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Spatial-temporal modeling of the geomagnetic field for 1980–2000 period and a candidate IGRF secular-variation model for 2000–2005

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A new generation of the IZMST series (STM—space-time models based on data from observatories, POGS and Ørsted) was developed as a model of the main geomagnetic field from 1980.0 up to 2000.0. A set of the natural orthogonal components (NOCs) was used as the basic time functions. The NOCs were derived from data series from 23 observatories widely distributed on the globe. These series were extrapolated by hand from epochs 1997.0 or 1998.0 to 2000.0. The data set for the spherical harmonic analyse included observed vector values from the worldwide network of observatories, synthesized F values at 700 km, computed from WMM92.5, and X, Y, Z values computed from IGRF 2000. Depending on the data used, this gave a series of models called STM-XXX. These models were then compared with WMM92.5 (based partly on POGS data) and with IGRF 2000.0 (based entirely on Ørsted data). This comparison shows a rather good agreement over the globe except for the vector components of the field in the Southeast Pacific and Indian Oceans. Adding the Ørsted data to the database decreased this disagreement. The observatory biases, derived from STM OPE (Observatories, POGS, Ørsted) are stable over the whole time interval. Also reported in this paper is the derivation of a candidate IGRF secular-variation model for the 2000.0–2005.0 period.

1. Introduction

The International Geomagnetic Reference Field (IGRF) is a series of spherical harmonic (SH) models of the main geomagnetic field up to "a degree and order useful for adequate representation of the data" (Alldredge, 1971).

The first IGRF model was developed for the 1965 epoch (Zmuda, 1971). Data from the first satellite magnetic survey (Cosmos-49), from the magnetic observatory network and from near-Earth surface surveys were utilized for the potential analysis (Cain *et al.*, 1967; Orlov, 1967). The same kinds of data, including data from OGO and POGO missions were utilized in the next generations of the IGRF family up to and including the third generation IGRF (Peddie and Fabiano, 1982; Peddie, 1983).

At this time those responsible for developing the IGRF recognized that "adequate representation of data" does not guarantee the uniqueness of the SH expansion of the geomagnetic potential (Lowes, 1975; Backus, 1968, 1970) because of the nonpotential character of the scalar total force data widely used in the models.

The Backus effect can be significantly reduced by joint use of satellite scalar and observatory vector data of comparable accuracy (Barraclough and Nevitt, 1976; Lowes and Martin, 1987), but at that time the observatory annual means contained both the main field and the crustal field at an observatory location. The root mean square (RMS) of the latter is about 200 nT, therefore we can estimate the accuracy of the model to be only a few hundred nT in spite of the very high accuracy of both satellite and observatory measurements.

The fourth generation of the IGRF was adopted at the IAGA General Assembly of 1985 (Barraclough, 1987). The DGRF 1980 was identical to the GSFC (12/83) model (Langel and Estes, 1985) but truncated at degree and order 10. This model is based mainly on vector data from the Magsat spacecraft. The dense global coverage and the high accuracy of the Magsat data allowed the development of a precise potential model using mainly satellite data.

The GSFC (12/83) model was used to determine the biases at magnetic observatories. The accuracy of this determination is about the same as the model accuracy and can be estimated as a few tens of nT. By subtracting the biases we can obtain main-field values at the observatory location with the same accuracy.

Using these "improved" data from observatories jointly with scalar data from the POGS magnetic survey satellite, Quinn and coworkers developed an IGRF1995 candidate model (Quinn *et al.*, 1995). RMS misfits of the data to this model were about 10–20 nT. But the problem of the uniqueness of the potential model was not solved.

Up to the present time we have had a combination of high-quality, well-distributed scalar data with high quality, badly distributed vector data. But large areas of the oceans at low latitudes and especially in the southern hemisphere are lacking in observatory data and for some of the IGRF epochs are lacking in satellite survey data. We cannot guarantee a good approximation of the real core field potential over these regions for each IGRF epoch, using the usual technique of the SH expansion.

To overcome this problem Langel *et al.* (1982) proposed a method for the joint use of scalar data from satellites and vec-

Table 1. Names and coordinates of the 23 observatories, used for NOC analysis (columns 1–3). Columns 4–6 contain RMS (σ) residuals between NOC model and the observations; units are nT.

Name	Latitudes	Longitudes	σ_x	σ_y	σ_z
Sitka	57.06	224.67	3.3	3.2	8.7
Meanook	54.62	246.65	5.3	2.8	5.4
Patrony	52.10	104.27	3.9	2.4	6.0
Niemegk	52.07	12.67	3.5	3.0	6.3
Hartland	50.99	355.52	4.8	2.2	5.3
Memambetsu	43.91	144.19	3.7	1.8	5.4
Coimbra	40.22	351.58	10.4	4.2	6.6
Tucson	32.257	249.17	5.0	6.4	6.8
Honolulu	21.32	202.00	5.7	1.8	5.8
Gnangara	−31.78	115.95	6.2	2.4	6.1
Hermanus	−34.42	19.22	6.4	8.7	5.6
Macquarie Island	−54.50	158.95	7.9	5.0	8.4
Apia	−13.81	188.22	6.0	4.9	4.8
Vassouras	−22.40	316.35	8.7	4.7	4.8
Lunping	25.00	121.17	4.5	4.7	7.2
Thule	77.48	290.83	7.1	3.3	9.2
Godhavn	69.15	306.28	6.0	2.3	7.9
Uelen	66.17	190.17	6.6	8.4	12.0
Leirvogur	64.18	338.30	3.3	2.5	8.0
L'Aquila	42.23	13.19	2.6	1.6	5.3
Arti	56.43	58.57	4.8	2.5	7.5
Alibag	18.64	72.87	5.5	5.0	6.9
Sodankylä	67.37	26.63	3.9	2.8	7.9

tor data from magnetic observatories in space-time modeling. The Magsat-based model was used as a reference model for other satellite surveys and 1980 was used as a reference epoch for data from magnetic observatories. Residuals of data with respect to the reference model/epoch were expanded in Taylor polynomials in time and in spherical harmonics in space. The model gives a sufficiently uniform distribution of data misfits in time.

