J. Geomag. Geoelectr., **40**, 645–702, 1988

Definitive IGRF Models for 1945, 1950, 1955, and 1960

R. A. LANGEL[1], D. R. BARRACLOUGH[2], D. J. KERRIDGE[2], V. P. GOLOVKOV[3], T. J. SABAKA[4], and R. H. ESTES[4]

[1] *Geophysics Branch, Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.*
[2] *British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, Scotland, U.K.*
[3] *IZMIRAN, U.S.S.R. Academy of Sciences, 142092 Troitsk, Moscow, U.S.S.R.*
[4] *Science Applications Research, 4400 Forbes Blvd., Lanham, MD 20706, U.S.A.*

(Received October 12, 1987; Revised March 24, 1988)

Definitive internal geomagnetic field models are derived for the epochs 1945, 1950, 1955, and 1960. Each model incorporates all data available to us within a five year period centered on the model epoch. For survey data, weighting was determined by examining the spread of residuals for the data, sorted by source and sorted by location, relative to the previous IGRF models. The solution included local biases for the fixed observatories. An *a priori* model for each epoch was derived by projecting the GSFC(12/83) model, based on Magsat data, backward in time. This projection was accomplished using a spline fit to annual secular-variation models. The spline coefficients were simultaneously fit to all spherical harmonic secular variation coefficients for the 1940 to 1980 time period. This fit included a full covariance analysis. The projected covariances were part of the *a priori* model for each epoch. An uncertainty model was adopted which included estimates of the effects of crustal and core fields not represented by the model. Differences between model coefficients midway in time between model epochs were compared to estimated coefficient uncertainties. Coefficient differences were within the estimated uncertainties, confirming the uncertainty model. A test for 1945 indicated that a solution without observatory biases was equal to that with such biases, within the expected uncertainties. Differences between biases from year to year are within the bounds expected based on the predicted uncertainties. The resulting models, their secular variation and their expected uncertainties are discussed in some detail.

1. Introduction

The International Geomagnetic Reference Field (IGRF) was revised for the third time at the 5th General Assembly of the International Association of Geomagnetism and Aeronomy (IAGA) in Prague in 1985 (BARRACLOUGH, 1987). Although it had been planned to adopt definitive models of the main geomagnetic field for 1945, 1950, 1955 and 1960 as part of that revision, it was decided that the candidate models submitted did not represent the best that could be done with existing data but that additional efforts would lead to improved descriptions of the field at these epochs. Preliminary models were therefore proposed and plans were made to adopt definitive models at the 19th General Assembly of the International Union of Geodesy and Geophysics (IUGG), in Vancouver in 1987.

The models described here were adopted as definitive IGRFs for 1945, 1950, 1955 and 1960 at the 19th General Assembly of the IUGG. They are based on more extensive data sets than the corresponding preliminary IGRFs (LANGEL and ESTES, 1987; BARRACLOUGH and KERRIDGE, 1987) and these data sets have been carefully screened for errors and duplicate entries. The technique used to produce the present models is more rigorous in the method of assigning *a priori* information at the model epoch and takes account of uncertainties in the data in a more complete fashion than did the methods used for the preliminary IGRFs.

Section 2 describes the data on which the four models are based and how these data were selected, edited and weighted. Section 3 discusses the use of *a priori* information and describes a new method for deriving the *a priori* covariance matrix. Section 4 describes the use of the correlated weight matrix to take account of truncation uncertainties and of the effects of the crustal anomaly field. The four candidate models are presented in Section 5 together with plots of field components and their estimated uncertainties. The usefulness of solving for bias fields at observatories, and the accuracy of such solutions is discussed in Section 6. Section 7 examines the estimated uncertainties in the spherical harmonic coefficients and Section 8 discusses the error involved in using a linear interpolation between models for determining secular variation, as is done with the IGRF. Basic characteristics of the temporal change of the field over the interval 1945 to 1960 are given in Section 9 and Section 10 describes the characteristics of the magnetic dipoles and poles, as determined from all the DGRF models published to date.

2. Data

It is convenient, because of the different ways in which they are analyzed, to consider the data used to produce the models in two categories: (a) annual mean values from magnetic observatories and (b) survey data. Included in the latter category are observations made on land (including those made at repeat stations), at sea, from aircraft and (for the 1960 model) from the VANGUARD 3 satellite.

Data from both categories were selected in time as follows. If T is the epoch of a particular model, all data with date, t, in the range $T-2.5\leq t<T+2.5$ were used, T and t being in years.

For observatory data, the fitting process included the derivation of biases representing the effects of crustal anomalies and instrumental error (LANGEL *et al.*, 1982). This technique requires data for at least three years at each observatory and consequently only observatories with at least three annual mean values within the particular five year interval were used. Observatories with fewer annual mean values were included with the survey data. The bias solution also requires values of the north (X), east (Y) and vertical (Z) components of the geomagnetic field. Consequently, whatever the observed elements were at a particular observatory, they were converted, before the analysis, to values of X, Y and Z.

In addition to data from the magnetic observatories, all survey and repeat data available to us were included in the fitting process. Preparation of this data involved an extensive process to weed out suspect data points and to assign appropriate weights. This process is described in Appendix 1, which also includes plots of the data distribution. Table 2, to be discussed in more detail later, shows the number of data points by type, component, and five year interval.

3. Use of *a priori* Information

In the preliminary IGRF models for 1945, 1950 and 1955 (LANGEL and ESTES, 1987) the fitting process made use of *a priori* information in the form of a spherical harmonic model. The identical procedure has been used in the present derivation, except that the *a priori* model used was derived in a more rigorous manner.

The *a priori* model was derived by projecting the GSFC(12/83) model (LANGEL and ESTES, 1985a), derived from MAGSAT satellite data supplemented by observatory data, backward in time to the desired epochs. (The main-field terms from the GSFC(12/83) model, truncated to degree 10, were adopted as the definitive IGRF for 1980.) The projection to the desired epochs was achieved by using a variation of the spline fitting of LANGEL *et al.* (1986). In the present case, annual secular-variation models were derived from first differences of observatory annual means for the period 1940 to 1980. These resulting secular-variation models were of degree 6 from 1940 to 1958 and degree 8 from 1959 to 1980. *A priori* models of degree 8 were needed for all years, so an extrapolation scheme was used to derive degree 7 and 8 terms for 1940 to 1958. In this scheme, a preliminary cubic spline function was fitted to the original secular-variation models (see, e.g., LANGEL *et al.*, 1986). The averages of each of the degree 7 or 8 secular variation coefficients from 1960–1970, as determined from the preliminary spline fit, were then appended to the degree 6 models for 1940 to 1958 to give models of degree 8.

The secular-variation models from 1940 to 1980, using their full covariance matrices, were then fitted simultaneously with cubic *B*-splines. Let $\dot{\boldsymbol{p}}$ be the vector of all secular-variation terms up to degree eight for the years 1940 to 1980, $V_{\dot{p}}$ be the covariance matrix corresponding to $\dot{\boldsymbol{p}}$, let ξ be the vector of spline coefficients, and let R be the matrix of partial derivatives of the ξ with respect to the $\dot{\boldsymbol{p}}$. Then we have:

$$\dot{\boldsymbol{p}} = R\xi, \tag{1}$$

with solution

$$\hat{\xi} = (R^T U R)^{-1} R^T U \dot{\boldsymbol{p}}, \tag{2}$$

which has the covariance matrix

$$V_{\hat{\xi}} = (R^T U R)^{-1}, \tag{3}$$

where $U = V_{\hat{p}}^{-1}$. Once the spline solution, ξ, is obtained, spherical harmonics may be computed from (1) with uncertainty estimate, or covariance, given by:

$$V_{\hat{p}} = RV_{\xi}R^T. \tag{4}$$

To project the GSFC(12/83) model backwards in time the following formulation was used. Let $\hat{p}_n$ be the estimated main-field coefficients for year n. Then:

$$\hat{p}_{n-k} = \hat{p}_n - \sum_{i=n-k}^{n-1} \dot{\hat{p}}_i \, \Delta t, \tag{5}$$

where Δt in our case is one year. The covariance of $\hat{p}_{n-k}$ can be shown to be:

$$V_{\hat{p}_{n-k}} = \left(\sum_{i=n-k}^{n-1} R_i \right) V_{\xi} \left(\sum_{i=n-k}^{n-1} R_i^T \right) + V_{\hat{p}_n}. \tag{6}$$

The appropriate $\hat{p}_{n-k}$, and its covariance matrix were used as the *a priori* main-field coefficients for each epoch. The *a priori* secular-variation coefficients for each epoch were computed from Eqs. (1) and (4). Because the degree 7 and 8 coefficients for 1940 to 1958 were based on the extrapolation scheme previously described, their covariances were regarded as overly optimistic. A more pessimistic view was adopted. First, the largest σ, say σ_{max}, from the initial secular-variation models between 1960 and 1970, was found. Then for epoch t, $1940 < t < 1959$, the standard error was taken to be $(1959 - t)\sigma_{max}$. For the degree 7 and 8 main-field terms from 1940 to 1958 the variances were taken to be the sum of the 1959 variance plus the cumulative secular-variation variance [times (Δt^2)]. The resulting *a priori* variances for the extrapolated terms are thus very large. Table A3, in Appendix 2, lists the *a priori* model coefficients together with their standard deviations. The covariance matrix was not diagonal, i.e. the *a priori* coefficients were correlated. All subsequent calculations were performed with the full covariance matrix.

4. Use of the Correlated Weight Matrix

Let $\boldsymbol{p}$ be the vector of gauss coefficients; $\hat{\boldsymbol{p}}$ its estimate; $\boldsymbol{C}$ the vector of data; $\delta \boldsymbol{C}$ the vector of data residuals from the previous iteration; A the matrix of partial derivatives of the field measurement with respect to the coefficients at the data locations; V_d the data covariance matrix; W the weight matrix, to be discussed; $\hat{\boldsymbol{p}}_n$ the solution from the previous iteration, $\hat{\boldsymbol{p}}_{n+1} = \hat{\boldsymbol{p}}_n + \delta\hat{\boldsymbol{p}}_{n+1}$ and $\hat{\boldsymbol{p}}_0$ the *a priori* model for the epoch with covariance Ω_0. Then the iterative least squares solution for $\boldsymbol{p}$ is given by (TARANTOLA and VALETTE, 1982; LANGEL, 1987) :

$$\delta\hat{\boldsymbol{p}}_{n+1} = (A^T W A + \Omega_0^{-1})^{-1}[A^T W \delta \boldsymbol{C} + \Omega_0^{-1}(\hat{\boldsymbol{p}}_0 - \hat{\boldsymbol{p}}_n)], \tag{7}$$

with solution covariance:

$$V_p = (A^T W A + \Omega_0^{-1})^{-1}. \tag{8}$$

Incorporation of the *a priori* model into the solution is accomplished by inclusion of $\hat{p}_0$ and Ω_0 in (7) and (8).

In conventional modeling the weight matrix, W, is taken to be the inverse of the data covariance matrix, V_d; the vector of gauss coefficients, $\boldsymbol{p}$, is assumed to represent the field originating in the core of the Earth and is truncated at some degree, n^*, determined by computer limitations and/or data limitations. These assumptions about $\boldsymbol{p}$ result in an underestimate of the uncertainties in (8) because the actual field is not truncated at degree n^* and consists not only of field from the core but also from the crust and from external sources.

LANGEL and ESTES (1988) have derived a formalism to account for these effects. The measured field has contributions from sources in the core and crust (ignoring external sources) so we write:

$$\boldsymbol{p} = \boldsymbol{\alpha} + \boldsymbol{\beta}, \tag{9}$$

where $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are the coefficients representing the fields from core and crustal sources, respectively. Under these circumstances $\boldsymbol{p}$ and $\delta\boldsymbol{p}$ in (7) and (8) should be replaced by $\boldsymbol{\alpha}$ and $\delta\boldsymbol{\alpha}$ respectively and W, the weight matrix, should be taken to be:

$$W^{-1} = V_d + Q, \tag{10}$$

where Q is called the inverse correlated weight matrix. Q contains contributions from main-field terms above the truncation level and from crustal terms at all degree and order. In particular

$$Q = A V_\beta A^T + A^{**} V_{\alpha^{**}} (A^{**})^T, \tag{11}$$

where A^{**} is the matrix of partial derivatives for neglected main-field terms, i.e., with degree greater than the maximum degree of the model, n^*, A is the infinite-dimensional matrix of all partials, and V_β and $V_{\alpha^{**}}$ are the corresponding *a priori* covariance matrices. The first term in (11) accounts for the presence of the crustal field and the second term for the presence of the main field represented by truncated terms in the spherical harmonic expansion.

V_β and $V_{\alpha^{**}}$ must be estimated from whatever prior information is available about the field, including information based on physical reasoning. Our estimates are taken from LANGEL and ESTES (1988). For satellite data Q is a full matrix but for surface data it can be taken to be diagonal. Entries for X and Y are very nearly equal to half the value of entries for Z; for Z the crustal contribution to Q is 163,000 (nT)^2. For the neglected core field the contribution for Z depends upon n^*, as given in Table A4, Appendix 3.

There is also a contribution to Q from truncating the degree of the secular-variation coefficients. This is much more uncertain because of uncertainties in knowledge of how fast the power in each degree decreases with increasing n. However an estimate has been made by LANGEL and ESTES (1988) which is reproduced in Table A5, Appendix 3.

When a bias solution is included for observatory data, the contribution to Q from truncating the main-field terms is zero, because any crustal field or truncated core field will be incorporated into the value of the bias found in the solution.

For the 1960 model, data from the VANGUARD 3 satellite were used. In principle, the Q for these data should be a full matrix. In practice this is at present computationally prohibitive so only the diagonal terms were included. This will result in slightly lower estimates of the uncertainty of the final coefficients for this model. However, the Vanguard data were only 3872 data points out of a total of 73,069 used to derive the model so the effect should be small.

5. The Models

The modeling method used, expressed in Eqs. (7) and (8), is described in detail by CAIN *et al.* (1967), TARANTOLA and VALETTE (1982), LANGEL *et al.* (1982) and LANGEL (1987). The parameter vector, $\boldsymbol{p}$, includes the main field and secular variation (first derivative) spherical harmonic coefficients and the observatory bias values, i.e., the method solves simultaneously for all these parameters. Coefficient values from the resulting four candidate main-field models are given in Table 1. As specified by IAGA Working Group I-1, the truncation level is $n^*=10$. The standard deviation of each coefficient, as derived from the covariance matrix, is also given. Units for the coefficients and standard deviations are nT. Also included in the Table (though not part of the DGRF submission) are the values of the secular variation coefficients and their associated standard deviations. These are truncated at degree 8. The units for the secular-variation coefficients are nT a^{-1}.

