1	–1	–1	0	0
–80	–3	–3	–3	–3	–4	–4	–5	–5	–6	–6	–6	–6	–6	–6	–6	–5	–5	–5	–4	–4	–3	–3	–3	–3

having equally-spaced knots from 1900 to 1995 at 2.5-year intervals for internal terms of degree 1–8 and for the 1st-degree external terms, 5-year intervals for degree 9–10, and 10-year intervals for degree 11–13). This contrasts with models for 1945 onward, which were adopted with a view to obtaining the best fit to the available data at discrete 5-year epochs with little or no regard to continuity.

The consequences of these different methods of derivation are illustrated in Fig. 2, which shows the variation of each MF coefficient during this century, grouped by degree up to $n = 8$. The coefficients change smoothly up to $n = 3$. Steps between 1940 and 1945 are detectable at $n = 4$, and become more prominent (in percentage terms) as n increases. These higher-degree coefficients vary somewhat irregularly between 1940 and about 1960, followed by an interval of smoother variation to the end of the century (the vertical scale of the plots is expanded as the degree increases, which amplifies the apparent irregularities). Plots are not shown for $n > 8$ since the percentage variations of the coefficients are large, but have relatively little effect on the main features of the field pattern.

The irregularities are more evident in plots of first differences, as shown in Fig. 3. Differences are expressed as the average annual change of a coefficient over the intervals between 5-year epochs. These plots again show that the IGRF changes smoothly from 1900 to 1940, more irregularly between 1940 and about 1960 (particularly between 1940 and 1945), then relatively smoothly again after about 1960. The irregularities are sufficiently large to mask any evidence of geomagnetic jerks.

An animation of the seventh generation IGRF secular-variation pattern during this century was produced in order to examine the behaviour and continuity of the field. As expected from Fig. 3, the field changes gradually and smoothly up to about 1940, displays considerably more variability thence to about 1960–1965, and changes relatively smoothly thereafter. This variability can be gauged from Figs. 4 and 5, in which the annual changes in F and Y are compared at the end points of the initial smooth interval (1900–1940), the disturbed interval (approximately 1940–1960), and the subsequent smoother interval (1960–2000).

The animation shows that the most prominent characteristics of the variation of the main field during the 20th century are growth and decay of features of the field. Superimposed on this, but much less prominent, is a longitudinal drift of some of those features, most going westward and a few eastward, combined with northward or southward drift of some others. This is consistent with the results of animations of longer spherical harmonic time sequences at the Earth's surface (Thompson, 1984) and at the core-mantle boundary (Bloxham *et al.*, 1991).

Sabaka *et al.* (1997) consider the behaviour of the continuous GSFC (S95-sc) model from 1900 to 1995. They compare their model with continuous model ufm1 (Bloxham and Jackson, 1992), examine the evidence for geomagnetic jerks, and discuss the correlation between westward drift and decade variations in the length of day. GSFC (S95-sc) forms the basis of the GSFC candidate models, so its properties are similar to those of the seventh generation IGRF.

9. Distribution of the SV

The range and distribution of the secular variation in F (denoted by dF) over the Earth's surface are shown in Fig. 6 for IGRF 1900 and IGRF 1995. The distribution is for dF calculated at $1° \times 1°$ grid points, using a spherical Earth approximation for calculating areas. The histograms show the area of the Earth's surface for which dF falls within 5 nT/yr bins. The offset of the distributions from zero reflects the decay of the dominant dipole terms (indeed, the offset is approximately equal to the annual change in g_1^0). Several changes in the distribution have occurred since 1900. First, the range of dF has shifted toward more positive values (from −140 to 40 nT/yr in 1900 to −120 to 60 nT/yr in 1995). Second, the distribution has remained non-Gaussian with a bias tailing toward large negative values, but this bias is less pronounced now than in 1900. Third, the distribution in 1900 was more clustered about the median value, and has since spread out with twin peaks developing at about −25 and 5 nT/yr.

The lower panel in Fig. 6 shows the cumulative percentage of the Earth's surface over which dF is below (or above) the value shown on the horizontal axis. The diagram can be used to determine the fraction