The same approach was used by Golovkov *et al.* (1997) for space-time modeling expanding the SH coefficients in natural orthogonal components (NOCs). We expected that the use of satellite data for different epochs in the space-time analysis would reduce the uncertainty of the model over the whole globe, including southern hemisphere ocean areas.

The space-time models described here were developed using the same technique as in Golovkov *et al.* (1997). These models cover the time interval from 1980 to 2000 and utilize different combinations of data from magnetic observatories and from the satellites Magsat (1979–1980), POGS (1991–1993) and Ørsted. The models described in this paper include the STM OP model, which was the IZMIRAN candidate model for IGRF 2000; this model did not include any Ørsted data. The family of models produced allows the testing of the method as well as estimation of the accuracy of a potential model over areas lacking vector data. From these space-time models the models on epoch 2000.0 were derived and compared with the Ørsted based IGRF 2000.0 model (Mandea and Macmillan, 2000; Olsen *et al.*, 2000).

2. The Description of the Method

Given the geometry of the Earth, spherical harmonic analysis is a natural choice for the production of global models. Assuming that the SH expansion coefficients are functions of time, a four-dimensional model can be developed.

$$U(r,\theta,\lambda,t) = a \cdot \sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n+1}\Big(g_n^m(t)\cos m\lambda + h_n^m(t)\sin m\lambda\Big)\cdot P_n^m(\cos\theta) \quad (1)$$

where a is the mean radius of the Earth; $P_n^m(\cos\theta)$ is the associated Legendre function of degree n and order m, normalized according to the convention of Schmidt; and g_n^m, h_n^m are functions depending only on time. The g_n^m and h_n^m are expanded in time as follows:

$$g_n^m = \sum_{k=1}^{K}\mathbf{g}_{nk}^m T_k(t); \qquad h_n^m = \sum_{k=1}^{K}\mathbf{h}_{nk}^m T_k(t). \quad (2)$$

Where $\mathbf{g}_{nk}^m$ and $\mathbf{h}_{nk}^m$ are constant.

Thus we can rewrite (1) as follows:

$$U(r,\theta,\lambda,t) = a \cdot \sum_{k=1}^{\infty} T_k(t)\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n+1}$$

$$\cdot\left(\mathbf{g}_{nk}^{m}\cos m\lambda+\mathbf{h}_{nk}^{m}\sin m\lambda\right)\cdot P_n^m(\cos\theta). \quad (3)$$

Choosing the correct temporal functions permits shorter temporal expansions and smaller effective errors due to truncation of the expansion. Cain *et al.* (1967) and Langel *et al.* (1982) have taken $T_k = (t - t_0)^{k-1}$ Other approaches for obtaining such functions have been made by Golovkov and Chernova (1988) and by Golovkov *et al.* (1994). They adopted the natural orthogonal component (NOC) analysis for the investigation of the geomagnetic secular variation.

The main idea of the NOC analysis is as follows. If we have a number of time series of data, which can be described by a rectangular matrix, in which each line $j \in [1, J]$ contains elements $H_{ij} (i \in [1, I])$, they can be represented as

$$H_{ij}=\sum_{k=1}^{K} C_{kj}\cdot T_{ki} \quad (4)$$

where C_{kj} do not depend on time and T_{ki} do not depend on position.

The solution of Eq. (4) is discussed by Langel (1987). The algorithm for the solution is derived from the conditions of orthogonality:

$$\sum_j C_{kj}\cdot C_{lj}\begin{cases}=0 & if \quad k\neq 0\\ \neq 0 & if \quad k=l\end{cases}$$

$$\sum_j T_{ki}\cdot T_{li}\begin{cases}=0 & if \quad k\neq 0\\ \neq 0 & if \quad k=l\end{cases}.$$

It allows us to obtain both families of numerical functions C_{kj} and T_{ki} which are natural in contrast to the "artificial" analytical functions. The T_{ki} are the basic temporal functions of the expansion (4). The product of C_{kj} on T_{ki} is the kth natural orthogonal component of the jth data series.

In our application of the NOC method to geomagnetic data we will apply (4) to the potential of (3), so the same NOC time functions $T_k(t)$ apply to each field component. But to obtain T_{ki} needs the joint NOC analysis of observed X, Y, and Z components of the magnetic field which are used as independent time series. Therefore the indices j of H_{ij} in (4) are different for each component. This means that j does not indicate a point in space, but only the number of a row in the data matrix.

At point p at the epoch t_i.

$$X_{ij}=\frac{1}{r}\cdot\frac{\partial U_{ip}}{\partial\theta}$$

$$Y_{iv}=-\frac{1}{r\sin\theta}\cdot\frac{\partial U_{ip}}{\partial\lambda}$$

$$Z_{iw}=-\frac{\partial U_{ip}}{\partial r}. \quad (5)$$

The convergence of the series (4) is improved, if the series does not contain a large constant contribution. Choosing some epoch as a reference we use changes of the field relative to the reference values as data for both the NOC analysis, and the spatial analysis. Below these differences are denoted by ΔX, ΔY, ΔZ, and the corresponding potential change by ΔU; here $\Delta X = X - X_r$ etc., where X_r is the value at the reference epoch. Combining (3), (4), and (5) and substituting ΔX, ΔY, ΔZ and ΔU for X, Y, Z, U we can write:

$$\Delta X(r,\theta,\lambda,t)=\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{m=0}^{n}T_k(t)\Big(\mathbf{g}_{nk}^{m}\cos m\lambda +\mathbf{h}_{nk}^{m}\sin m\lambda\Big)\cdot\frac{dP_n^m(\theta)}{d\theta}\cdot\left(\frac{a}{r}\right)^{n+2}$$

$$\Delta Y(r,\theta,\lambda,t)=\frac{1}{\sin\theta}\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{m=0}^{n}T_k(t)m\Big(\mathbf{g}_{nk}^{m}\sin m\lambda -\mathbf{h}_{nk}^{m}\cos m\lambda\Big)\cdot P_n^m(\theta)\cdot\left(\frac{a}{r}\right)^{n+2}$$

$$\Delta Z(r,\theta,\lambda,t)=-\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{m=0}^{n}T_k(t)\cdot(n+1) \cdot\Big(\mathbf{g}_{nk}^{m}\cos m\lambda+\mathbf{h}_{nk}^{m}\sin m\lambda\Big)\cdot P_n^m(\theta)\left(\frac{a}{r}\right)^{n+2}. \quad (6)$$

In this form each of the Eqs. (6) corresponds to (4) taking into account that $T_{ki} = T_k(t)$ and the index i is the number of the epoch t.