All models are expressed in terms of Schmidt quasi-normalized associated Legendre functions and refer to a sphere of radius 6371.2 km, the mean radius of the Earth. All positions of input data and vectors were given relative to a spheroidal Earth, i.e., in a geodetic coordinate system. That coordinate system was assumed to be relative to an Earth with an equatorial radius of 6398.165 km and reciprocal flattening of 298.25.

It should be noted that the standard deviations quoted do not include any allowance for the effects of fields originating outside the Earth's surface. The only coefficient likely to be substantially affected by such fields is g_1^0. It is estimated that the standard deviation for this coefficient should be increased by approximately 6 nT, to account for this (systematic) error.

The residuals of the data with respect to the models are shown in Table 2, for each 5-year interval and for each data type. Only non-flagged data were included (see Appendix 1). Except for the observatory residuals without biases, with a few exceptions the mean residuals are nearly zero. The largest exceptions are in the Aeromagnetic data (Project Magnet and Canadian) for 1955 and 1960 and the Z component of the survey data for 1960, and these are less than 20 nT. The standard deviations of the observatory data, with biases, are very low, generally below 20 nT, as would be expected. The standard deviations of the *H*, *Z* and *B* components of the Aeromagnetic and Survey data are in the 80–170 nT range, which is consistent with what is expected of near surface residuals dominated by crustal anomaly fields (LANGEL *et al.*, 1982; see also PEDDIE and FABIANO, 1982, and DAWSON and NEWITT, 1982a.)

As noted above, the analysis included a solution for the biases at each observatory for which 3 or more annual mean values were available in each 5-year interval. The values of these biases for *X*, *Y* and *Z*, together with their standard error, are included in Table A1, in Appendix 1.

Figure 1 contains global contour maps of *X*, *Y*, *Z* and *B* derived from the candidate model for 1945. At the scale used in these figures, corresponding maps for the other 3 epochs are barely distinguishable from these; they are therefore not presented.

The uncertainties in the core field values, derived from the covariance matrices, do, however, vary from epoch to epoch. Contour maps of these uncertainties (δX, δY, δZ and δB) at the four epochs are given in Figs. 2 to 5, except for latitudes poleward of 80°. Note that the contour interval is 20 nT for 1945, 1950 and 1955 but is 5 nT for 1960. These uncertainties are calculated as described by LANGEL (1987) and by LANGEL and ESTES (1988), following JENKINS and WATTS (1968) and GUBBINS (1983). They represent the predicted uncertainty, or standard deviation, of the field; i.e., there is about a 68.3% probability that the error will be less than the predicted uncertainty. This is an approximation since the error distribution of the data is not strictly Gaussian. As already pointed out these uncertainty estimates take into account the presence of unmodeled crustal fields and the effects of a finite truncation of the spherical harmonic series, but not the presence of external fields. The effect of the inclusion of the *a priori* models is to constrain the model field in regions where there are few or no data available during the epoch of the model. If our derivation of the *a priori* model with its covariance is correct, we have also reduced the error in those regions. The uncertainty estimate is obviously reduced. LANGEL and ESTES (1987) showed that the estimated uncertainty is greatly reduced, up to a factor of two or more, in such regions. Comparison of Figs. 2–5 with Figs. A1–A8 shows that the estimates of uncertainty remain greater in areas where few or no data are available, as expected. The uncertainties for 1945 show a prominent maximum in the southern Pacific (about 250 nT, 160 nT, 320 nT and 320 nT for *X*, *Y*, *Z* and *B*, respectively), and are high also in the Atlantic and Indian Oceans. For 1950 the availability of additional data in the Pacific and Indian Oceans, in South Africa and in Antarctica reduced the uncertainties in these regions considerably. The addition of Project Magnet data in the northern Atlantic and, some, in the southern Pacific in 1955 made a large difference in the uncertainties; the peak uncertainty in the southern Pacific is now about 120 nT, 90 nT, 170 nT and 150 nT for *X*, *Y*, *Z* and *B*, respectively. Project Magnet furnished a nearly global survey in the time span covered by the 1960 model. When combined with the other available data, the total data distribution is quite good. This is clearly reflected in the uncertainty plots of Fig. 5 where the peak

Table 1. Candidate model main-field coefficients, and standard deviations (nT); associated secular-variation coefficients and standard deviations (nT a^{-1}).

	N	M	1945 G,H	SIG	GT,HT	SIG	1950 G,H	SIG	GT,HT	SIG	1955 G,H	SIG	GT,HT	SIG	1960 G,H	SIG	GT,HT	SIG
G	1	0	-30594.5	(6.7)	7.9	(0.7)	-30554.1	(5.6)	6.5	(0.5)	-30499.5	(3.7)	11.0	(0.4)	-30421.0	(1.3)	17.8	(0.3)
G	1	1	-2285.0	(7.2)	7.4	(0.8)	-2250.0	(6.1)	8.9	(0.6)	-2215.4	(3.8)	9.1	(0.5)	-2168.7	(2.0)	8.2	(0.4)
H	1	1	5809.5	(7.5)	2.1	(0.8)	5815.4	(6.4)	0.4	(0.6)	5819.8	(4.4)	-0.6	(0.5)	5791.4	(1.9)	-2.4	(0.4)
G	2	0	-1243.9	(6.6)	-19.0	(0.7)	-1341.3	(5.4)	-18.7	(0.5)	-1439.9	(3.9)	-20.1	(0.4)	-1554.7	(1.6)	-22.8	(0.3)
G	2	1	2989.5	(6.8)	2.5	(0.7)	2997.6	(5.7)	1.2	(0.5)	3003.4	(4.0)	-0.2	(0.4)	3001.8	(1.6)	-0.9	(0.3)
H	2	1	-1702.4	(7.6)	-23.2	(0.8)	-1809.8	(6.2)	-18.7	(0.6)	-1898.3	(4.5)	-15.3	(0.5)	-1967.4	(1.3)	-12.6	(0.4)
G	2	2	1578.3	(6.4)	-0.7	(0.6)	1576.0	(5.8)	0.0	(0.5)	1581.2	(3.9)	2.0	(0.4)	1590.0	(1.8)	2.7	(0.4)
H	2	2	477.1	(6.7)	-17.1	(0.7)	381.4	(5.7)	-18.9	(0.6)	291.1	(3.7)	-19.3	(0.5)	206.5	(1.8)	-17.5	(0.4)
G	3	0	1281.9	(6.2)	5.3	(0.6)	1297.0	(5.0)	2.1	(0.4)	1301.6	(3.5)	-0.1	(0.4)	1301.6	(1.4)	-0.4	(0.3)
G	3	1	-1834.5	(5.8)	-11.4	(0.5)	-1888.8	(4.9)	-12.3	(0.4)	-1943.6	(3.5)	-11.0	(0.4)	-1991.6	(1.6)	-9.3	(0.3)
H	3	1	-499.4	(6.7)	3.3	(0.7)	-476.3	(5.6)	3.6	(0.5)	-461.9	(4.3)	3.8	(0.4)	-413.6	(1.4)	4.9	(0.3)
G	3	2	1255.3	(5.7)	3.5	(0.5)	1274.2	(5.1)	3.6	(0.4)	1288.3	(3.9)	2.3	(0.3)	1289.0	(1.5)	0.1	(0.3)
H	3	2	186.5	(6.4)	4.1	(0.5)	206.1	(5.4)	2.9	(0.4)	215.9	(4.1)	1.9	(0.4)	223.7	(1.4)	1.8	(0.3)
G	3	3	913.4	(6.1)	-3.6	(0.5)	896.2	(5.3)	-2.5	(0.4)	881.6	(3.9)	-2.5	(0.4)	877.7	(1.7)	-2.4	(0.3)
H	3	3	-10.8	(5.4)	-7.4	(0.5)	-45.7	(4.8)	-7.3	(0.4)	-83.1	(3.3)	-8.5	(0.4)	-129.7	(1.6)	-8.4	(0.3)
G	4	0	944.4	(5.6)	1.8	(0.5)	954.0	(4.7)	0.9	(0.4)	957.6	(3.4)	0.1	(0.3)	957.3	(1.3)	-0.3	(0.3)
G	4	1	775.7	(5.1)	3.9	(0.4)	792.1	(4.2)	2.5	(0.3)	796.4	(2.9)	1.2	(0.3)	799.9	(1.4)	0.3	(0.2)
H	4	1	143.9	(5.9)	-2.6	(0.5)	135.8	(4.9)	-1.5	(0.4)	133.2	(3.8)	0.4	(0.3)	135.0	(1.3)	1.7	(0.3)
G	4	2	544.1	(5.0)	-3.8	(0.4)	527.8	(4.5)	-3.4	(0.4)	510.3	(3.5)	-4.0	(0.3)	503.9	(1.4)	-4.0	(0.3)
H	4	2	-275.9	(6.3)	-0.5	(0.5)	-277.9	(5.4)	0.9	(0.4)	-274.0	(4.1)	1.1	(0.4)	-277.5	(1.5)	0.8	(0.3)
G	4	3	-420.9	(5.7)	2.2	(0.4)	-407.6	(4.7)	2.1	(0.3)	-397.4	(3.7)	1.6	(0.3)	-393.6	(1.4)	0.7	(0.3)
H	4	3	-55.2	(4.8)	3.9	(0.3)	-37.1	(4.3)	3.6	(0.3)	-23.3	(3.2)	2.9	(0.3)	3.1	(1.4)	3.2	(0.2)
G	4	4	303.7	(5.3)	1.6	(0.5)	302.7	(4.5)	-1.2	(0.4)	290.2	(3.2)	-3.2	(0.3)	269.0	(1.5)	-3.7	(0.3)
H	4	4	-178.1	(5.2)	-5.8	(0.4)	-209.6	(4.6)	-5.3	(0.3)	-229.6	(3.3)	-4.1	(0.3)	-254.8	(1.5)	-3.3	(0.3)
G	5	0	-253.4	(5.1)	2.2	(0.5)	-240.4	(4.1)	2.7	(0.3)	-228.8	(3.2)	2.5	(0.3)	-222.1	(1.2)	1.7	(0.2)
G	5	1	345.6	(4.6)	1.0	(0.4)	349.3	(3.7)	1.7	(0.3)	359.5	(2.7)	1.5	(0.3)	362.5	(1.2)	0.5	(0.2)
H	5	1	-11.5	(5.1)	3.9	(0.4)	2.7	(4.3)	3.1	(0.3)	14.9	(3.3)	2.2	(0.3)	15.6	(1.2)	1.1	(0.2)
G	5	2	194.2	(4.4)	3.3	(0.4)	210.9	(3.7)	4.1	(0.3)	229.9	(2.8)	4.1	(0.3)	242.0	(1.3)	3.4	(0.2)
H	5	2	94.7	(5.4)	1.3	(0.4)	103.0	(4.4)	1.3	(0.3)	109.6	(3.4)	1.8	(0.3)	124.8	(1.3)	1.8	(0.2)
G	5	3	-20.5	(5.9)	0.8	(0.5)	-19.5	(5.1)	0.5	(0.4)	-22.8	(3.9)	0.0	(0.3)	-26.1	(1.4)	-1.0	(0.3)
H	5	3	-67.2	(4.6)	-4.0	(0.4)	-87.0	(3.9)	-2.9	(0.3)	-97.7	(2.9)	-2.3	(0.3)	-117.1	(1.3)	-2.6	(0.2)
G	5	4	-142.1	(4.8)	-1.4	(0.4)	-146.8	(4.0)	-0.9	(0.3)	-151.6	(3.0)	-0.9	(0.3)	-156.5	(1.3)	-0.3	(0.2)
H	5	4	-119.4	(5.0)	-0.1	(0.3)	-121.9	(4.4)	0.5	(0.3)	-120.7	(3.5)	1.0	(0.3)	-114.4	(1.3)	1.4	(0.2)
G	5	5	-82.3	(4.9)	1.4	(0.4)	-76.4	(4.3)	1.1	(0.3)	-68.8	(3.0)	1.1	(0.3)	-63.4	(1.4)	0.9	(0.3)
H	5	5	82.4	(5.0)	-0.4	(0.4)	80.1	(4.1)	-0.9	(0.3)	78.4	(2.9)	-1.0	(0.3)	80.8	(1.4)	0.0	(0.2)
G	6	0	58.7	(3.9)	-0.9	(0.3)	53.9	(3.2)	-1.0	(0.3)	47.0	(2.5)	-1.1	(0.2)	46.5	(1.1)	-1.0	(0.2)
G	6	1	56.9	(3.7)	0.2	(0.3)	57.2	(3.1)	-0.2	(0.3)	57.4	(2.4)	0.1	(0.2)	57.9	(1.1)	0.4	(0.2)
H	6	1	5.7	(3.9)	-1.5	(0.3)	-1.2	(3.3)	-1.3	(0.3)	-9.3	(2.6)	-1.3	(0.2)	-10.2	(1.1)	-0.5	(0.2)
G	6	2	6.4	(3.6)	-0.4	(0.3)	4.3	(3.0)	-0.4	(0.3)	3.2	(2.3)	0.0	(0.2)	1.3	(1.1)	0.3	(0.2)
H	6	2	100.3	(4.1)	-0.4	(0.3)	98.9	(3.4)	-0.1	(0.3)	96.4	(2.6)	-0.2	(0.2)	99.2	(1.2)	0.3	(0.2)
G	6	3	-245.7	(4.4)	-1.1	(0.3)	-247.3	(3.8)	-0.3	(0.3)	-246.6	(3.1)	0.7	(0.2)	-237.3	(1.3)	1.9	(0.2)
H	6	3	15.5	(3.6)	3.5	(0.3)	33.1	(3.0)	3.3	(0.3)	48.2	(2.4)	2.8	(0.2)	60.3	(1.2)	2.0	(0.2)
G	6	4	-24.7	(4.5)	1.7	(0.4)	-16.3	(3.8)	1.3	(0.3)	-8.2	(3.0)	1.2	(0.3)	-0.6	(1.3)	0.5	(0.2)
H	6	4	-9.0	(4.4)	-1.0	(0.3)	-11.6	(3.9)	-1.6	(0.3)	-16.4	(3.1)	-1.5	(0.2)	-19.9	(1.2)	-1.2	(0.2)
G	6	5	21.4	(4.1)	-1.6	(0.3)	12.0	(3.7)	-1.4	(0.3)	6.6	(2.9)	-1.0	(0.2)	-2.3	(1.2)	-0.3	(0.2)
H	6	5	-15.9	(4.3)	0.1	(0.3)	-12.2	(3.6)	0.4	(0.3)	-12.4	(2.8)	0.4	(0.2)	-10.8	(1.2)	-0.1	(0.2)
G	6	6	-104.2	(4.4)	-0.3	(0.4)	-105.1	(3.6)	-0.1	(0.4)	-107.1	(2.7)	-0.8	(0.3)	-113.1	(1.3)	-0.7	(0.2)
H	6	6	-38.7	(4.7)	2.1	(0.4)	-29.8	(4.0)	1.3	(0.4)	-24.5	(2.7)	1.1	(0.3)	-16.6	(1.3)	1.1	(0.2)
G	7	0	69.9	(8.6)	-0.9	(0.6)	65.0	(6.5)	-1.2	(0.6)	65.0	(3.4)	0.6	(0.5)	67.4	(1.0)	-0.1	(0.3)
G	7	1	-40.3	(8.7)	0.5	(0.6)	-54.9	(5.9)	0.4	(0.5)	-56.5	(3.1)	0.1	(0.5)	-55.6	(1.0)	0.7	(0.3)
H	7	1	-44.7	(8.2)	-0.5	(0.6)	-35.1	(6.1)	0.4	(0.6)	-50.2	(3.2)	-0.9	(0.5)	-54.7	(1.0)	-2.2	(0.3)
G	7	2	-0.2	(7.1)	0.7	(0.6)	2.3	(5.8)	-0.7	(0.6)	1.6	(3.0)	0.3	(0.5)	5.0	(1.0)	0.7	(0.3)
H	7	2	-17.7	(9.1)	-0.3	(0.6)	-17.0	(6.2)	0.2	(0.5)	-23.9	(3.2)	0.2	(0.4)	-28.1	(1.1)	-0.9	(0.3)
G	7	3	0.3	(8.0)	-1.3	(0.6)	0.8	(6.0)	0.1	(0.5)	10.4	(3.3)	0.8	(0.5)	15.1	(1.1)	0.9	(0.3)
H	7	3	1.7	(8.0)	-0.7	(0.6)	-0.5	(6.1)	-0.5	(0.5)	-4.5	(3.0)	0.2	(0.5)	-6.0	(1.1)	0.3	(0.3)