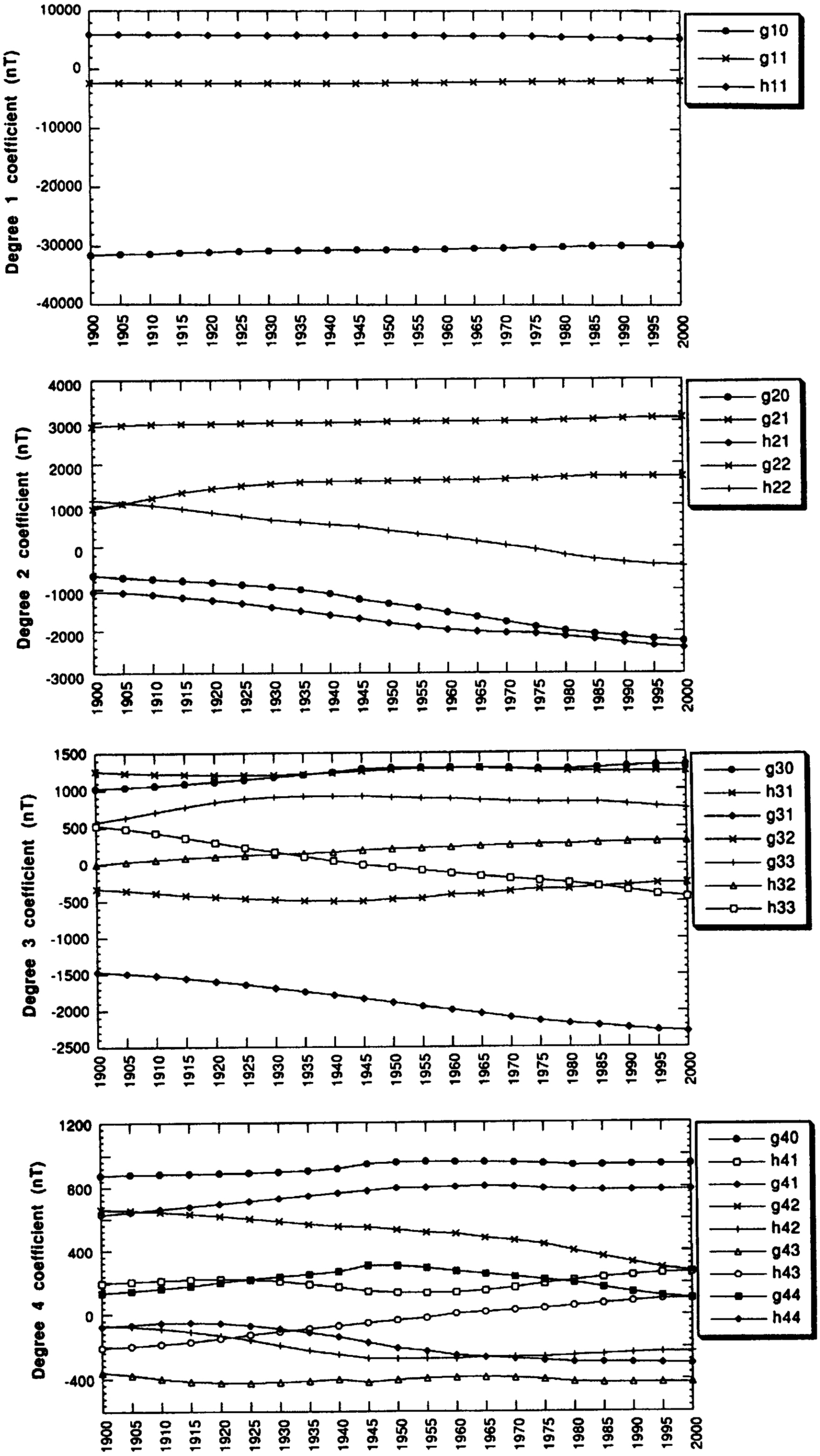

Fig. 2. The variation of each seventh generation IGRF coefficient during this century, grouped by degree up to $n = 8$.

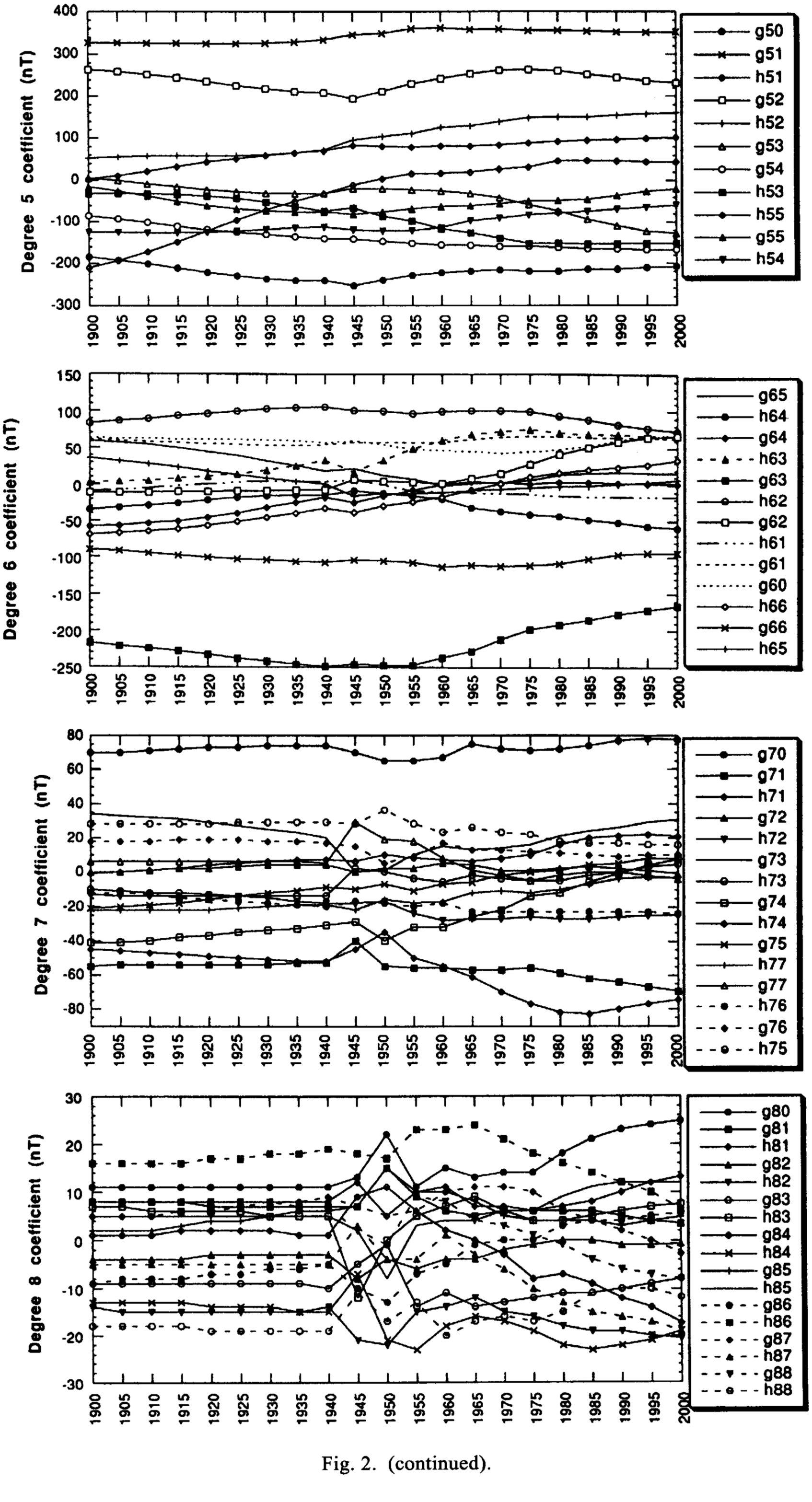

Fig. 2. (continued).