We cannot use (6) directly as equations of condition to obtain the $\mathbf{g}_{nk}^m$, $\mathbf{h}_{nk}^m$ until we obtain the $T_k(t)$ independently. Langel *et al.* (1982) used "artificial" functions for this purpose, but we suggest finding the "natural" ones from (4). We need to make the assumption that the field variations at any point on the globe can be expanded using the same T_k as at the limited number of observatory locations chosen for the NOC

Table 2. Temporal functions obtained in the NOC analysis; dimensionless units.

Year	T_1	T_2	T_3
1981	−247.1	−88.7	31.8
1982	−512.9	−180.7	41.9
1983	−782.7	−248.4	59.0
1984	−1057.7	−297.1	84.0
1985	−1324.9	−335.0	102.5
1986	−1580.8	−359.4	111.8
1987	−1832.7	−363.2	105.7
1988	−2079.7	−353.5	75.3
1989	−2331.1	−347.6	19.8
1990	−2583.8	−325.3	−26.5
1991	−2836.1	−280.3	−74.7
1992	−3091.0	−223.3	−117.6
1993	−3346.4	−156.7	−134.3
1994	−3618.2	−89.7	−134.0
1995	−3900.6	−14.5	−106.4
1996	−4181.1	86.2	−49.0
1997	−4471.6	190.9	−9.3
1998	−4769.6	282.6	37.3
1999	−5049.6	382.5	83.7
2000	−5331.0	484.7	143.3

Table 3. SH coefficients of the STM OPE model; units are 10^{-2} nT, and corresponding full SH coefficients at 2000.0, units nT.

		NOC1		NOC2		NOC3		Full STM OPE 2000	
n	m	$\mathbf{g}_{n1}^{m}$	$\mathbf{h}_{n1}^{m}$	$\mathbf{g}_{n2}^{m}$	$\mathbf{h}_{n2}^{m}$	$\mathbf{g}_{n3}^{m}$	$\mathbf{h}_{n3}^{m}$	g_n^m	h_n^m
1	0	−7.630	0.000	−5.830	0.000	−0.885	0.000	−29614.8	.0
1	1	−4.199	7.760	2.151	−0.279	−2.739	−1.110	−1725.7	5187.4
2	0	5.205	0.000	2.409	0.000	−2.727	0.000	−2266.7	.0
2	1	−0.978	6.203	−1.088	−2.476	0.168	−3.890	3074.1	−2477.3
2	2	−0.706	5.428	−5.020	7.774	−0.956	−3.499	1674.9	−456.7
3	0	−1.205	0.000	−1.140	0.000	1.595	0.000	1342.0	.0
3	1	2.091	−2.043	−0.098	−1.771	3.115	3.626	−2287.5	−230.5
3	2	0.093	−0.697	1.288	−1.335	1.207	−2.729	1254.0	297.8
3	3	1.840	4.402	−4.948	−2.130	3.762	2.810	716.3	−493.0
4	0	−0.069	0.000	−1.075	0.000	−1.940	0.000	933.7	.0
4	1	−0.041	−1.214	1.415	−0.104	−3.436	−4.160	786.1	270.3
4	2	2.762	−0.449	−0.965	0.437	3.702	−0.799	251.4	−232.1
4	3	−0.081	−1.236	2.016	0.050	−0.233	−0.375	−405.2	118.6
4	4	2.093	0.036	2.814	−1.129	6.584	0.800	110.5	−303.2
5	0	−0.083	0.000	0.788	0.000	−4.564	0.000	−216.3	.0
5	1	0.169	0.036	−0.218	−0.359	1.511	1.615	349.1	44.7
5	2	0.694	−0.332	1.400	−0.277	−5.622	4.161	222.7	172.3
5	3	1.246	−0.093	2.228	2.336	−0.884	−0.623	−130.9	−135.6
5	4	0.042	−0.520	−0.699	1.392	−1.049	1.730	−169.1	−41.1
5	5	−0.732	−0.364	1.133	−0.553	−5.295	−1.081	−11.1	107.2
6	0	−0.458	0.000	−0.712	0.000	2.710	0.000	72.8	.0
6	1	−0.014	0.028	−0.487	−0.943	2.034	3.103	67.3	−16.6
6	2	−0.575	0.491	−0.963	0.208	3.150	−2.989	72.5	63.5
6	3	−0.589	0.017	−1.125	−1.308	3.700	1.049	−160.8	65.3
6	4	0.081	0.278	−0.246	−0.802	−2.593	0.509	−5.2	−61.0
6	5	−0.114	−0.100	−0.726	0.501	0.217	−2.888	16.9	1.6
6	6	−0.425	−0.337	−0.456	0.524	−1.981	4.510	−90.4	44.0
7	0	−0.202	0.000	−0.763	0.000	0.267	0.000	79.5	.0
7	1	0.287	−0.242	0.650	2.003	−2.715	−3.721	−75.0	−64.7
7	2	−0.011	−0.057	−1.082	0.348	1.300	−1.237	−.8	−24.0
7	3	−0.234	−0.218	0.825	0.308	−3.204	−0.936	32.9	6.8
7	4	−0.468	−0.140	−0.918	1.014	0.561	−3.196	9.3	23.8
7	5	−0.115	0.090	−0.299	−0.186	0.693	2.144	6.7	15.4
7	6	0.079	−0.026	0.308	−0.223	−0.174	−1.951	8.0	−25.5
7	7	0.044	−0.172	−0.202	−0.802	2.870	−0.504	−1.2	−5.4
8	0	−0.175	0.000	0.103	0.000	−1.344	0.000	25.9	.0
8	1	0.009	−0.172	−0.062	−0.492	0.804	−1.363	6.4	11.8
8	2	0.152	0.091	0.504	−0.495	−2.431	2.305	−9.1	−21.9
8	3	−0.059	−0.047	0.089	0.566	0.100	−0.685	−7.3	8.3
8	4	0.212	−0.039	−0.138	−1.032	1.194	2.477	−17.3	−21.4
8	5	0.004	−0.067	1.643	0.151	−1.838	1.469	9.1	15.4
8	6	−0.111	0.160	−0.454	0.332	0.231	−0.393	7.0	8.5
8	7	0.268	0.063	0.122	−0.163	0.026	1.270	−7.7	−15.3
8	8	0.108	−0.265	0.295	0.154	−1.593	−1.759	−7.6	−2.6
9	0	0.005	0.000	0.135	0.000	0.080	0.000	5.5	.0
9	1	0.047	−0.055	0.113	−0.519	0.770	0.564	9.1	−19.8

Table 3. (continued).