G	7	4	-28.7 (8.7)	0.1 (0.7)	-40.0 (6.2)	0.1 (0.6)	-32.2 (3.6)	0.2 (0.5)	-31.7 (1.2)	-0.1 (0.3)
H	7	4	5.9 (8.6)	0.3 (0.6)	10.3 (6.4)	0.3 (0.5)	8.1 (3.2)	0.2 (0.5)	6.8 (1.1)	0.1 (0.3)
G	7	5	-10.0 (8.0)	-0.3 (0.5)	-6.8 (7.1)	1.1 (0.5)	-11.3 (3.3)	-0.7 (0.5)	-6.6 (1.2)	1.0 (0.4)
H	7	5	27.7 (8.5)	-0.1 (0.6)	36.0 (7.0)	0.6 (0.6)	27.8 (3.4)	0.5 (0.5)	23.4 (1.2)	-0.6 (0.4)
G	7	6	14.7 (7.2)	-0.9 (0.5)	4.6 (6.8)	-0.7 (0.5)	9.0 (3.1)	0.4 (0.5)	16.6 (1.1)	-0.4 (0.4)
H	7	6	-16.8 (7.8)	0.6 (0.5)	-17.6 (7.2)	0.0 (0.5)	-20.4 (3.0)	-0.7 (0.5)	-18.4 (1.1)	-0.3 (0.4)
G	7	7	28.6 (7.3)	0.5 (0.7)	18.8 (8.2)	-0.7 (0.7)	18.4 (3.0)	-0.8 (0.5)	7.6 (1.2)	-1.6 (0.4)
H	7	7	-21.9 (8.5)	1.2 (0.7)	-16.5 (7.0)	1.3 (0.7)	-18.5 (3.0)	0.1 (0.5)	-17.2 (1.2)	0.5 (0.4)
G	8	0	13.4 (12.3)	-0.4 (0.6)	22.3 (7.0)	0.3 (0.5)	11.2 (2.9)	-0.3 (0.4)	14.7 (0.9)	0.5 (0.3)
G	8	1	7.3 (9.9)	-0.2 (0.6)	14.8 (5.9)	0.2 (0.5)	8.8 (2.8)	-0.4 (0.4)	5.5 (0.9)	-0.4 (0.3)
H	8	1	11.6 (10.7)	0.8 (0.6)	4.8 (6.4)	0.1 (0.5)	10.3 (2.7)	0.0 (0.5)	11.2 (0.8)	0.9 (0.3)
G	8	2	-7.9 (8.2)	-0.9 (0.6)	-3.8 (5.5)	0.1 (0.5)	-5.6 (2.7)	-0.4 (0.4)	-4.2 (0.8)	-0.6 (0.3)
H	8	2	-20.9 (12.6)	0.7 (0.5)	-22.4 (7.0)	-0.9 (0.5)	-15.4 (2.8)	-0.3 (0.4)	-14.1 (0.9)	0.5 (0.3)
G	8	3	-5.0 (9.5)	0.5 (0.5)	-1.2 (5.8)	0.6 (0.5)	-14.2 (3.0)	-0.7 (0.4)	-11.3 (1.0)	-0.9 (0.3)
H	8	3	-11.7 (9.1)	0.3 (0.5)	0.5 (6.2)	0.2 (0.5)	5.2 (2.7)	-0.4 (0.4)	7.3 (0.9)	-0.7 (0.3)
G	8	4	8.9 (8.7)	-0.4 (0.6)	11.0 (5.6)	-0.1 (0.6)	6.4 (3.2)	-0.5 (0.5)	2.2 (1.0)	-0.6 (0.3)
H	8	4	-6.6 (9.1)	0.1 (0.5)	-21.4 (6.1)	-0.2 (0.5)	-22.8 (3.0)	0.1 (0.4)	-17.6 (1.0)	-0.3 (0.3)
G	8	5	6.9 (7.6)	-0.3 (0.5)	15.3 (6.1)	-1.0 (0.5)	10.5 (3.1)	-0.3 (0.4)	10.0 (1.0)	-0.9 (0.3)
H	8	5	2.0 (8.1)	-0.5 (0.5)	-8.4 (5.9)	-0.2 (0.5)	2.8 (3.1)	-0.5 (0.4)	4.2 (1.0)	0.4 (0.3)
G	8	6	-10.1 (7.3)	0.3 (0.5)	-13.0 (6.0)	-0.2 (0.5)	-6.8 (2.9)	0.7 (0.4)	-5.3 (1.0)	0.9 (0.3)
H	8	6	17.7 (6.8)	0.4 (0.5)	17.0 (5.9)	0.4 (0.5)	22.6 (2.8)	0.4 (0.4)	22.9 (1.0)	-0.2 (0.3)
G	8	7	6.9 (6.4)	0.8 (0.5)	5.3 (6.5)	0.7 (0.5)	6.4 (2.6)	0.7 (0.4)	10.5 (1.0)	1.0 (0.3)
H	8	7	2.6 (6.8)	0.3 (0.5)	-4.2 (6.7)	-1.2 (0.5)	-3.8 (2.6)	-0.1 (0.4)	0.8 (1.0)	-0.6 (0.3)
G	8	8	2.2 (6.4)	-0.6 (0.7)	-0.8 (8.1)	0.1 (0.7)	8.9 (2.6)	0.0 (0.5)	8.1 (1.1)	0.0 (0.4)
H	8	8	-11.2 (6.8)	-0.5 (0.7)	-17.3 (7.0)	-0.4 (0.7)	-13.2 (2.6)	-0.3 (0.5)	-19.9 (1.0)	-0.8 (0.4)
G	9	0	4.6 (12.7)		2.7 (7.6)		3.9 (3.4)		4.0 (1.1)	
G	9	1	-21.4 (9.6)		-7.2 (6.5)		9.2 (2.8)		5.6 (1.0)	
H	9	1	-27.0 (11.0)		-23.8 (7.0)		-11.4 (3.2)		-18.0 (1.0)	
G	9	2	0.6 (8.1)		-0.6 (5.9)		-4.0 (3.2)		-0.5 (1.1)	
H	9	2	17.0 (13.5)		19.4 (6.6)		11.8 (3.4)		11.6 (1.1)	
G	9	3	-10.8 (9.5)		-24.6 (6.6)		-4.9 (3.4)		-9.3 (1.1)	
H	9	3	28.8 (9.1)		11.7 (6.4)		7.1 (3.1)		2.3 (1.1)	
G	9	4	3.1 (9.0)		9.8 (5.8)		1.9 (3.4)		1.3 (1.2)	
H	9	4	-9.2 (8.5)		1.6 (6.3)		5.9 (3.3)		-0.5 (1.2)	
G	9	5	15.5 (7.5)		4.6 (6.4)		3.9 (3.1)		4.3 (1.2)	
H	9	5	4.4 (7.6)		2.0 (6.2)		-1.9 (3.3)		-3.4 (1.2)	
G	9	6	-2.9 (7.2)		-5.2 (6.0)		1.1 (3.1)		-0.7 (1.1)	
H	9	6	9.1 (7.3)		8.0 (5.8)		9.6 (3.0)		9.2 (1.1)	
G	9	7	-3.6 (6.5)		-2.5 (5.8)		1.9 (2.7)		-1.5 (1.1)	
H	9	7	5.6 (6.1)		7.8 (5.6)		6.8 (2.7)		8.0 (1.1)	
G	9	8	-3.2 (5.8)		3.1 (7.1)		2.2 (2.5)		2.7 (1.1)	
H	9	8	1.3 (5.9)		-11.1 (6.4)		-5.9 (2.5)		0.0 (1.1)	
G	9	9	-4.3 (6.3)		8.2 (7.1)		5.3 (2.4)		-1.1 (1.2)	
H	9	9	7.8 (6.6)		-6.7 (7.2)		5.3 (2.4)		5.0 (1.2)	
G	10	0	-2.7 (7.5)		-7.7 (4.9)		-2.7 (2.5)		1.1 (1.0)	
G	10	1	11.4 (6.8)		3.8 (5.0)		-5.2 (2.3)		-3.3 (0.9)	
H	10	1	4.8 (7.1)		13.0 (5.2)		-3.9 (2.5)		3.5 (0.9)	
G	10	2	1.3 (5.5)		-0.7 (4.4)		-0.8 (2.4)		3.7 (0.9)	
H	10	2	0.8 (7.7)		-1.9 (4.7)		-0.3 (2.6)		1.4 (1.0)	
G	10	3	2.1 (6.4)		13.1 (5.1)		2.0 (2.7)		0.2 (1.0)	
H	10	3	-19.7 (6.3)		-10.0 (5.1)		-7.6 (2.3)		0.4 (1.0)	
G	10	4	-4.8 (6.5)		-3.7 (4.7)		-3.2 (2.5)		-1.0 (1.1)	
H	10	4	-0.8 (5.9)		1.9 (4.6)		-2.4 (2.6)		2.2 (1.1)	
G	10	5	-0.8 (5.9)		3.7 (5.0)		6.7 (2.4)		3.5 (1.0)	
H	10	5	-6.2 (5.5)		-3.3 (5.0)		-4.3 (2.6)		-4.6 (1.1)	
G	10	6	8.2 (6.0)		11.6 (4.8)		3.7 (2.5)		5.6 (1.0)	
H	10	6	5.8 (5.4)		5.6 (4.9)		1.4 (2.3)		0.8 (1.0)	
G	10	7	-0.7 (4.9)		3.4 (4.9)		-2.5 (2.2)		0.9 (1.0)	
H	10	7	-4.0 (4.9)		-2.7 (4.5)		-3.3 (2.3)		-1.4 (1.0)	
G	10	8	-2.6 (4.7)		1.8 (5.1)		5.5 (2.1)		-0.6 (1.0)	
H	10	8	-2.5 (5.0)		5.7 (5.0)		6.6 (2.1)		5.9 (1.0)	
G	10	9	5.1 (5.5)		10.1 (6.2)		-2.3 (2.0)		1.9 (1.0)	
H	10	9	0.1 (5.3)		10.7 (5.6)		-0.9 (2.0)		0.4 (1.0)	
G	10	10	-1.6 (5.9)		2.6 (5.9)		-0.3 (1.9)		0.4 (1.1)	
H	10	10	-1.9 (5.7)		8.1 (7.2)		-3.2 (2.0)		-6.8 (1.1)	

Table 2. Statistics of the data used in the models relative to the corresponding model.

Data Type	1945			1950			1955			1960		
	pts.	mean	σ	pts.	mean	σ	pts.	mean	σ	pts.	mean	σ
Observatory												
without biases												
X	294	4.0	175	360	-11.6	162	464	-16.0	159	669	-7.6	227.1
Y	294	-33.8	162	360	-31.7	224	464	-23.4	192	669	-41.0	321.8
Z	294	4.2	316	360	22.6	287	464	14.3	269	669	-0.9	372.7
with biases												
X	294	0.0	10.8	360	-0.3	10.2	464	-0.1	12.9	669	0.14	18.3
Y	294	0.0	7.2	360	-0.1	9.4	464	-0.0	8.8	669	0.001	12.2
Z	294	0.2	19.1	360	-0.4	20.4	464	-0.0	19.8	669	0.05	25.5
Survey/Repeat												
D	11613	-0.0	0.43	3601	-0.01	0.57	4574	-0.0	0.39	9603	0.01	0.43
I	1305	0.01	0.21	889	-0.01	0.23	1730	-0.01	0.21	1743	0.01	0.24
H	2258	4.0	106.4	2081	-7.1	100	3434	4.4	91.4	8247	-8.1	97.9
B	0			0			1	(167)		2235	8.6	149.1
X	0			1	(0.2)		0			1	(47.3)	-----
Y	0			1	(-56.7)		0			1	(45.5)	-----
Z	1085	-10.	173	1104	-5.2	191	2435	-0.5	119	8003	-17.6	163.8
Project Magnet												
D							6654	-0.03	0.29	5700	0.03	0.38
I							8301	0.02	0.17	8569	0.06	0.20
B							8739	-14.7	91.3	9416	-16.0	99.7
Canadian Aeromagnetic												
D							1466	-0.08	0.54	4497	-0.13	0.45
H							1556	-16.1	78.6	4000	18.8	86.6
Z							2080	-0.6	111.9	5180	10.7	122.8
Vanguard 3												
B										3872	-1.2	12.0

uncertainties are now about 30 nT, 30 nT, 50 nT and 40 nT for X, Y, Z and B, respectively. For comparison, the estimated uncertainties for the GSFC(12/83) model, based on Magsat satellite data, were about 16.5 nT for Z and 9 nT for both X and Y (LANGEL, 1987), showing the value of high accuracy satellite data. Note that, because of the relative amounts of data, all the models are dominated by the survey data, rather than the observatory data, although the observatory data are probably more determinative for secular variation.