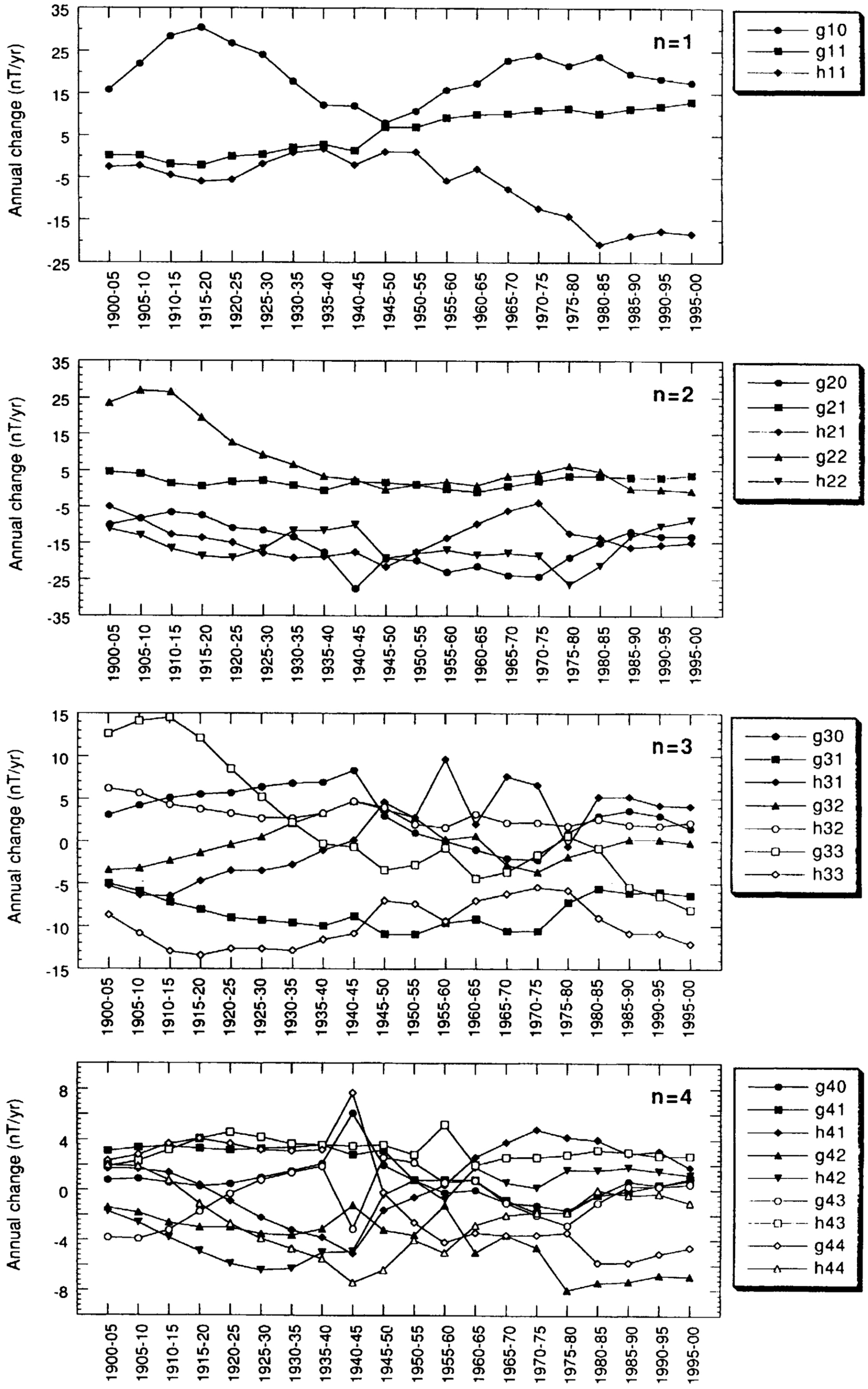

Fig. 3. First differences between successive epochs of coefficients of the seventh generation IGRF. Differences are expressed as the average annual change of each coefficient between 5-year epochs.