		NOC1		NOC2		NOC3		Full STM OPE 2000	
n	m	$\mathbf{g}_{n1}^m$	$\mathbf{h}_{n1}^m$	$\mathbf{g}_{n2}^m$	$\mathbf{h}_{n2}^m$	$\mathbf{g}_{n3}^m$	$\mathbf{h}_{n3}^m$	g_n^m	h_n^m
9	2	−0.034	0.072	−0.421	0.407	1.317	−0.267	2.7	13.8
9	3	−0.089	−0.085	−0.445	−0.557	1.017	1.216	−8.0	12.6
9	4	0.055	0.039	0.436	0.246	−1.208	−0.087	6.5	−6.0
9	5	0.041	−0.006	−1.132	0.221	1.564	−2.039	−8.4	−7.5
9	6	−0.026	−0.041	−0.415	−0.887	0.254	0.940	−1.3	8.2
9	7	−0.065	0.112	0.286	−0.021	−1.652	−0.011	9.5	3.9
9	8	0.038	0.067	−0.515	0.198	−0.922	0.022	−3.8	−8.6
9	9	0.070	−0.008	−0.019	−0.120	0.436	1.904	−8.2	4.6
10	0	−0.015	0.000	−0.030	0.000	0.579	0.000	−2.5	.0
10	1	0.036	0.016	0.077	0.217	−0.369	0.216	−6.1	1.5
10	2	0.020	−0.033	−0.005	−0.248	0.165	−0.375	1.1	.0
10	3	−0.021	−0.052	0.444	−0.063	−0.713	−0.757	−2.8	4.4
10	4	0.002	0.038	0.005	0.380	0.832	−0.436	−.9	5.2
10	5	0.005	−0.006	0.132	−0.498	−0.716	0.283	4.3	−5.7
10	6	0.073	0.070	0.485	0.520	−0.164	−0.153	1.2	−1.4
10	7	−0.050	0.088	−0.451	0.531	0.181	0.227	1.7	−2.8
10	8	−0.019	0.066	−0.076	−0.431	1.281	1.221	4.5	.1
10	9	0.049	0.090	0.204	0.737	−0.135	−0.556	1.2	−2.0
10	10	0.023	0.013	−0.435	0.036	1.294	−0.540	−1.5	−7.3

Table 4. RMS (σ) year by year misfit of data from the observatories utilized in the models development, units are nT.

	STM O			STM OP			STM OE			STM OPE		
Year	σ_X	σ_Y	σ_Z	σ_X	σ_Y	σ_Z	σ_X	σ_Y	σ_Z	σ_X	σ_Y	σ_Z
1981	7.3	6.1	10.5	7.4	6.3	10.5	7.4	6.1	10.5	7.5	6.4	10.5
1982	10.9	8.8	12.3	10.8	8.9	12.3	11.1	8.8	13.6	11.3	8.9	13.6
1983	11.4	10.0	12.7	11.3	10.0	12.7	11.7	10.3	13.6	11.8	10.3	13.5
1984	11.2	9.2	12.3	11.2	9.3	12.3	11.2	9.3	12.2	11.3	9.3	12.2
1985	10.9	10.5	11.3	11.0	10.6	11.4	11.0	10.4	11.3	11.1	10.4	11.4
1986	13.1	10.1	13.3	13.1	10.0	13.3	13.3	10.3	13.7	13.3	10.3	13.8
1987	13.2	10.8	13.3	13.1	10.9	13.5	13.4	10.9	14.4	13.4	10.9	14.5
1988	14.1	11.7	17.8	14.2	11.6	17.9	14.2	12.0	18.5	14.3	11.9	18.7
1989	14.3	10.9	13.3	14.9	11.6	13.5	14.4	11.1	13.6	15.0	11.6	13.8
1990	14.5	11.6	14.3	15.5	12.7	14.7	15.1	12.3	14.6	15.8	13.1	15.3
1991	13.9	9.8	11.2	15.8	11.3	12.5	14.8	10.6	12.1	16.3	11.7	13.9
1992	13.3	9.8	11.9	15.3	11.4	12.3	13.8	10.5	12.8	15.5	12.5	13.5
1993	13.4	10.7	13.6	14.9	11.9	14.7	12.8	10.9	13.3	14.5	12.1	15.0
1994	12.4	10.4	13.9	14.1	10.9	14.9	12.8	9.8	14.1	14.6	10.8	15.7
1995	9.8	8.3	11.7	11.5	8.5	12.7	11.0	9.0	13.3	12.6	10.3	14.5
1996	9.6	9.5	10.7	10.4	9.5	11.2	13.4	11.0	16.2	13.4	11.7	16.3
1997	10.4	9.6	11.3	10.4	9.8	11.5	17.6	11.5	14.5	17.2	13.5	16.7
1998	9.5	8.3	12.6	9.4	8.8	13.3	15.5	11.7	17.4	14.5	11.8	18.0
1999	11.6	7.6	10.0	11.8	7.4	10.1	17.7	16.5	5.0	17.7	17.2	5.1
2000	14.7	10.7	13.9	15.6	10.4	15.3	4.7	5.1	7.5	5.0	5.2	7.7
Total	12.2	9.9	12.8	12.8	10.4	13.2	12.4	10.0	13.3	12.9	10.5	13.8

analysis. If we use T_k as the basic functions for the temporal expansion in the space-time modeling, we obtain the spatial distribution of the NOCs, described on the globe by the SH expansion. While the NOC functions are orthogonal over the 23 observatories, used to determine them, the SH representations of the different NOCs are not exactly orthogonal on the globe. But they can be approximately orthogonal on the globe if the observatories used in the NOC analysis are distributed on the globe randomly and uniformly (representative selection). This means that we have the opposite situation to that for spherical harmonics: the SHs are orthogonal on the globe and in general are not orthogonal on any set of data. But the use of the least-squares method can give us a good enough solution of the problem of space-time modeling.