Contour maps of the secular variation ($\dot{X}$, $\dot{Y}$ and $\dot{Z}$) for the four epochs are given in Figs. 6 to 9, with their corresponding uncertainties ($\delta\dot{X}$, $\delta\dot{Y}$ and $\delta\dot{Z}$) in Figs. 10 to 13. The uncertainty estimates are particularly high for the Southern Pacific, for all years, reflecting the lack of observatory data in that region.

6. Observatory Biases

Solutions including observatory biases have been questioned by LOWES (1985); the biases have been shown to be highly dependent on the adequacy of the main-field and secular-variation models (LANGEL and ESTES, 1985a); and inspection of Table A1, Appendix 1, shows a large variation of biases between model epochs for the same

MAIN MAGNETIC FIELD, 1945

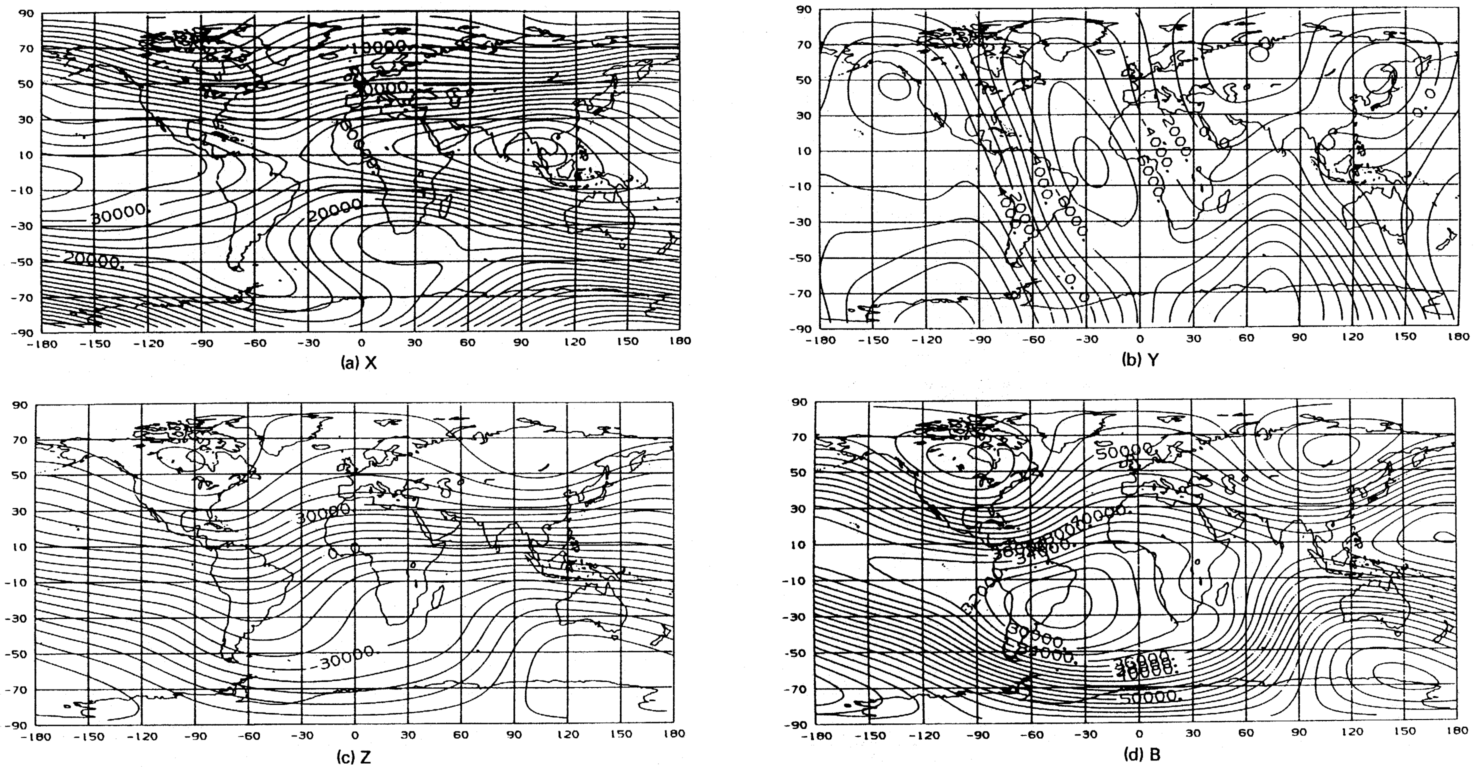


Fig. 1. Contour maps of: (a) north component (X), (b) east component (Y), (c) vertical component (Z), (d) total intensity (B), computed from the candidate DGRF model for 1945. Units are nT; contour interval is 2000 nT for (a), (b), and (d); 5000 nT for (c). Cylindrical equidistant (Plate Carree) projection.

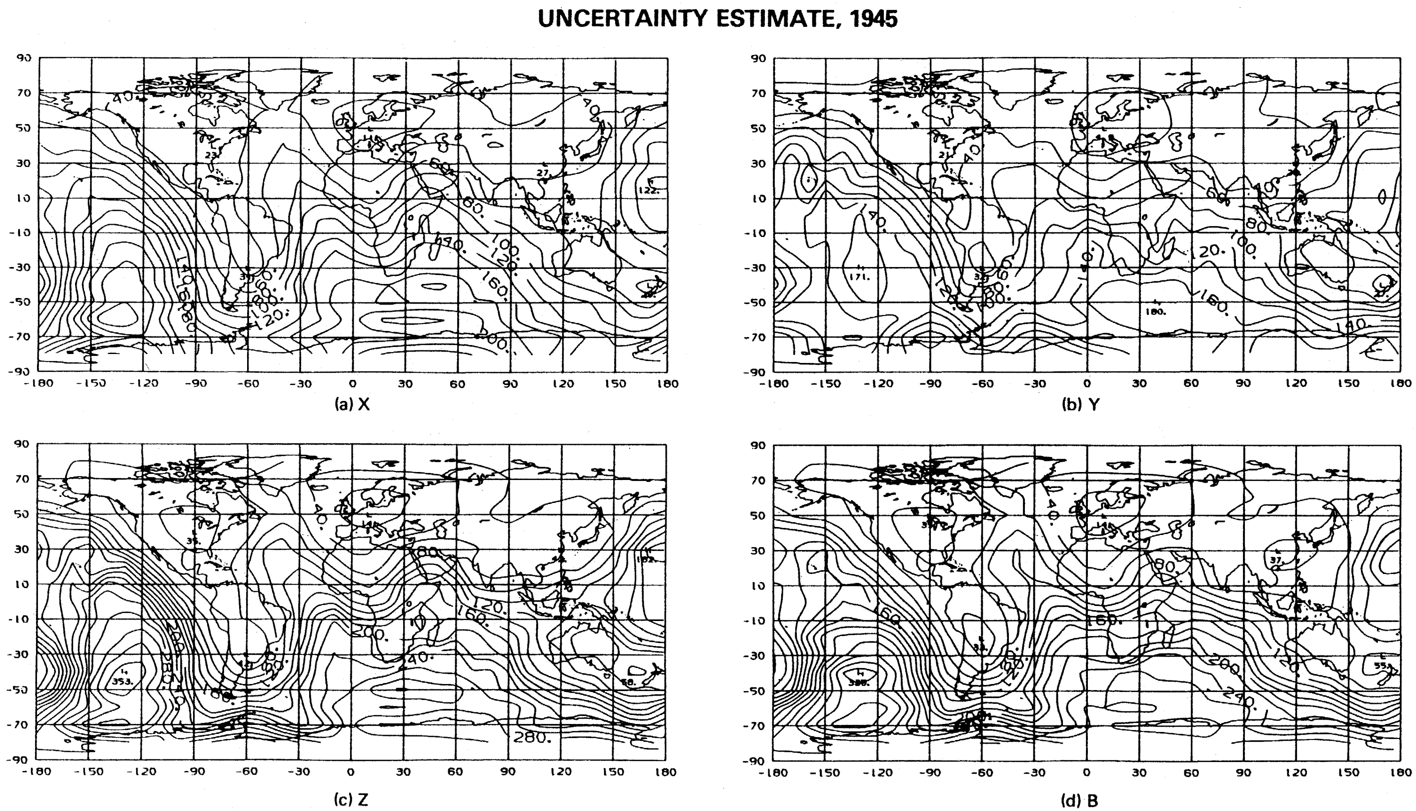


Fig. 2. Predicted uncertainty in (a) X, (b) Y, (c) Z, (d) B, for candidate DGRF model for 1945. Units are nT; contour interval is 20 nT. Cylindrical equidistant projection.

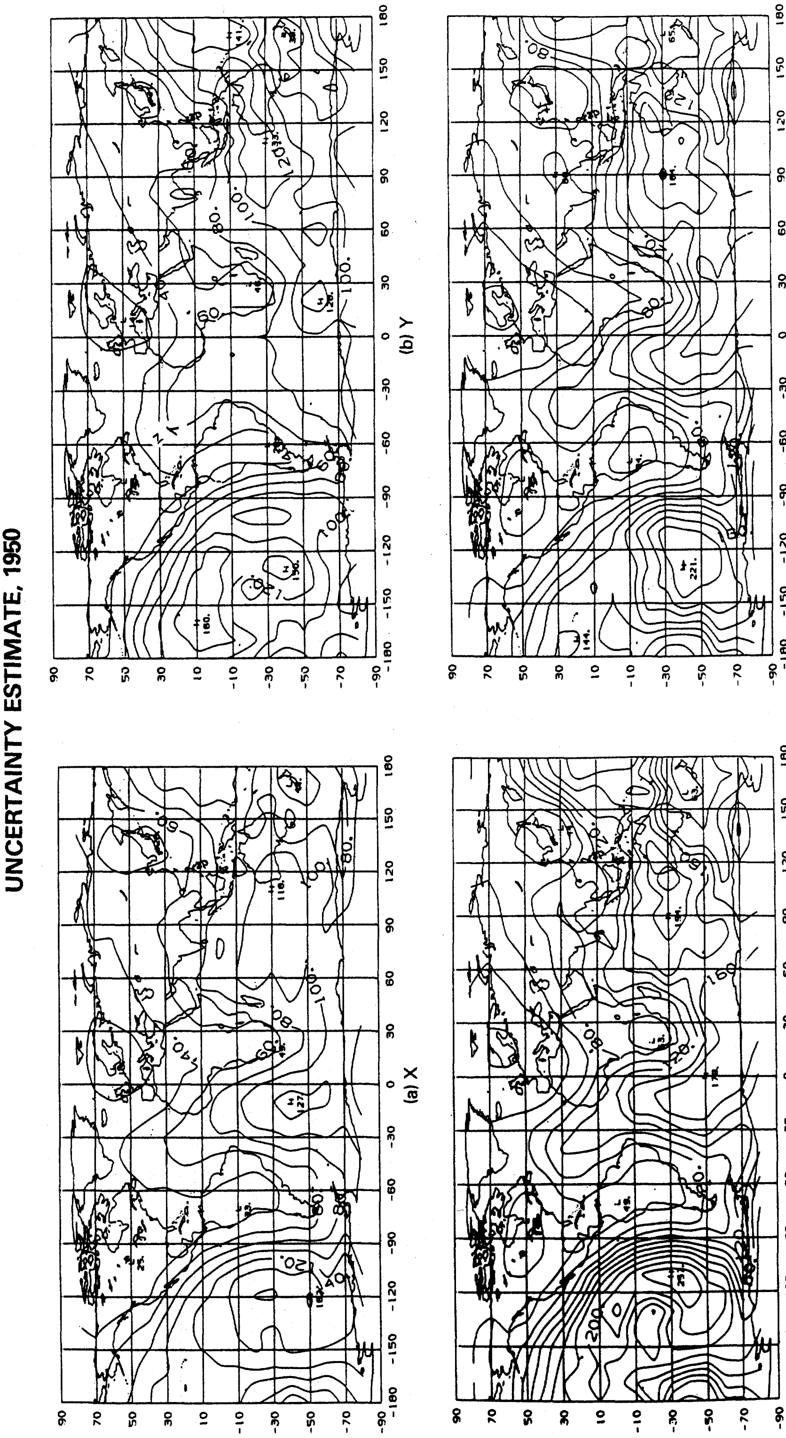


Fig. 3. Predicted uncertainty in (a) X, (b) Y, (c) Z, (d) B, for candidate DGRF model for 1950. Units are nT; contour interval is 20 nT. Cylindrical equidistant projection.

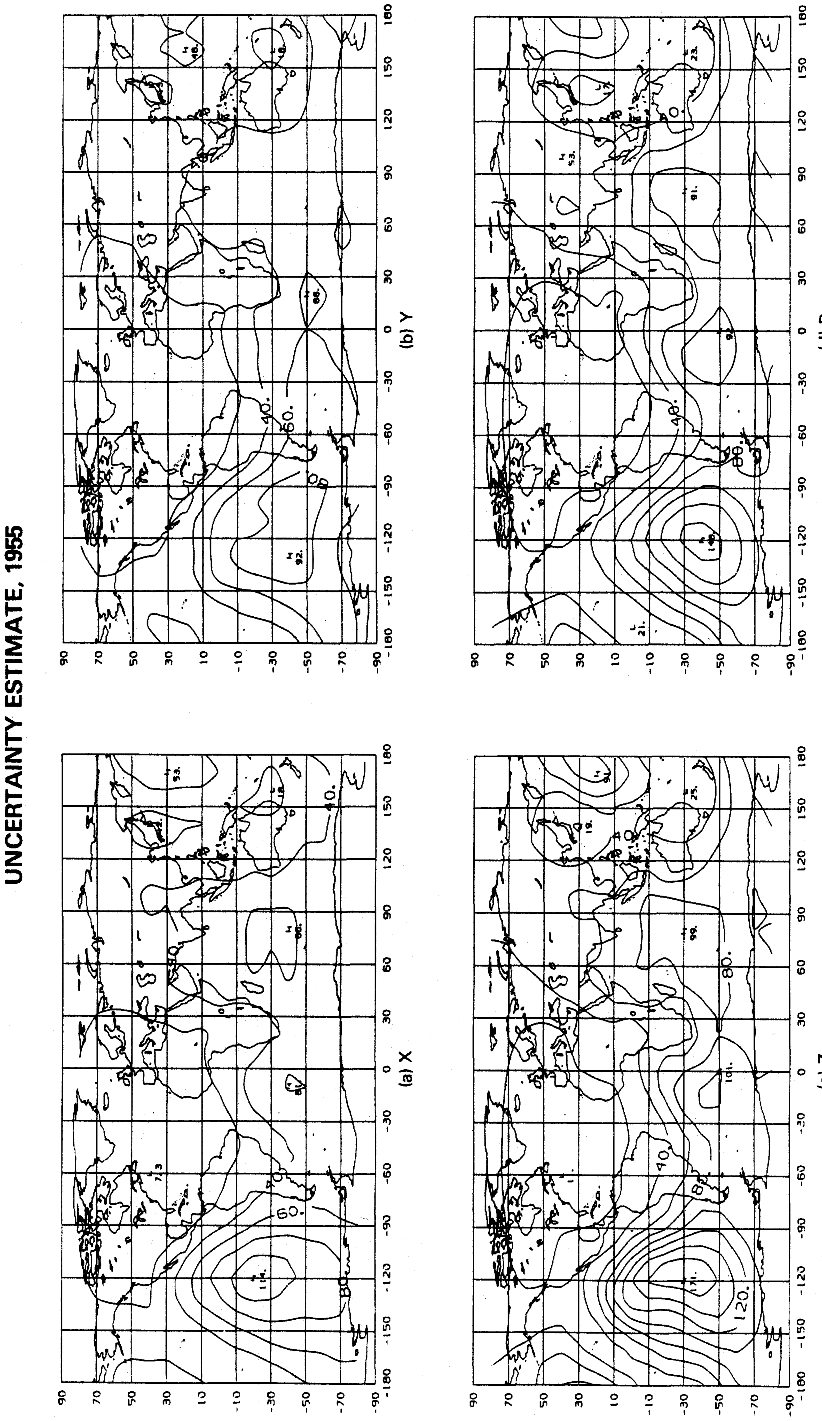


Fig. 4. Predicted uncertainty in (a) X, (b) Y, (c) Z, (d) B, for candidate DGRF model for 1955. Units are nT; contour interval is 20 nT. Cylindrical equidistant projection.