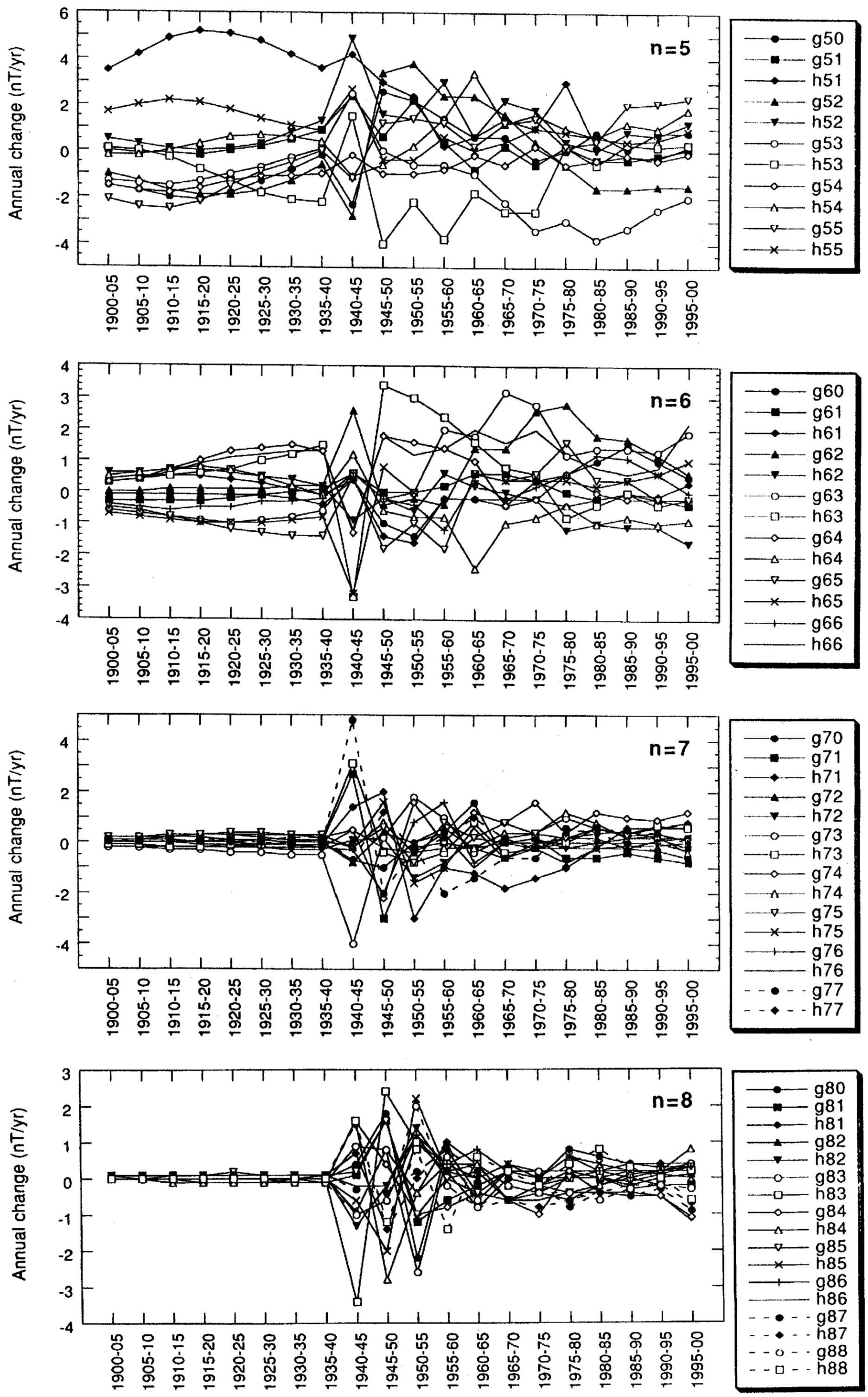

Fig. 3. (continued).