The algorithm for spatial-temporal analysis must begin with choosing a set of observatories whose data represent secular variations of different nature. In other words we have to choose a set of observatories which cover the globe more or less uniformly and have uninterrupted series of annual means for the whole time interval. Their number must be sufficient to give good statistics when calculating all the independent values of T_k. Since we use a reference field model at epoch t_r in the spatial analysis we must represent the data at the chosen observatories as the differences between these data for epochs t and t_r.

Substituting $T_k(t)$, obtained in this way, in (6) we can use these equations as equations of condition for the spatial analysis.

To use the scalar data from satellites in the analysis the field intensity values have to be linearized. Taking into account the rather small changes in the field relative to its mean value during the 20 years time interval, we can use the first partial derivatives method of linearization

$$\Delta F = \frac{X_r}{F_r} \cdot \Delta X_r + \frac{Y_r}{F_r} \cdot \Delta Y_r + \frac{Z_r}{F_r} \cdot \Delta Z_r \qquad (7)$$

where X_r, Y_r, Z_r, and F_r are the values at the reference epoch, used for the NOC analysis and $\Delta F = F - F_r$, where F is the observed value taken from a satellite magnetic survey. Full coefficients of the SH model for the i th epoch can be calculated as follows:

$$g_{ni}^m = \mathbf{g}_{nr}^m + \sum_k \mathbf{g}_{nk}^m \cdot T_{ki}$$

$$h_{ni}^m = \mathbf{h}_{nr}^m + \sum_k \mathbf{h}_{nk}^m \cdot T_{ki}. \qquad (8)$$

3. NOC Analysis

As mentioned above, the database for the NOC analysis should be represented in the form of a rectangular matrix. This means that data from the chosen observatories should be represented as a continuous series from the earliest to the latest epoch for which the series is to be valid.

We have chosen 23 observatories having data satisfying the condition of wide distribution over the globe. Their names and coordinates are given in Table 1. Annual means of the three components X, Y, and Z from 1979.5 were used to prepare data for the analysis. In choosing the observatories we took into account the length of their time series. Most of them have data up to 1998 but some of them only to 1997 or earlier. We filled them up to and including 2000.5 by values extrapolated by hand.

For extrapolation, first differences were obtained by subtracting an annual mean from the annual mean of the next year. Series of first differences were plotted for the whole time interval from 1980.0 and extrapolated by hand to 2000.0. Extrapolated values (2 or 3 values for each series) were transformed back into annual means for epochs 1997.5 to 2000.5.

Taking into account that IGRFs are produced for epochs XXXX.0, the series of annual means were reduced to values at the beginning of a year by averaging two adjoining annual means. The resulting annual mean value for the reference epoch 1980.0 was then subtracted from the others obtained in this way to obtain the ΔX, ΔY, and ΔZ for the NOC analysis. The input data consisted of 1380 values: 23 observatories $\times$ 3 components $\times$ 20 epochs.

The results of the NOC analysis are given in the following tables. The three temporal functions are presented in Table 2. The accuracy of the NOC modeling for each observatory component series, as indicated by the RMS residuals, is shown in columns 4, 5 and 6 of Table 1.

It is necessary to note that the analytical functions $g_n^m(t)$,

Table 5. RMS residuals between the models and the total force data from POGS (WMM92.5) and Ørsted (quiet days of April 1999), units are nT.

Year	STM O	STM OP	STM OE	STM OPE
1992.0	48.2	—	48.0	—
1999.0	257.7	256.8	53.5	52.9

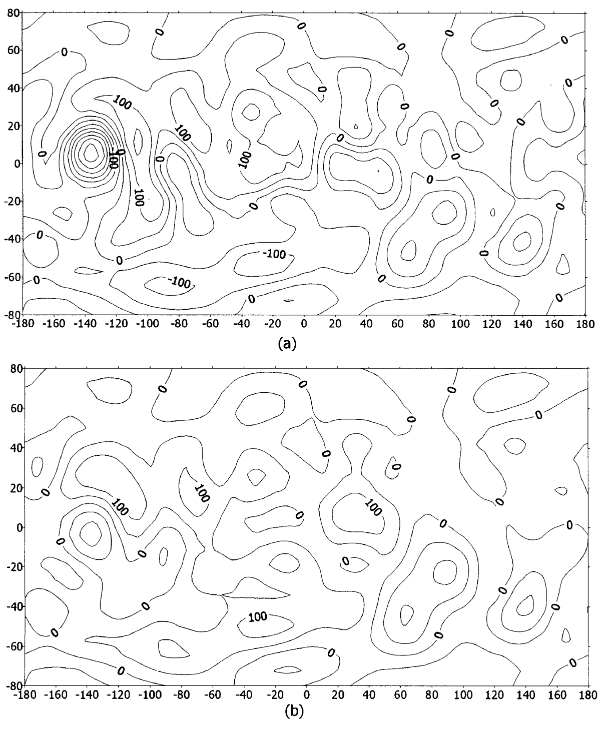

Fig. 1. Differences between STM OPE and WMM92. Units are nT; contour interval 50 nT, altitude 0 km. (a) Z or down component; (b) F or total intensity.

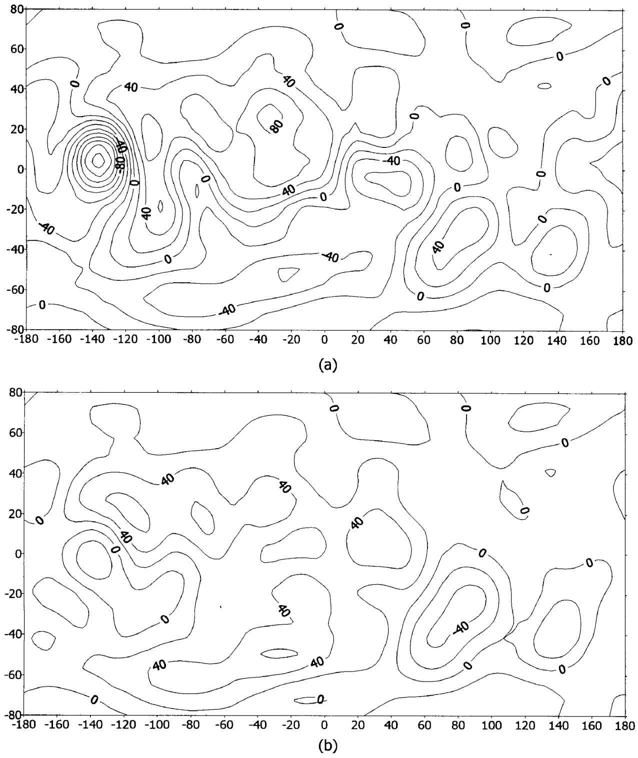

Fig. 2. Differences between STM OPE and WMM92. Units are nT; contour interval 20 nT, altitude 700 km. (a) Z or down component; (b) F or total intensity.