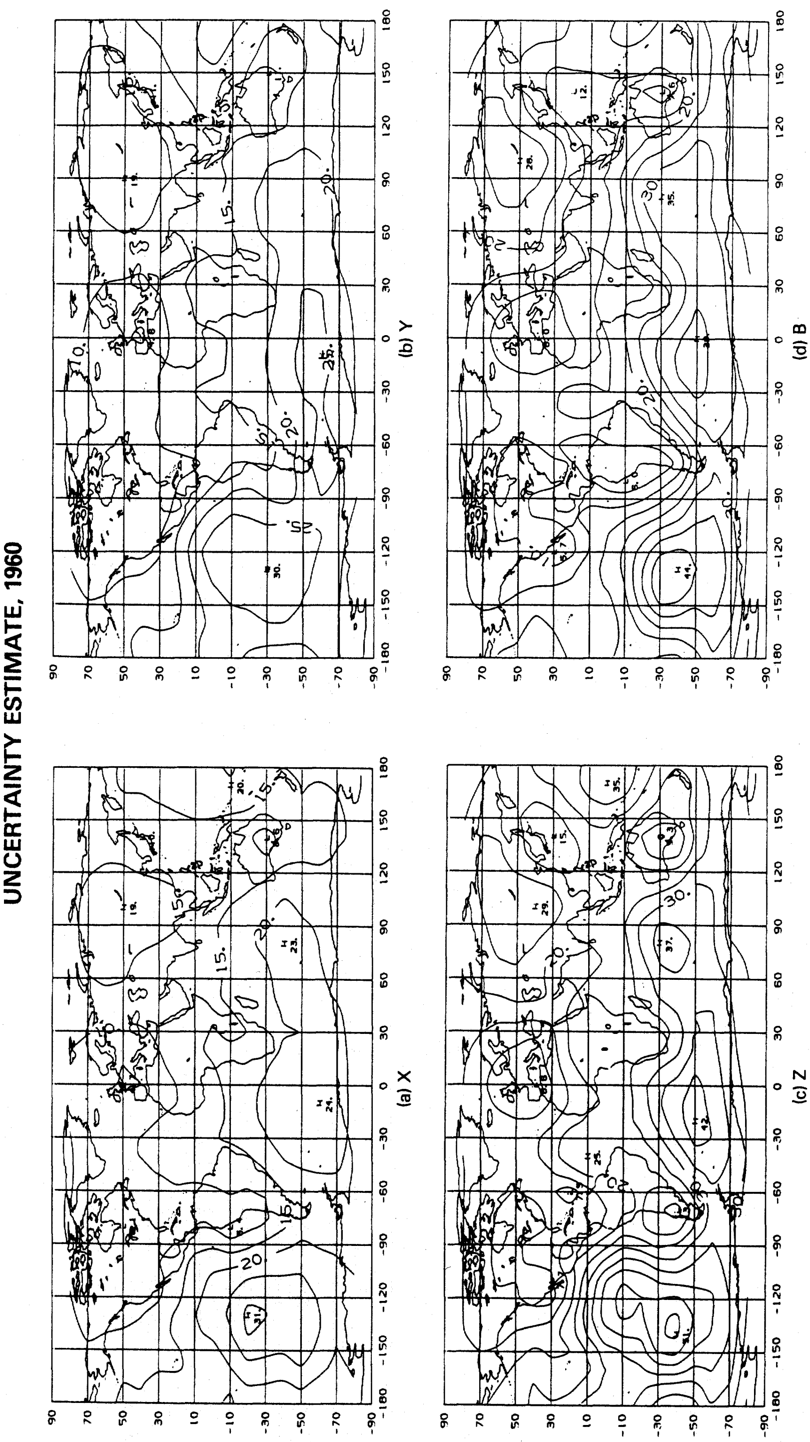


Fig. 5. Predicted uncertainty in (a) *X*, (b) *Y*, (c) *Z*, (d) *B*, for candidate DGRF model for 1960. Units are nT; contour interval is 5 nT. Cylindrical equidistant projection.

SECULAR VARIATION, 1945

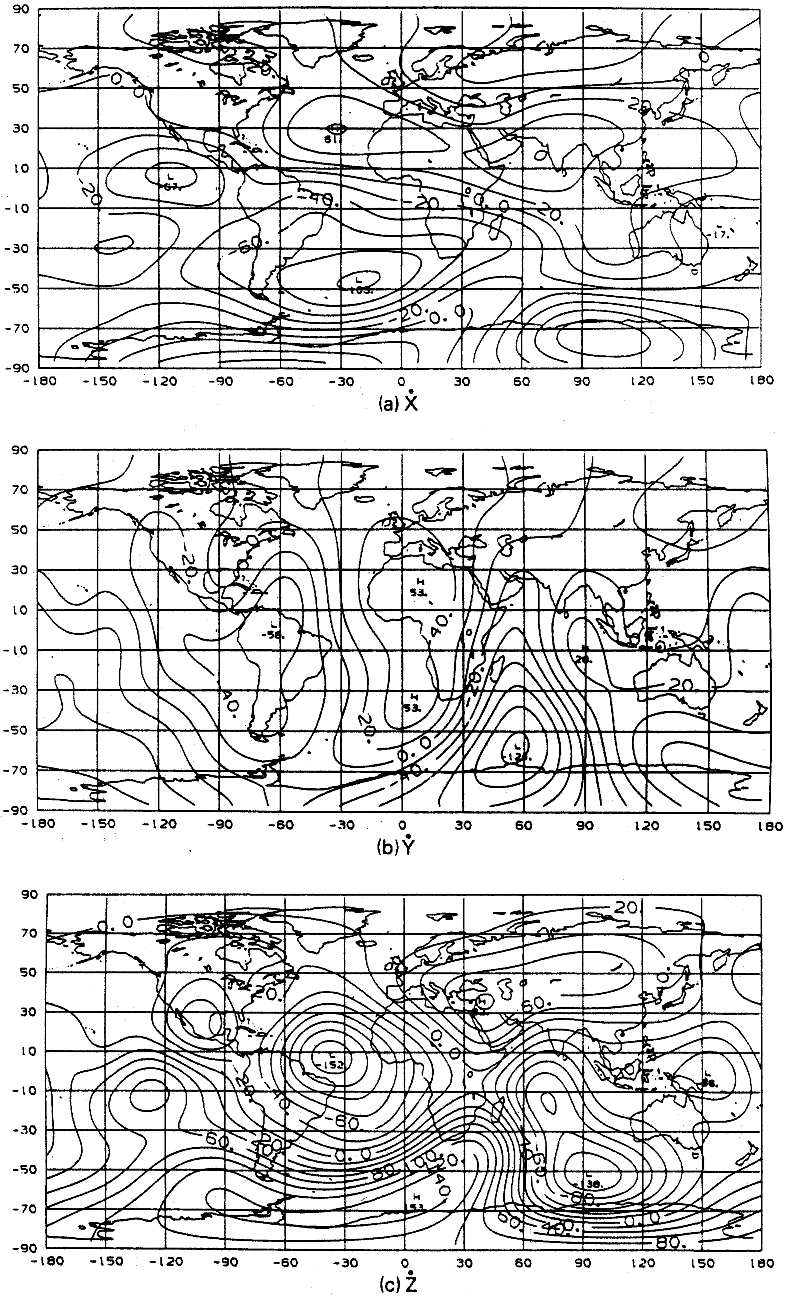


Fig. 6. Secular variation in (a) north component ($\dot{X}$), (b) east component ($\dot{Y}$), (c) vertical component ($\dot{Z}$), for 1945. Units are nT a^{-1}; Contour interval is 20 nT a^{-1}. Cylindrical equidistant projection.

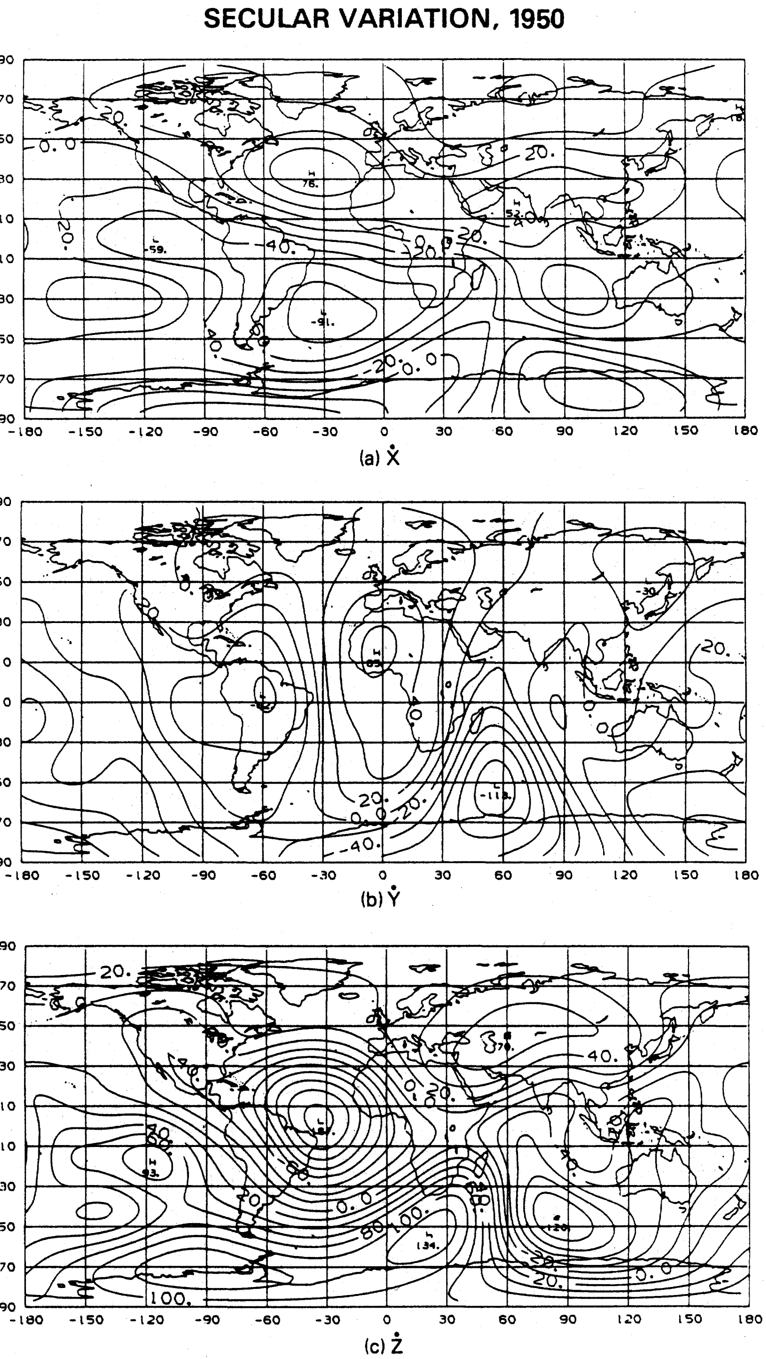


Fig. 7. Secular variation in (a) north component ($\dot{X}$), (b) east component ($\dot{Y}$), (c) vertical component ($\dot{Z}$), for 1950. Units are nT a^{-1}; Contour interval is 20 nT a^{-1}. Cylindrical equidistant projection.