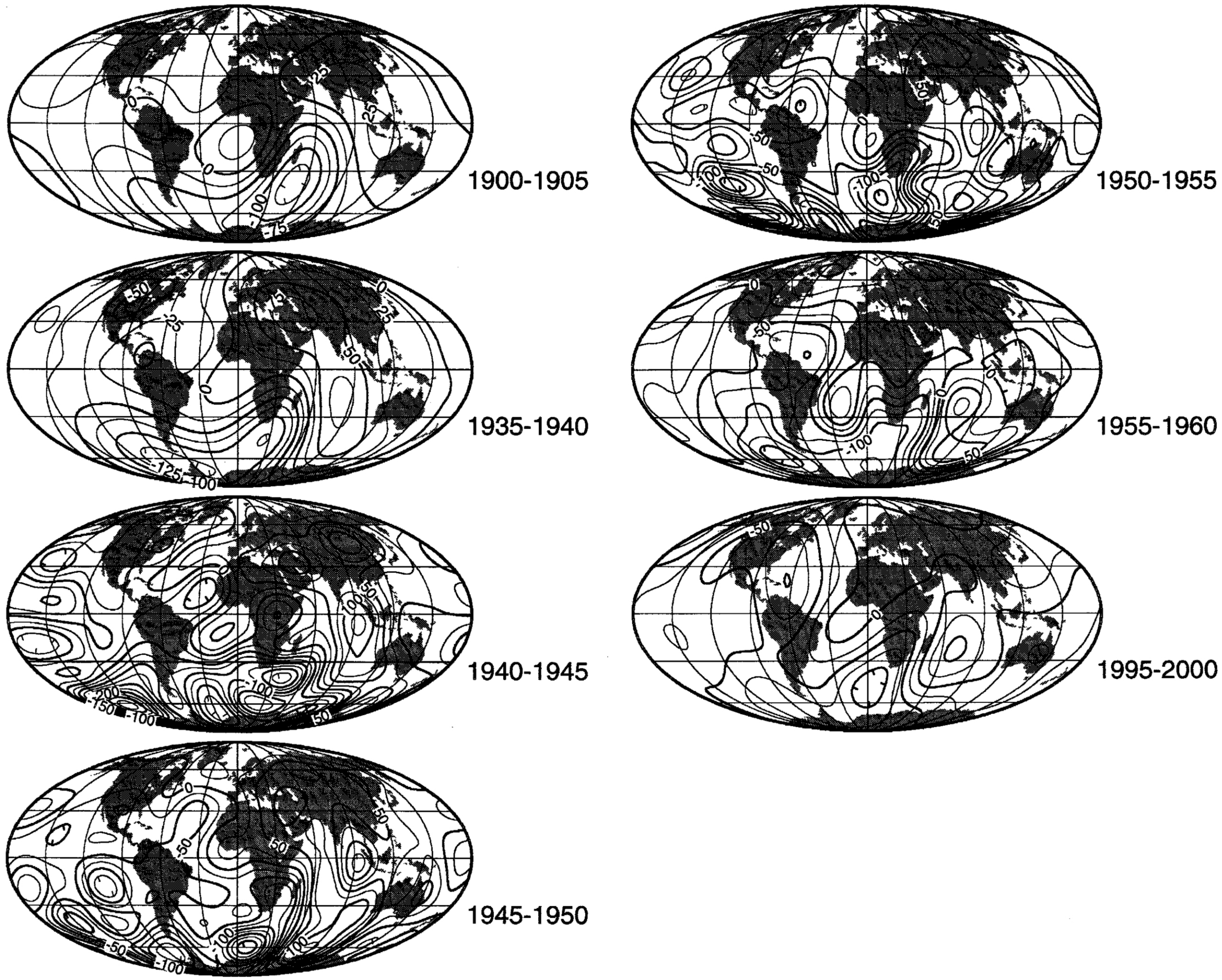

Fig. 4. Maps of the secular change in F during this century, given by the seventh generation IGRF. Images for the 5-year intervals from 1905 to 1935 are omitted as the field evolves smoothly between the two end configurations; the same applies from 1960 to 2000, although the variation is less smooth than for the earlier interval.

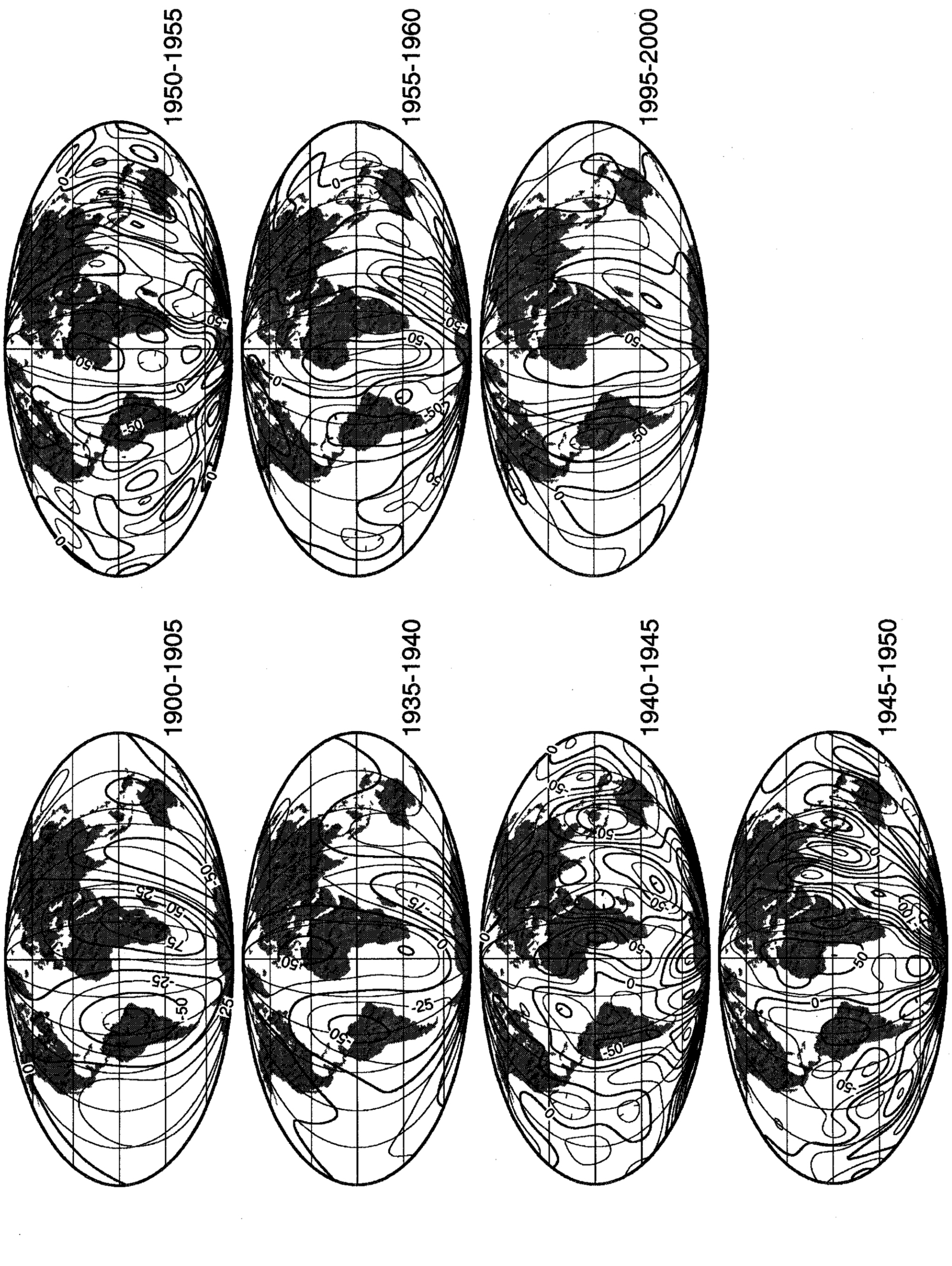

Fig. 5. Same as Fig. 4, but for the secular change in *Y*.