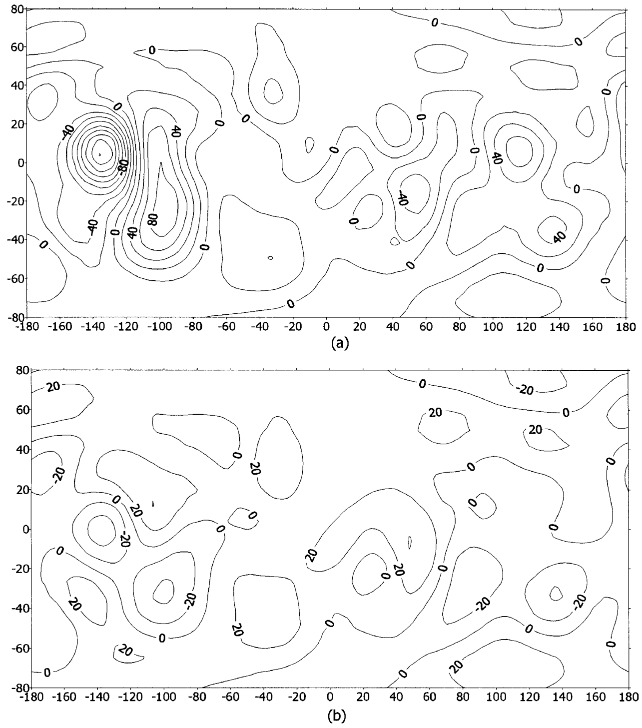

Fig. 4. Differences between STM OPE and IGRF1992. Units are nT; contour interval 20 nT, altitude 700 km. (a) Z or down component; (b) F or total intensity.

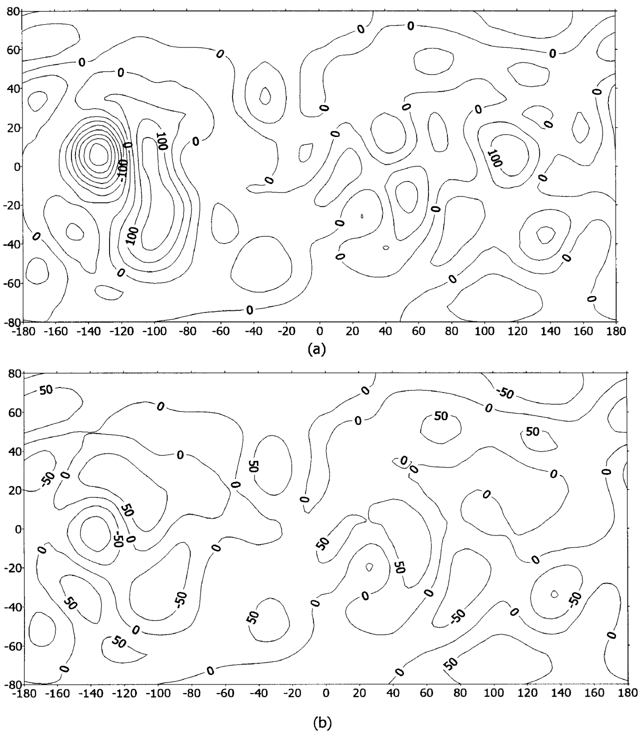

Fig. 3. Differences between STM OPE and IGRF1992. Units are nT; contour interval 50 nT, altitude 0 km. (a) Z or down component; (b) F or total intensity.

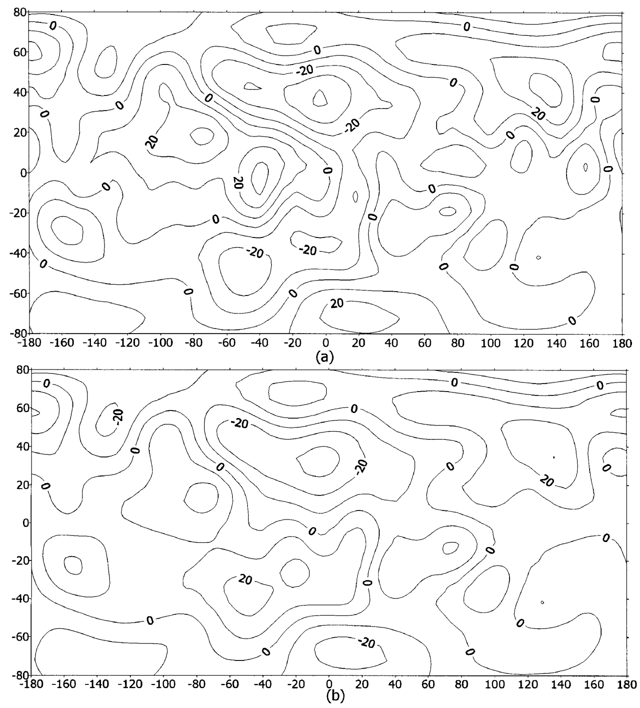

Fig. 5. Differences between STM OPE and IGRF2000. Units are nT; contour interval 10 nT, altitude 0 km. (a) Z or down component; (b) F or total intensity.

$h_n^m(t)$ are usually taken to depend on time in a linear or parabolic way, and that the $\dot{g}_n^m$, $\dot{h}_n^m$ are expressed in nT/yr and so on. But NOC analysis does not permit the direct expression in some units of either the temporal or spatial functions. Taking into account that the product $T_{ki} \times C_{kj}$ is expressed in nT we could refer this unit to either T_{ki} or C_{kj}. Since g_n^m and h_n^m in conventional SH analyses are expressed in units of nT we use the same units here for $\mathbf{g}_{nk}^m$ and $\mathbf{h}_{nk}^m$. The T_{ki} in Table 2 are expressed in dimensionless units.