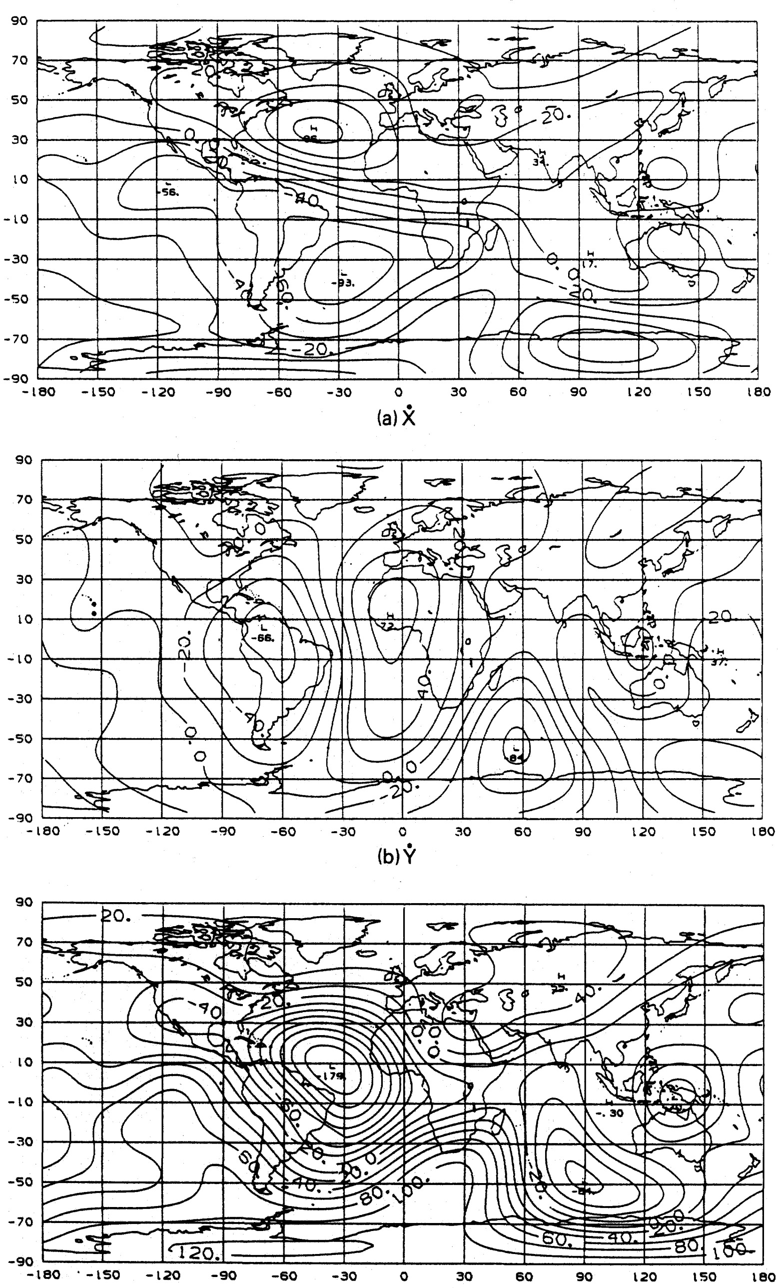


Fig. 8. Secular variation in (a) north component ($\dot{X}$), (b) east component ($\dot{Y}$), (c) vertical component ($\dot{Z}$), for 1955. Units are nT a^{-1}; Contour interval is 20 nT a^{-1}. Cylindrical equidistant projection.

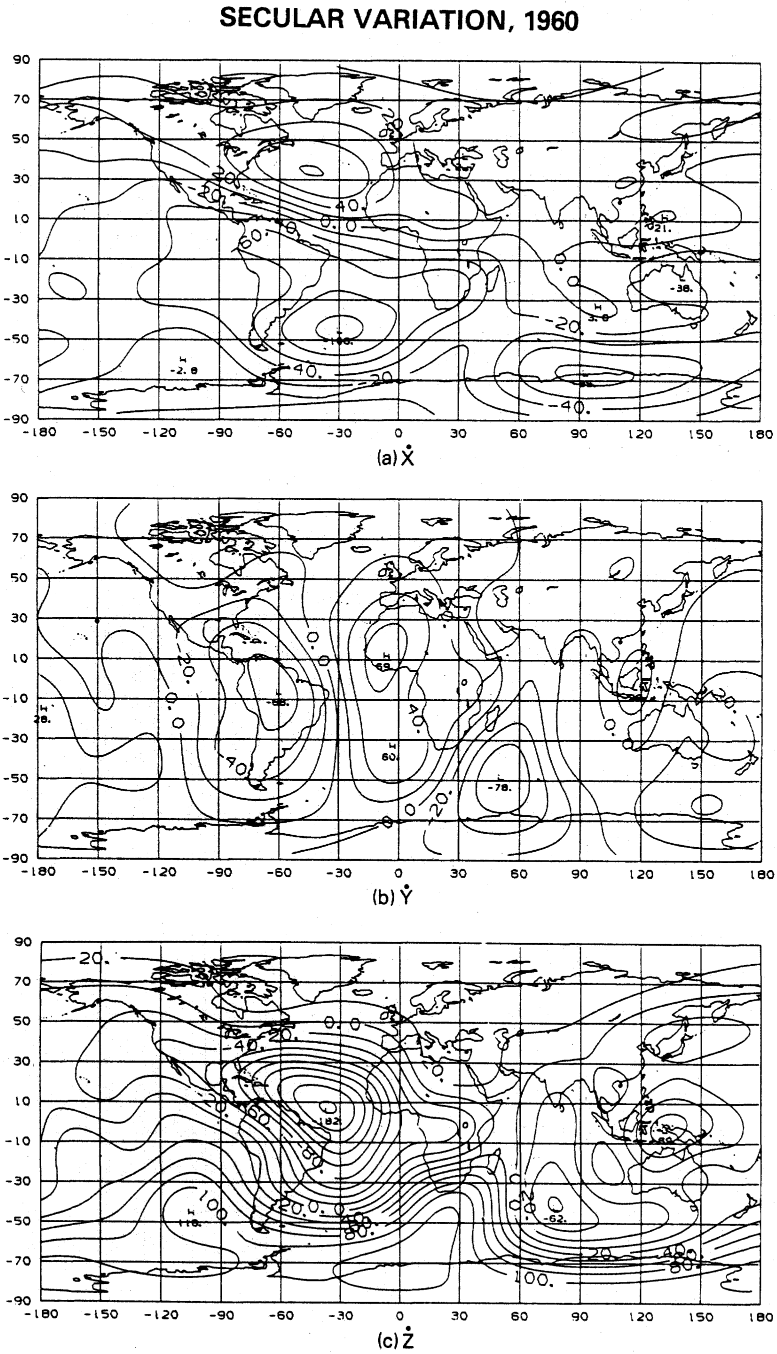


Fig. 9. Secular variation in (a) north component ($\dot{X}$), (b) east component ($\dot{Y}$), (c) vertical component ($\dot{Z}$), for 1960. Units are nT a^{-1}; Contour interval is 20 nT a^{-1}. Cylindrical equidistant projection.

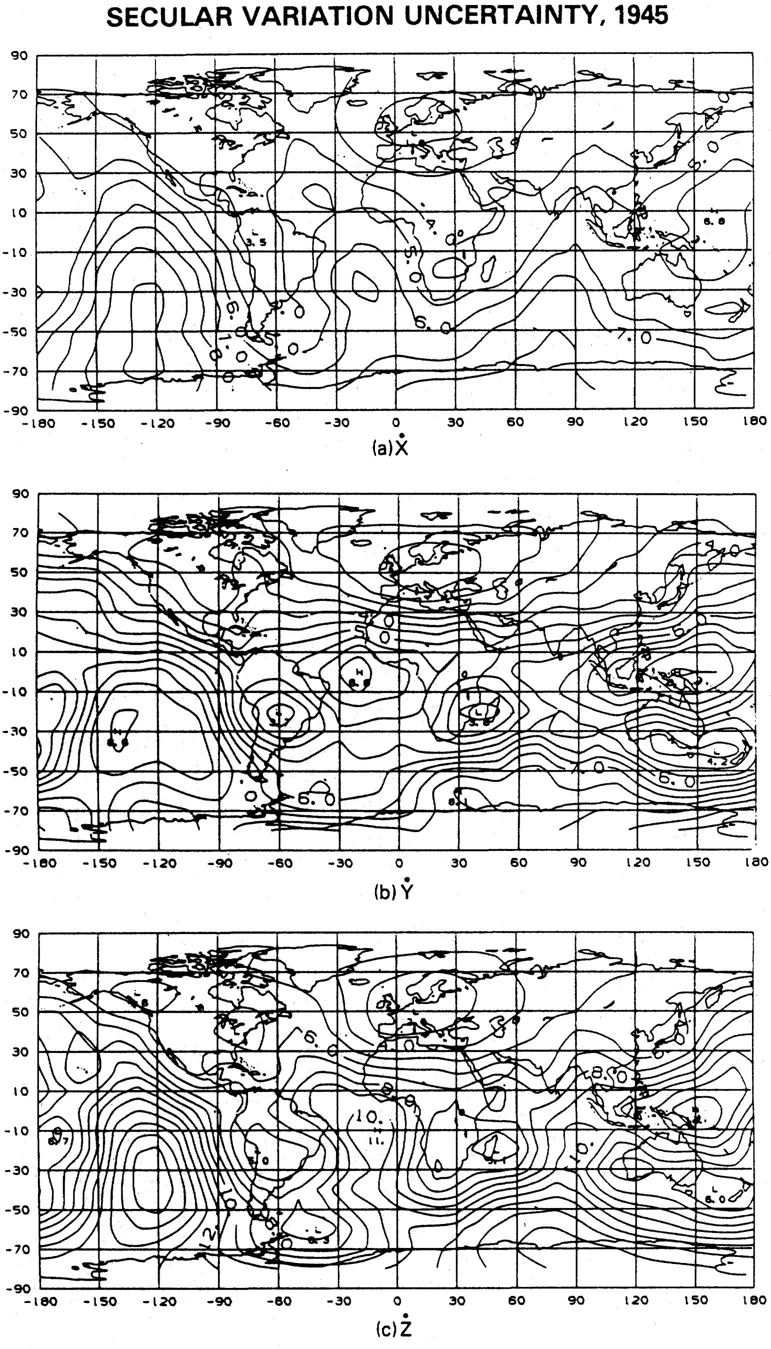


Fig. 10. Predicted uncertainties in (a) $\dot{X}$, (b) $\dot{Y}$, (c) $\dot{Z}$ for 1945. Units are nT a^{-1}; contour interval is 1 nT a^{-1}; Cylindrical equidistant projection.

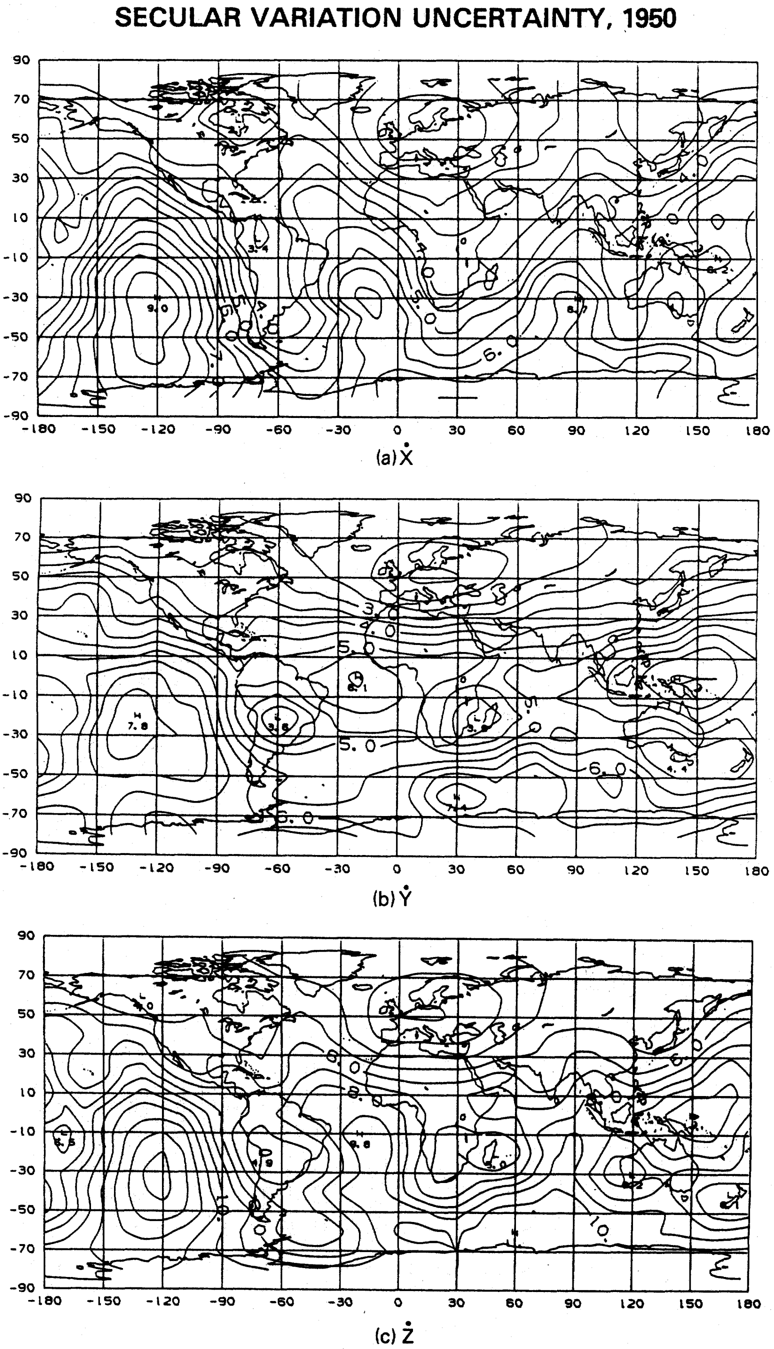


Fig. 11. Predicted uncertainties in (a) $\dot{X}$, (b) $\dot{Y}$, (c) $\dot{Z}$ for 1950. Units are nT a^{-1}; contour interval is 0.5 nT a^{-1} for (a) and (b), 1.0 nT a^{-1} for (c); Cylindrical equidistant projection.