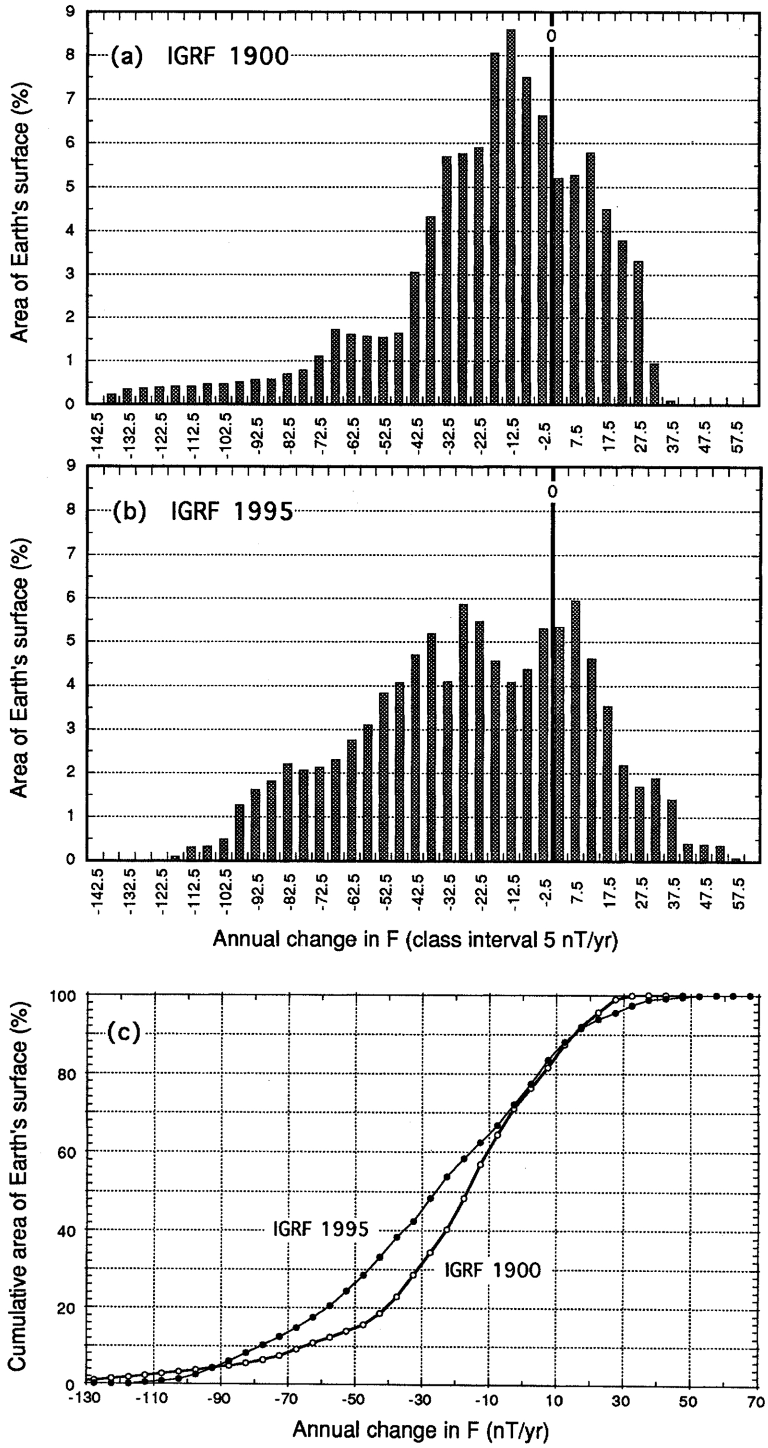

Fig. 6. Distribution over the Earth's surface of the IGRF annual change in F (dF, nT/yr) in 1900 and 1995. (a) and (b) show the area of the Earth's surface for which dF lies within 5 nT/yr intervals; (c) shows the same information as a cumulative area plot. The analysis was done using dF evaluated at $1° \times 1°$ grid points and a spherical Earth approximation for calculating areas.

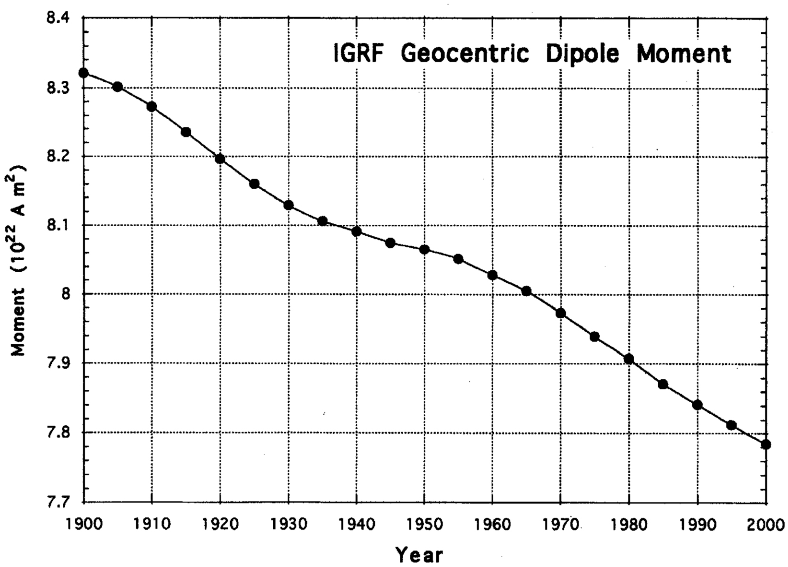

Fig. 7. Decay of the dipole moment of the Earth, as determined from the IGRF.

of the Earth's surface for which dF lies within a particular range. For example, the absolute value of dF for 1995 is less than 10 nT/yr over about 20% of the Earth's surface.

10. The Earth's Dipole Moment

The geocentric dipole moment (M) is given by the first three Gauss coefficients. In SI units,

$$M = \frac{4\pi a^3}{\mu_0}\sqrt{\left(g_1^0\right)^2 + \left(g_1^1\right)^2 + \left(h_1^1\right)^2}. \tag{3}$$

A steady decrease of M during historic and recent times has long been noted (e.g., McDonald and Gunst, 1967). This is reflected in Fig. 7, which shows that M given by the seventh generation IGRF has decreased by 6.5% since 1900. The rate of decrease was about 0.69×10^{22} A m^2 per century from 1900 to 1930, slowed to about 0.26×10^{22} from 1935 to 1955, and has been linear during the past 30 years at 0.625×10^{22} A m^2 per century. At the present rate of decrease, M would become zero about 1250 years hence. Since the Earth's dipole appears to be recovering from an historical high reached about 2000 years ago (e.g., McElhinny and Senanayake, 1982), the decrease of the dipole moment should not be taken as evidence of an impending polarity reversal.