It is shown by Langel (1987), (equation 321) that the contribution of each term of the expansion (4) is determined by

$$\lambda_k = \frac{1}{I} \cdot \sum_{i=1}^{I} \sum_{j=1}^{J} C_{kj}^2 \cdot T_{ki}^2. \tag{9}$$

Such determination of λ_k leads to obtaining C_{kj} limited by ± 1. In this case we obtain the magnitude of T_{ki} approximately proportional to its contribution to the data approximation.

The statistical significance of the T_{ki} over the whole time interval is shown by decreasing the data set for analysis to 12 observatories. Almost halving of the data set does not increase the RMS misfit of data series.

The use of extrapolated values for the last two or three years should not spoil the T_{ki} obtained with respect to those from observed data, taking into account the rather random distribution of the extrapolation errors on the set of analyzed time series. The T_{ki} reflect the common changes of the field and the randomly distributed errors in the data should not influence significantly the values of the T_{ki} if the statistics are good enough.

4. Spherical Harmonic Analysis

Annual means of observed values from 150 observatories, selected on the basis of their geographical positions, the length of the available time series and data quality were utilized for the analysis. Observatories were not used where a significant change (e.g. a shift of location, jump in baseline) was known to have occurred, or where the annual means for 1980 were missing. Some high quality observatories were not used in regions of high observatory density. These 150 observatories included the 23 observatories data from which were used for the NOC analysis. Annual means were reduced to epochs XXXX.0 in the same way as it was done for the NOC analysis.

Data from the POGS and Ørsted satellites were used indirectly in the form of pseudo-data, calculated from the WMM92.5 model (Quinn *et al.*, 1995) and from IGRF2000 (Mandea and Macmillan, 2000) at an altitude of 700 km, the mean altitude of the surveys. The POGS F pseudo-data were used to fill in over the oceans, but excluding high latitudes and within ±15 geographic latitude. This was done to reduce the influence of ionospheric electrojets.

There are reasons in favor of using pseudo-data rather than measured values from the satellite magnetic surveys. The main reason is that the measured values contain the effects of crustal magnetic anomalies and of external sources in the ionosphere and magnetosphere of the Earth whereas the models attempt to describe the main field only. The second reason is the need to subtract reference field values computed from a SH model. Choosing 1980.0 as the reference epoch, the natural choice of a reference model is the DGRF 1980.0. This model was used as the reference when calculating the ΔF of Eq. (8).

There is a difference between the chosen epoch XXXX.0 for the majority of data and that of WMM92.5. But taking into account the errors of both WMM92.5 and DGRF 1980, estimated as a few tens of nT each, the effect of half-year time shift seems to be admissible especially for ocean areas where we have no independent data. Using the WMM92.5 model, POGS F "data" were synthesized at an altitude of 700 km, the mean altitude of the survey. These "data" were used to fill in over the oceans, using a 10° by 10° grid, but excluding high latitudes $|\varphi| \leq 60°$ and a belt within ±15° geographic latitude −441 points in all. This exclusion was done to reduce the influence of ionospheric electrojets.

The IGRF model for 2000.0 (Mandea and Macmillan, 2000), which was based on Ørsted data, was used to synthesize (X, Y, Z) data on a 10° × 10° grid at the Earth's surface with the same exclusion as above. No weighting was done to simulate equal-area coverage. In addition, real Ørsted Overhauser magnetometer (OVH) F data, for the three quiet days of 19, 22, 23 April 1999, taking every fifth (nominal) second value from the night side of the orbit, were used as an independent data set for testing the models.

Different combinations of the data were used to develop a series of space-time models.

5. Models

All models are expressed in terms of Schmidt quasi-normalized associated Legendre functions and are referred to a sphere of radius 6371.2 km, the mean radius of the Earth. All data at zero altitude including those obtained from the IGRF 2000.0, are given relative to a spheroidal Earth with an equatorial radius of 6398.165 km and a reciprocal flattening of 298.25. All observed data from Ørsted are given at the survey altitude. The POGS pseudo-data are refered to a sphere of radius 7071.2 km the mean radius of the survey. Models were compared on these same two surfaces.

Four models were produced as follows:

- STM O, based only on vector data from observatories;
- STM OP, based on vector data from observatories and scalar pseudo-data from the WMM92.5 model (Quinn *et al.*, 1995);
- STM OE, based on vector data from observatories and from the IGRF 2000 model (Mandea and Macmillan, 2000);
- STM OPE, in which all three types of data were utilized.

The coefficients of the STM OPE and full coefficients for the epoch 2000.0 (Eq. (8)) model are presented in Table 3.

The RMS residuals of the data from observatories including extrapolated values for 1998.0 to 2000.0, with respect to the models are shown in Table 4 for each year. The residuals of independent data (i.e. not utilized in a particular model) with respect to that model are shown in Table 5. These data are the Overhauser scalar data from Ørsted (row 1999) and the scalar pseudo-data from WMM92.5 (row 1992). The set

Table 6. Global RMS residuals between models; units are nT.

Models	Altitude	σ_X	σ_Y	σ_Z	σ_F
STM OPE-WMM92.5	0	42.6	43.0	67.5	51.4
STM OPE-WMM92.5	700	20.4	19.8	33.4	25.0
STM OPE-IGRF92	0	33.5	43.3	59.9	39.7
STM OPE-IGRF92	700	15.1	20.8	28.7	16.7
WMM92.5-IGRF92	0	30.9	32.6	50.3	39.1
WMM92.5-IGRF92	700	14.9	15.3	25.1	18.6
STM OPE-IGRF85	0	58.8	44.6	79.7	69.5
STM OPE-IGRF90	0	36.2	37.7	57.1	44.9
STM OPE-IGRF95	0	41.5	51.4	73.3	50.8
STM OPE-IGRF2000	0	9.6	7.7	13.6	12.4

of WMM92.5 pseudo-data is the same as used for developing the STM OP and STM OPE models.