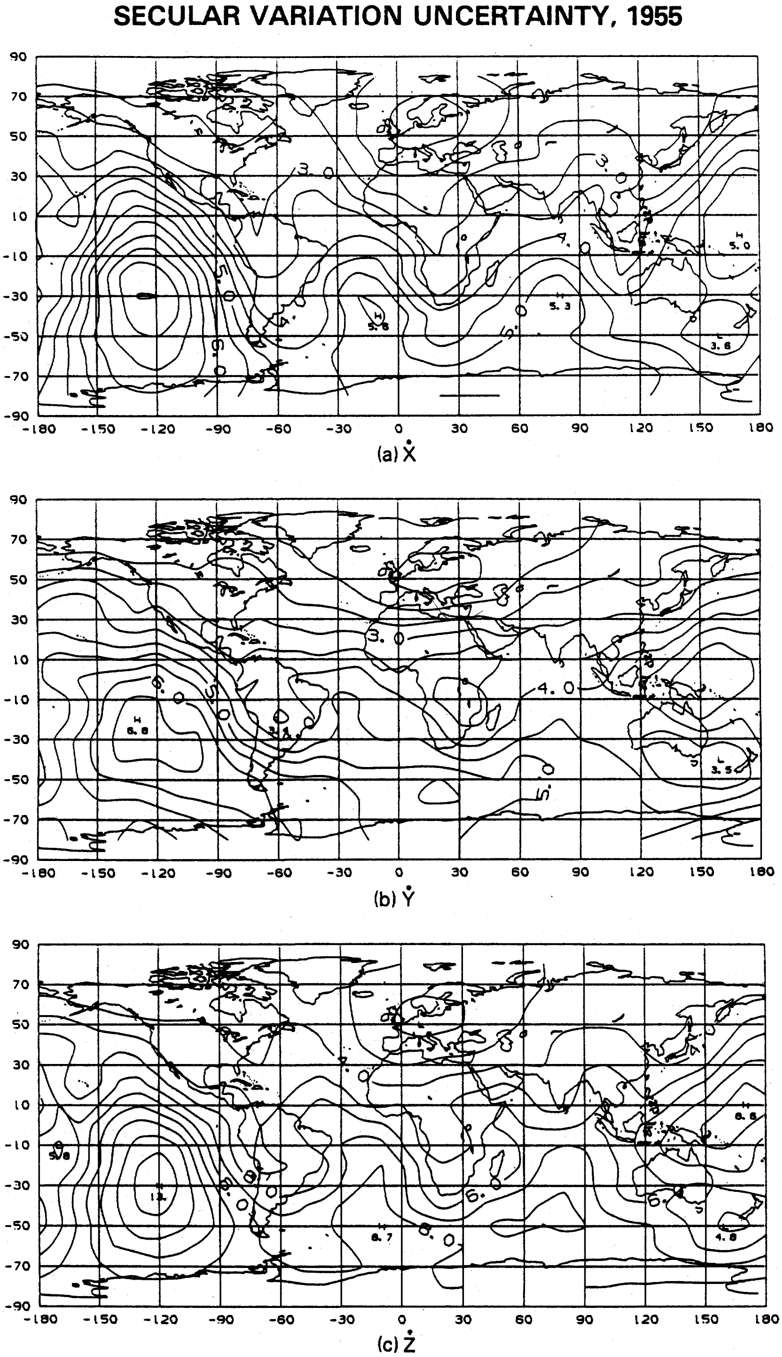


Fig. 12. Predicted uncertainties in (a) $\dot{X}$, (b) $\dot{Y}$, (c) $\dot{Z}$ for 1955. Units are nT a^{-1}; contour interval is 0.5 nT a^{-1} for (a) and (b), 1.0 nT a^{-1} for (c); Cylindrical equidistant projection.

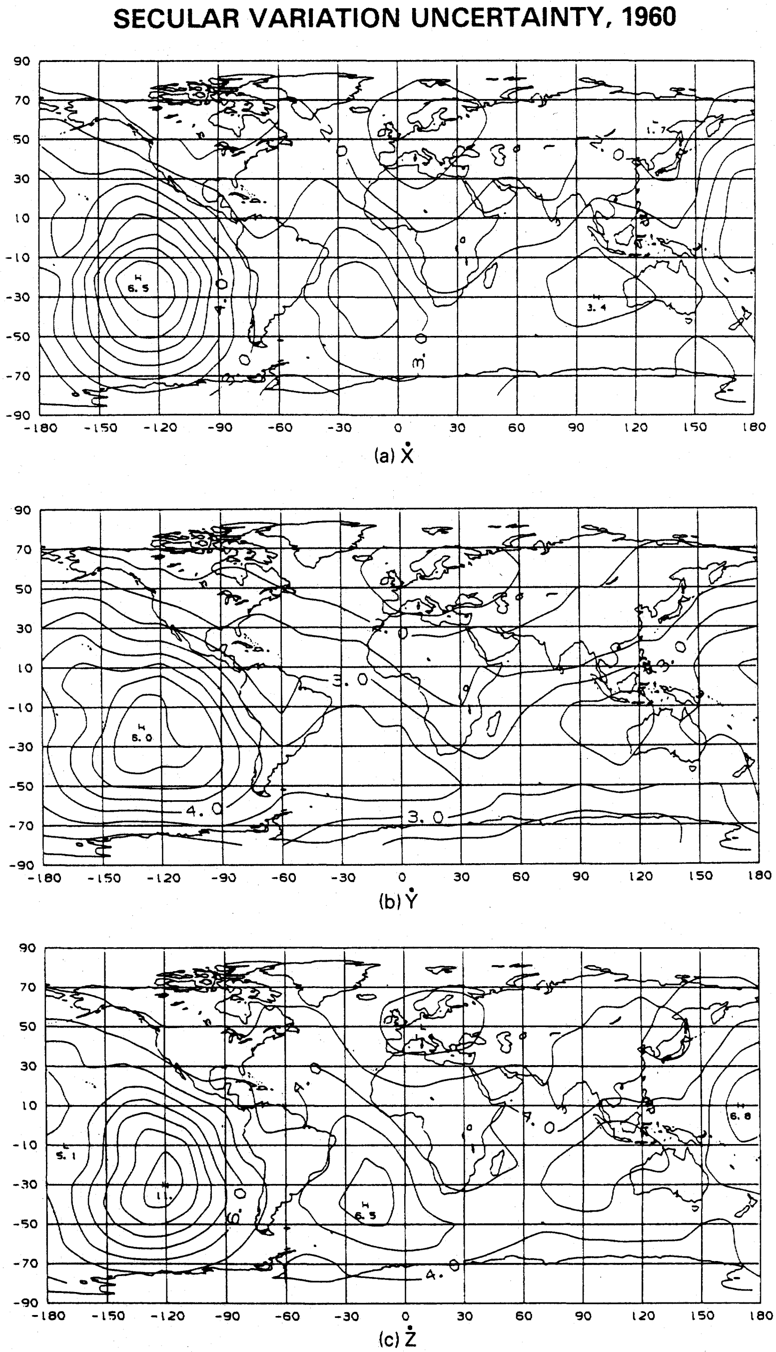


Fig. 13. Predicted uncertainties in (a) $\dot{X}$, (b) $\dot{Y}$, (c) $\dot{Z}$ for 1960. Units are nT a^{-1}; contour interval is 0.5 nT a^{-1} for (a) and (b), 1.0 nT a^{-1} for (c); Cylindrical equidistant projection.

observatory. It is clear that more study, beyond the scope of this paper, of the accuracy and effect of such bias solutions is needed. However some statements can be made. In a preliminary study using less data and a less stringent *a priori* model, the effects of the use of biases and *a priori* models was examined. Four models were derived for each epoch, with and without *a priori* models and with and without biases. The results and their uncertainty estimates were compared. Figure 14 shows some of the results for 1945. Plotted are the first 8 coefficients for both main-field and secular-variation, with appropriate uncertainty bars. In most cases, three of the four uncertainty bars overlap, and the fourth is the same within two uncertainty bars. This gives confidence in the uncertainty estimation procedure. The solutions with *a priori* models, with and without biases, are in close agreement with each other throughout, certainly within their uncertainty estimates. The *a priori* information has a major effect on the solution, at least for the lower degree/order terms. It does indeed constrain those terms; it also imparts greater stability to the solution. For the main-field coefficients, the solution with neither *a priori* model nor biases shows less deviation from the nearly identical solutions with *a priori* model than does the solution with biases but no *a priori* model. This suggests that the solution with biases is less stable than the solution without, in spite of the presence of a large quantity of survey data which did not include biases. The secular-variation solution, on the other hand, was more stable with biases than without. This is probably because the secular-variation solution is highly dependent on the continuous data from fixed locations furnished by the observatories. Inclusion of biases for those observatories removes the effect of local anomalies and allows the data to be weighted more highly, thus providing a more definitive input regarding temporal change.

When deriving the final model for 1945, fitting was done both with and without biases and the results compared. The difference between coefficients was compared with half the sum of the corresponding uncertainty estimates. 80.8% of the coefficients agreed within this tolerance, 95.0% within double this tolerance, and 99.2% within triple this tolerance. We conclude that the two models are the same to within our uncertainty estimates, and that our uncertainty estimates are realistic.

Based on the above results, the proposed models used both the *a priori* model and biases.

Figure 15 shows plots of X, Y, and Z from eight observatories widely separated in location. Data were available from each of these observatories for all four model epochs. The plots show the measured data and the data computed from the models, with and without biases. The models with the biases match the data very well, as expected. Examination of these plots shows that a single linear secular variation could not fit the trends nearly as well as the piecewise linear trends used here. Five years seems to be a reasonable span of time for representation by linear secular variation, at least for the 1943–1963 time period. During a "jerk" a linear variation will be inadequate even for periods shorter than five years.

As can be seen from the plots without biases, and from Table A1, the differences between bias values from model to model are large. Table A1 also shows the 1σ uncertainty estimates for the bias values as determined in the fitting procedure. The

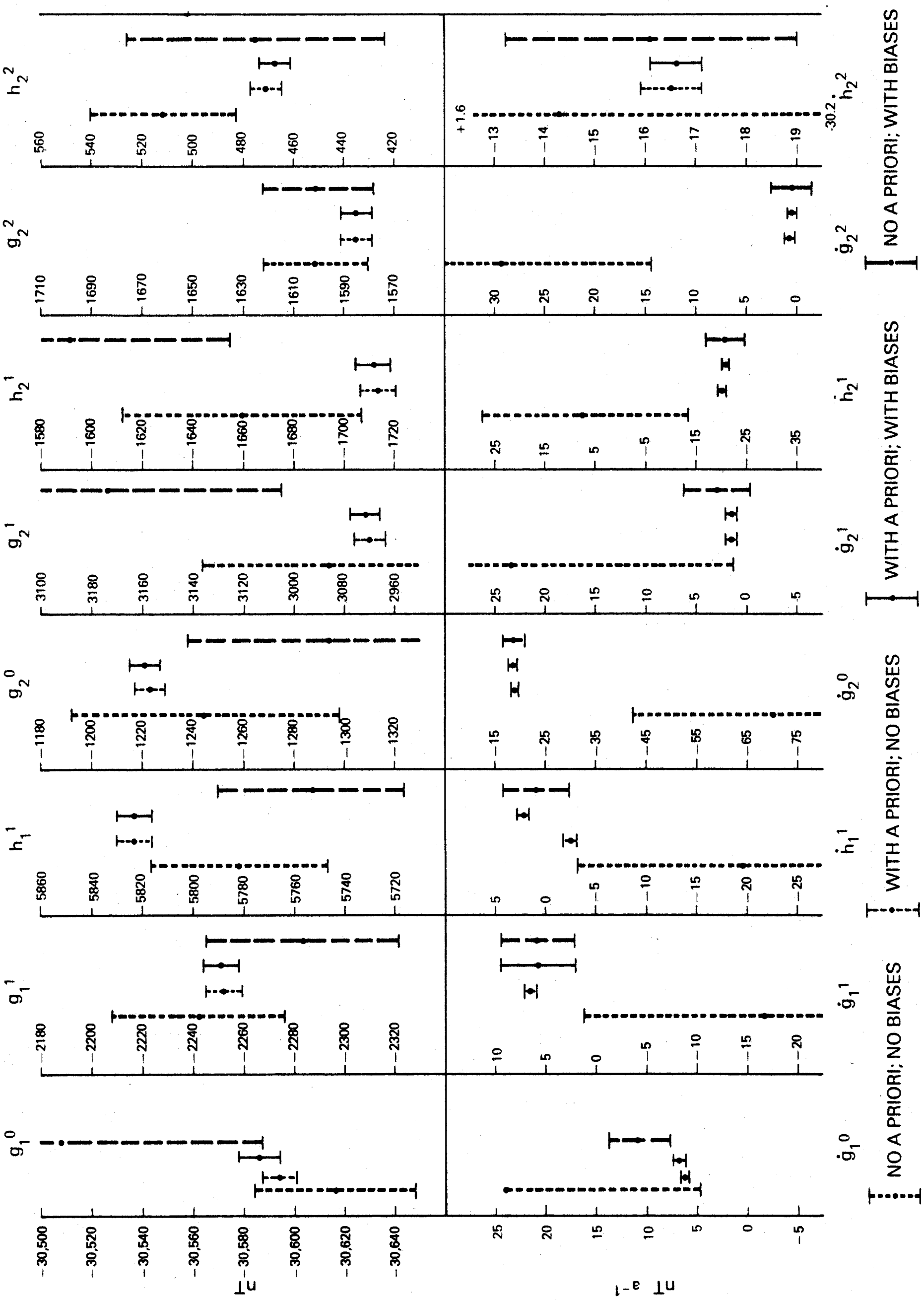
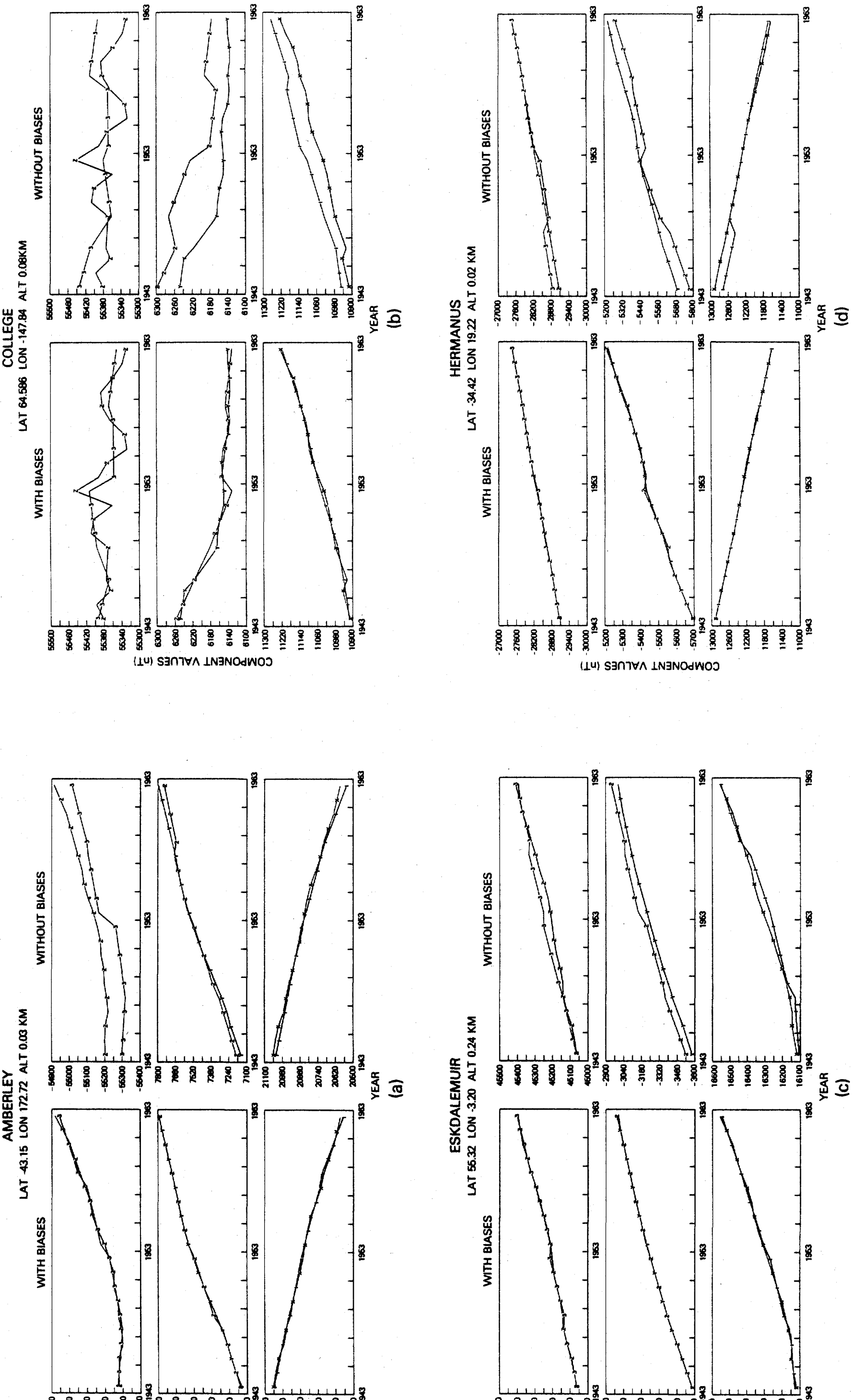


Fig. 14. Comparison of coefficient values and uncertainty estimates from four models for 1945: (i) no *a priori* model, no biases; (ii) no *a priori* model, with biases; (iii) with *a priori* model, with biases; (iv) with *a priori* model, no biases.