11. The Geomagnetic and Magnetic Poles

The geomagnetic poles, where the geocentric dipole axis intersects the surface of the Earth, are also given by the first three Gauss coefficients:

$$\tan \lambda_S = \frac{g_1^0}{\sqrt{\left(g_1^1\right)^2 + \left(h_1^1\right)^2}}, \quad \tan \phi_S = \frac{h_1^1}{g_1^1}, \tag{4}$$

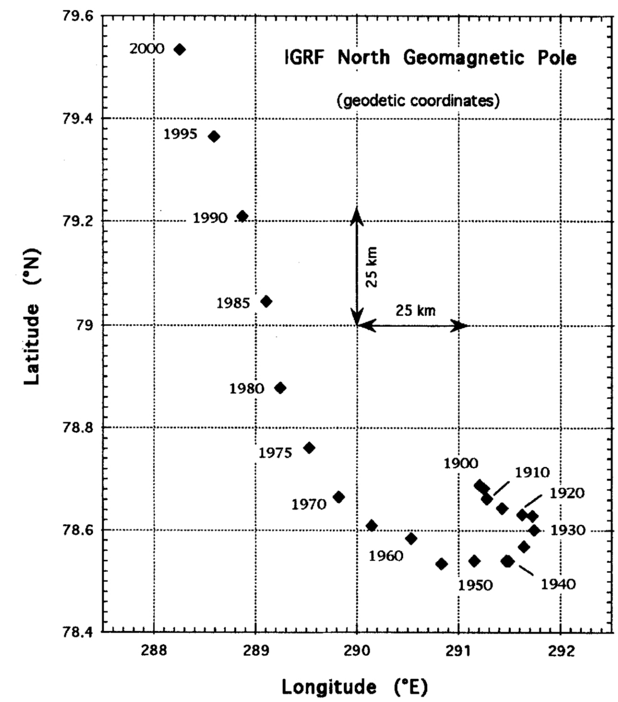

Fig. 8. Locus of the North Geomagnetic Pole for the seventh generation IGRF. Geodetic (spheroidal) coordinates are used.

where λ_S and ϕ_S are the geocentric latitude and longitude of the South Geomagnetic Pole in degrees (the North Geomagnetic Pole being antipodal to the South). The locus of the North Geomagnetic Pole is shown in Fig. 8; latitudes have been converted to geodetic (spheroidal) coordinates. The geomagnetic axis precessed uniformly clockwise during the first half of this century, followed by a more rapid translation in a near polarward direction in recent times. The tilt of the geomagnetic axis away from the geographic axis reached a maximum of 11.54° in 1955, dropped back to 10.7° by 1995, and is projected to be 10.5° in the year 2000.

The magnetic (dip) poles of the Earth are the principal points on the surface where the magnetic inclination is 90°. These have to be computed iteratively and are shown in Fig. 9. Both IGRF dip poles have moved approximately northward during this century, but the IGRF North Magnetic Pole appears to be accelerating (presently moving at 21 km/yr on a bearing of N 19°W), whereas the IGRF South Magnetic Pole is slowing down (presently moving at 5 km/yr on a bearing of N 27°W). Relatively erratic movements of the two poles occur near mid-century, though not simultaneously—notably from 1955 to 1975 for the North Magnetic Pole and from 1940 to 1950 for the South Magnetic Pole. The 1969/1970 geomagnetic jerk appears not to be resolved.

12. Is a Single, Continuous Time-Dependent IGRF Model Needed?

Hitherto, IGRF models have been developed as a series of discrete 5-yearly epoch models. The system has worked well as it readily accommodates new epoch models for forward and backward extension in time, and the replacement of IGRF-designated models by their DGRF counterparts. The disadvantage is that discontinuities in the first derivative of the field are introduced at the 5-year epoch boundaries, which are physically implausible and invite treatment (e.g., Alldredge, 1985, 1988). The