Figures 1–5 contain global maps of ΔZ and ΔF, the residuals of the STM OPE model with respect to WMM92.5 and to the IGRF 1992.5 and 2000.0. These residuals are calculated at the Earth's surface and at 700-km altitude. Table 6 contains RMS differences of the X, Y, Z components and of F between these models obtained as the RMS on a $10^\circ \times 10^\circ$ grid over the whole globe but excluding latitudes higher than 60°. The RMS estimates were made without any weighting.

6. A Candidate IGRF Secular-Variation Model

A candidate IGRF secular-variation model for 2000.0–2005.0 was computed in the early stages of the work reported in this paper. In the file of observatory annual means maintained by IZMIRAN, 165 observatories were selected as being useful for estimating recent secular variation. These estimates were obtained by taking differences between annual means for the period 1980 till the last epoch when data were available. Estimates for epochs where it was not possible to derive values from observations were predicted as follows: up to 2000.0 SV estimates were obtained from the STM OP model. Each component from each observatory for the period 1980 onwards was plotted along with values from STM OP. In these plots the observations and modelled values agree well. In some cases a change in slope in the observations occurred at around 1991–93. These abrupt changes in the second time derivative of the geomagnetic field have been observed in the past (Courtillot *et al.*, 1978; Kerridge and Barraclough, 1985; Golovkov and Simonyan, 1991) and are frequently called geomagnetic jerks. Thus, after 1993 combinations of the observed values and those obtained from the STM OP time series were approximated with straight-line segments. Continuation of these lines to 2005.0 gives the required secular-variation estimates.

The input data to the spherical harmonic analysis therefore comprises the secular-variation estimates at 2002.5 from these straight-line fits and some synthetic data for 51 locations in areas where there are no observatories, for example, south-east Pacific, south Atlantic, and the equatorial part of the Indian Ocean. These synthetic data were generated from the 7th generation IGRF extended beyond 2000.0 by assuming constant secular variation for 1995.0 onwards. The resultant coefficients, which constituted the IZMIRAN candidate secular-variation model for 2000.0–2005.0, are listed in Table 7.

7. Discussion

Taking into account that IGRF2000.0 has been produced using vector and scalar data from Ørsted by the special Task Group (this issue) we consider it be an accurate description of the main geomagnetic field at this epoch. It gives us a good opportunity of studying the secular changes of the field during the time interval between two vector satellite surveys.

Therefore the main task of this paper has been an estimation of the accuracy, over the globe and over particular regions, of the space-time models produced without using satellite vector data.

Let us investigate the accuracy of the models step by step, depending on the data utilized in their production.

The accuracy of the algorithm of the space-time modeling can be estimated by comparing Table 1 and Table 4. The misfit between the data series from the 23 observatories and the three-term expansion in NOCs (Table 1) is about 10 nT and this is not much less than the misfit between the data from all the 150 observatories and the four space-time models. It is obvious that the data from the whole set of observatories used for the spatial modeling cannot be of better quality than these selected for the NOC analysis. Therefore we can conclude, that the STM misfits are of the same order as the observatory data errors. Moreover we can conclude that the misfit of the data from observatories does not depend on the additional satellite data utilized in the STMs.

However the STMs cannot describe sufficiently well the data which were not utilized in these models, and which covers the areas where there are no observatories. This is clearly seen from Table 5. Comparison of independent models, describing such data (WMM92.5 and Ørsted) with the STMs shows that the largest differences are located in areas where observatories are lacking and mainly at the low latitudes. Evidently, the main cause of errors is the nonuniformity of the global vector data distribution. A second cause could be the Backus effect, taking into account that WMM92.5 was created mainly from scalar data from POGS.

Table 7. SH coefficients of SV model proposed by IZMIRAN; units nT/year.

n	m	$\dot{g}_n^m$	$\dot{h}_n^m$	n	m	$\dot{g}_n^m$	$\dot{h}_n^m$
1	0	15.4	0.	6	2	1.1	−2.1
1	1	12.2	−22.4	6	3	1.7	−0.8
2	0	−11.9	0.	6	4	−0.7	−1.9
2	1	2.4	−19.6	6	5	−0.6	0.
2	2	−0.1	−9.2	6	6	1.8	0.1
3	0	0.9	0.	7	0	−1.	0.
3	1	−5.7	4.9	7	1	−0.9	1.2
3	2	0.4	0.3	7	2	−0.5	0.
3	3	−7.4	−14.9	7	3	1.1	0.5
4	0	−1.4	0.	7	4	1.	0.1
4	1	0.9	2.8	7	5	−0.9	−0.1
4	2	−7.4	1.8	7	6	0.7	−0.6
4	3	2.6	4.6	7	7	−0.9	0.9
4	4	−3.	2.1	8	0	0.	0.
5	0	0.9	0.	8	1	0.3	1.2
5	1	−1.	0.6	8	2	−0.2	0.1
5	2	−1.4	0.6	8	3	0.7	0.6
5	3	−2.5	2.2	8	4	−1.2	0.5
5	4	−0.8	0.8	8	5	0.6	0.9
5	5	3.8	0.	8	6	−0.5	0.3
6	0	1.5	0.	8	7	−0.9	0.3
6	1	−0.8	−1.	8	8	0.2	2.

Both STM OE and STM OPE agree very well with the Ørsted model. The RMS deviations of these models are not much larger than the disagreements between different models based only on Ørsted data. Consequently, vector data from observatories and from Ørsted do not contradict each other and this justifies their joint use for the space-time modeling.

A more complicated problem is the coordination of the STMs with WMM92.5. Rather large disagreements between these models can be seen over the Pacific and Indian Oceans, particularity over the Pacific. There is better agreement at 700-km altitude for F, i.e. when modeled values are close to observed ones. ΔF values between WMM92.5 and STM OPE and between WMM92.5 and IGRF92.5 are almost the same at 700-km altitude, but ΔZ between WMM92 and STM OPE is very large at the Earth's surface. It seems that the Backus effect is significant in WMM92.5 over ocean regions. In our opinion, STM OPE 92.0 describes the components of the field better than does WMM92.5.

Taking into account that the 7th generation of IGRFs from 1985.0 to 1995.0 depend very much on data from WMM92.5 we conclude that it would be desirable to develop a new generation of the IGRF for this time interval using the STM, developed with joint use of data from the Ørsted and POGS missions.

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