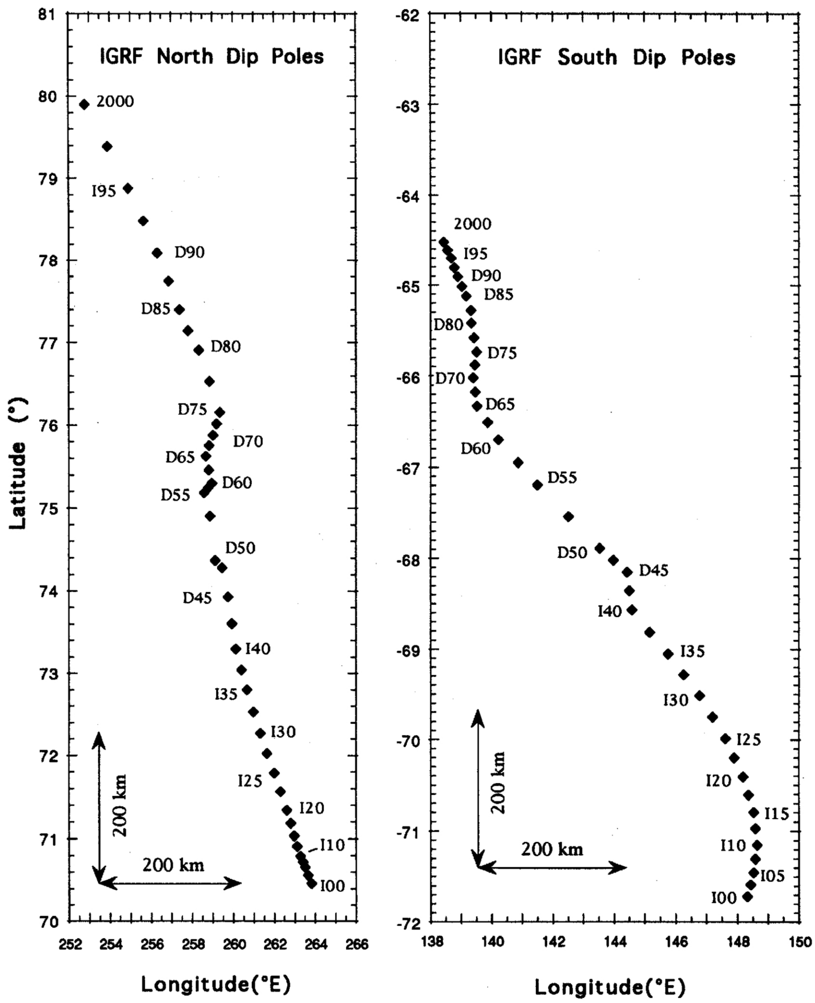

Fig. 9. Locus of the IGRF North and South Magnetic (dip) Poles for the seventh generation IGRF. Latitudes are in geodetic (spheroidal) coordinates. I00, I05, ··· denotes IGRF 1900, IGRF 1905, ···, and D45, D50, ··· denotes DGRF 1945, DGRF 1950, ···.

GSFC series of candidate models was derived from a single continuous field model with time-dependent terms, GSFC (S95-sc), by extracting coefficients for a particular epoch and truncating to $N = 10$ to conform to the traditional IGRF formulation (Sabaka *et al.*, 1997). These authors, Andrew Jackson, Frank Lowes, and several other luminaries have pointed out that this process degrades the information in the original model and provides an unsatisfactory basis for describing the temporal behaviour of the geomagnetic field. The WG discussed the case for developing a continuous IGRF model as a replacement for, or in addition to, the existing IGRF formulation. The disadvantage of a continuous model is that any extension in time or resolution requires recomputation of all the coefficients. This is unsatisfactory for applications that require a fixed reference standard (e.g., reduction of aeromagnetic survey data to obtain anomaly values). A continuous model is physically plausible, would appeal to persons studying the temporal variation (see Sabaka *et al.*, 1997), and would be convenient to use. WG V-8 resolved not to pursue this approach for the 1995 revision of the IGRF, but to re-consider it in 1997.

13. Conclusions

The seventh generation of the IGRF substantially enlarges IAGA's standard description of the Earth's main field to cover the interval 1900 to 2000. The traditional formulation is retained. With the inclusion of the newly-adopted models, the IGRF now consists of a set of "IGRF" models at 5-year intervals from 1900 to 1940, the existing "DGRF" models at 5-year intervals from 1945 to 1985, the new DGRF 1990 model that replaces IGRF 1990, and the new IGRF 1995 model with SV terms for forward continuation of the 1995 field to the year 2000.0. Coefficients for dates between the 5-year epochs are obtained by linear interpolation between corresponding coefficients for neighbouring 5-year epochs. The field defined by linear interpolation between the latest DGRF model, now DGRF 1990, and the subsequent IGRF model, now IGRF 1995, is termed a provisional IGRF (PGRF). This nomenclature may also be applied to the field obtained by interpolation between IGRF 1940 and DGRF 1945. The IGRF 1995 model will be superseded when a definitive model of the main field at 1995.0 is adopted at some later date. Similarly, the IGRF models for 1900 to 1940 may be revised later.

The field pattern depicted by the IGRF varies smoothly from 1900 to about 1940, and again from about 1960 or 1965 onward. The field defined by the IGRF is more variable between these intervals. The advantages a single time-dependent model to cover the whole interval covered by the IGRF are recognized by WG V-8, and merit further consideration by the international community.

Files of the IGRF coefficients and computer programs for synthesizing field components are available from the World Wide Web, the World Data Centers, cooperating national geomagnetic observatory agencies and geological surveys throughout the world, and IAGA Working Group V-8. Some relevant electronic addresses are listed below.

NOAA, WDC-A, World Wide Web	http://www.ngdc.noaa.gov/seg/potfld/igrf95.html
British Geological Survey, Edinburgh	http://ub.nmh.ac.uk/gifs/igrf.html
Australian Geological Survey, Canberra	http://www.agso.gov.au/geophysics/geomag/igrf.html
World Data Center A: Solid Earth Geophysics, Colorado	info@ngdc.noaa.gov
World Data Center-B2, Moscow	sgc@adonis.iasnet.com
World Data Centre C1: Geomagnetism, Edinburgh	drbar@wpo.nerc.ac.uk
World Data Center-C2: Geomagnetism, Kyoto University	request@kugi.kyoto-u.ac.jp
World Data Center A: Rockets and Satellites, NASA/GSFC	request@nssdca.gsfc.nasa.gov
IAGA Working Group V-8	cbarton@agso.gov.au

IGRF is produced by IAGA Division V, Working Group V-8: *Analysis of the Global and Regional Geomagnetic Field and its Secular Variation*; participating members: R. T. Baldwin, D. R. Barraclough, C. E. Barton, S. Bushati, M. Chiappini, Y. Cohen, R. Coleman, G. Hulot, P. Kotzé, V. P. Golovkov, A. Jackson, R. A. Langel, F. J. Lowes, D. J. McKnight, S. Macmillan, L. R. Newitt, N. W. Peddie, J. M. Quinn, and T. J. Sabaka. The Chairman of IAGA Division V was D. J. Kerridge. Production of the IGRF depends on the efforts of the staff of magnetic observatories and survey organisations world-wide, and the free-interchange of data. I thank Bob Langel, David Barraclough, Susan Macmillan, and another referee for their helpful comments. Andrew Lewis prepared Figs. 4 and 5 and Timothy Patrick produced the IGRF animations. This paper is published with permission from the Executive Director, Australian Geological Survey Organisation.

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