COLLEGE
LAT 64.586 LON -147.84 ALT 0.08KM
WITH BIASES
WITHOUT BIASES
(b)
HERMANUS
LAT -34.42 LON 19.22 ALT 0.02 KM
WITH BIASES
WITHOUT BIASES
(d)
AMBERLEY
LAT -43.15 LON 172.72 ALT 0.03 KM
WITH BIASES
WITHOUT BIASES
(a)
ESKDALEMUIR
LAT 55.32 LON -3.20 ALT 0.24 KM
WITH BIASES
WITHOUT BIASES
(c)
COMPONENT VALUES (nT)
YEAR

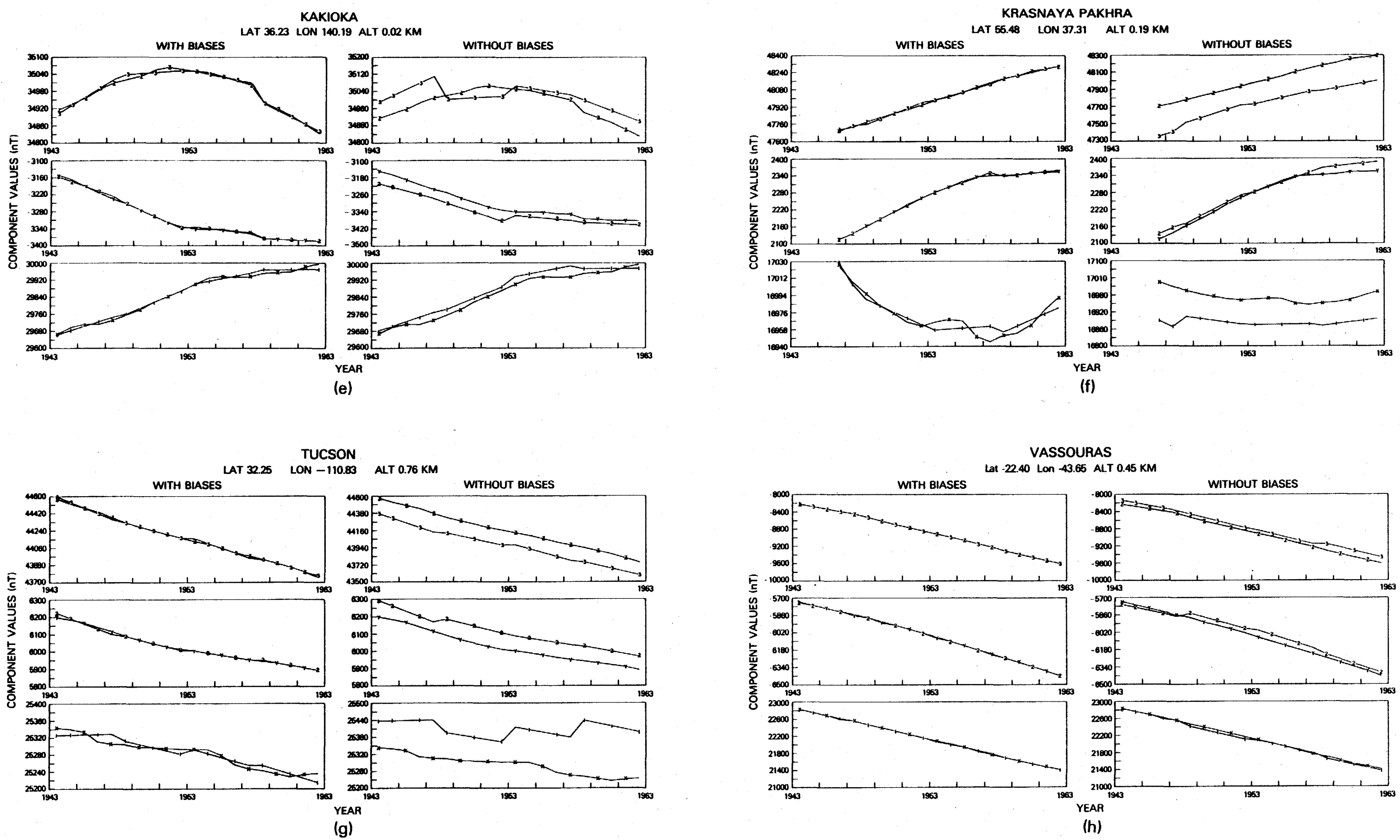


Fig. 15. Comparison of measured data at observatories (Amberley, College, Eskdalemuir, Hermanus, Kakioka, Krasnaya Pakhra, Tucson, Vassouras) with computed values from the proposed models, with and without biases. Letters (X, Y, Z) indicate the measured elements; numbers (1, 2, 3) the corresponding values computed from the models.

expected value of the difference between two determinations of the same bias is zero within the uncertainty estimate, or 1σ value, given by the square root of the sum of squares of the 1σ values of each of the individual determinations. Table 3 gives the bias differences between temporally adjacent models and the 1σ uncertainty estimates of those differences. The determined biases are fairly well in accord with these uncertainty estimates. For 1945–1950, 72%, 93% and 97% of the bias differences were

Table 3. Comparison of bias differences between models at adjacent epochs with uncertainty estimates at the observatory locations at the midpoint of the two epochs. Units are nT.

Uncertainty estimates and bias differences for years: 1945 - 1950

	BIAS DIFFERENCES			UNCERTAINTY ESTIMATE		
	X	Y	Z	X	Y	Z
ABINGER	24.6	4.0	26.0	14.5	12.8	21.1
AGINCOURT	55.0	4.8	62.4	23.4	22.2	39.2
ALIBAG	75.8	339.4	54.5	60.7	54.1	81.5
AMBERLEY	16.5	27.1	1.3	28.9	32.4	76.0
APIA	162.3	125.3	175.2	106.1	128.3	178.8
CASTELLACCIO	40.2	16.8	32.3	16.8	11.1	19.8
CHAMBON FORET	43.0	10.9	10.3	16.0	10.6	20.0
CHELTENHAM	22.5	7.4	75.2	26.2	24.9	41.2
COIMBRA	7.0	19.0	300.8	26.3	24.9	27.9
COLLEGE	25.8	51.6	73.9	41.9	30.4	63.0
DIKSON	16.1	226.8	69.9	41.7	31.3	53.4
DUSHETI	65.5	9.0	148.5	39.6	27.9	47.8
EBRO	5.8	13.7	60.8	19.7	13.5	25.1
ELISABETHVILLE	180.4	63.7	55.8	99.0	90.5	143.2
ESKDALEMUIR	7.1	20.6	27.3	14.3	15.9	22.9
FURSTNFELDBRUCK	24.7	14.7	32.4	14.0	10.7	18.5
GODHAVN	32.2	9.7	69.5	39.1	29.2	54.7
HELWAN	32.1	85.5	56.2	48.0	39.6	66.9
HERMANUS	198.3	61.7	308.8	134.4	117.7	159.2
HONOLULU	131.3	610.8	31.7	127.3	114.4	192.0
HUANCAYO	9.3	25.8	3.2	38.7	44.6	62.5
JASSY	45.9	66.6	106.8	20.0	17.1	25.9
KAKIOKA	0.5	4.1	123.5	32.2	33.9	47.7
KELES	16.4	49.4	66.6	45.7	40.4	62.6
KRASNAYA PAKHRA	51.7	9.7	97.0	20.2	18.5	27.3
KSARA	9.9	66.5	131.7	48.6	34.7	59.4
LA QUIACA	42.1	5.6	28.6	37.4	34.6	50.9
LERWICK	14.0	26.3	8.3	15.0	16.4	20.9
LOVO	23.5	17.2	28.6	12.7	11.9	16.4
MAURITIUS	41.9	153.5	53.2	139.1	101.7	175.7
MEANOOK	30.4	3.2	100.0	30.6	28.1	41.0
NANTES	31.1	4.6	171.7	18.1	13.2	21.0
NIEMEGK	13.0	13.7	54.6	11.8	11.3	17.6
ORCADAS DEL SUR	47.0	156.1	225.1	103.1	116.2	138.6
PILAR	37.9	34.6	26.0	37.3	33.1	52.2
PRUHONICE	11.3	20.4	31.8	12.7	11.5	18.4
RUDE SKOV	11.1	12.5	31.3	11.5	11.7	16.5
SAN FERNANDO	16.0	6.5	35.8	24.3	24.1	33.8
SAN JUAN	26.1	15.5	67.2	37.0	45.0	66.2
SAN MIGUEL	12.1	73.6	175.3	49.5	44.6	67.4
SHESHAN	4.0	44.2	102.3	37.3	34.9	52.5
SITKA	6.2	11.8	14.4	42.5	33.9	55.9
SODANKYLA	29.5	47.0	39.1	18.7	13.7	21.4
SREDNIKAN	3.6	26.4	98.4	46.5	43.5	73.1
SWIDER	21.0	3.8	75.4	13.0	13.3	19.9
TANANARIVE	12.6	116.3	92.0	135.8	96.9	145.2
TEOLOYUCAN	3.0	38.7	68.2	44.3	50.0	61.4
TIKSI	5.9	34.2	140.5	40.8	44.5	67.6
TOOLANGI	145.3	54.1	48.0	57.6	53.6	94.2
TROMSO	13.7	10.5	78.0	20.0	14.3	23.0
TUCSON	29.3	27.3	24.7	42.2	39.6	56.3
VALENTIA	63.4	22.0	19.3	19.8	21.7	27.3
VASSOURAS	53.4	59.4	5.2	51.6	55.3	70.8
VYSOKAY DUBRAVA	82.2	22.3	107.1	31.8	29.9	47.1
WATHEROO	34.1	126.1	124.4	94.2	98.4	150.2
WIEN AUHOF	29.7	8.7	33.8	14.1	12.1	19.3
WINGST	0.3	11.6	24.4	11.6	11.3	17.4
WITTEVEEN	0.3	13.7	13.3	12.1	11.1	18.2
ZAYMISHCHE	83.1	13.1	96.1	26.4	24.8	35.8
ZUY	70.5	15.8	8.2	43.3	41.4	66.5

Table 3. (continued).

Uncertainty estimates and bias differences for years; 1950 - 1955

	BIAS DIFFERENCES			UNCERTAINTY ESTIMATE		
	X	Y	Z	X	Y	Z
ABINGER	28.1	13.3	24.3	12.9	11.8	19.6
ABISKO	22.4	1.6	78.1	14.3	14.8	20.4
AGINCOURT	39.5	4.8	7.5	18.7	17.5	29.1
ALIBAG	118.5	165.5	148.5	60.0	53.0	82.7
AMBERLEY	9.5	0.4	53.3	29.8	31.7	63.8
APIA	170.8	58.1	62.8	73.0	97.8	118.1
BARROW	9.8	61.5	4.7	37.7	27.1	55.0
BUDAKESZI	7.0	29.7	1.6	13.8	15.0	19.2
CASTELLACCIO	12.2	34.4	27.3	14.5	11.6	17.9
CHAMBON FORET	20.3	6.5	40.2	14.3	10.6	18.3
CHELTENHAM	50.5	8.2	31.5	20.2	20.7	30.9
COIMBRA	19.6	18.7	38.7	20.2	19.9	22.4
COLLEGE	17.2	66.4	45.0	38.5	27.1	52.5
DIKSON	107.3	127.9	269.9	34.6	27.4	45.5
DUSHETI	26.0	31.2	18.4	35.8	28.0	49.4
EBRO	9.0	7.0	41.5	16.5	12.1	21.8
ELISABETHVILLE	133.8	31.0	54.7	44.3	41.7	63.6
ESKDALEMUIR	18.8	27.0	6.2	12.3	13.4	21.0
FURSTNFELDBRUCK	7.8	26.2	19.3	12.4	11.9	17.2
GODHAVN	25.2	6.5	90.2	24.8	20.3	37.3
HELWAN	98.4	3.3	55.2	34.9	31.4	51.2
HERMANUS	8.1	24.7	72.5	49.8	54.3	71.4
HONOLULU	116.6	54.6	60.4	84.1	103.0	128.1
HUANCAYO	36.9	0.2	11.4	32.6	38.7	51.9
HURBANOVO	7.9	24.9	34.9	13.4	14.6	18.9
ISTANBL KNDILLI	33.1	0.5	32.2	25.7	22.9	30.2
JASSY	20.7	18.1	88.6	19.2	19.6	25.4
KAKIOKA	15.2	23.5	51.5	22.1	23.6	35.1
KELES	68.4	28.4	11.4	42.7	39.8	57.8
KODAIKANAL	84.4	33.4	334.2	56.3	50.3	103.2
KRASNAYA PAKHRA	2.8	10.1	15.1	23.0	20.5	30.2
KSARA	62.6	30.4	27.5	36.7	30.5	49.5
KUYPER	87.3	271.7	54.4	66.9	71.4	108.2
LA QUIACA	60.0	75.7	27.0	36.3	34.7	50.4
LERWICK	4.4	34.1	0.2	13.4	14.1	19.0
LOVO	18.5	19.4	20.2	12.8	14.1	17.2
MACQUARIE ISLND	114.2	82.2	23.9	55.7	56.7	72.0
MANHAY	35.8	14.3	6.8	12.2	11.0	17.6
MAURITIUS	3.8	130.6	218.8	89.5	71.3	110.0
MEANOOK	20.4	35.5	2.5	21.6	21.5	30.6
MUNTINLUPA	62.8	56.6	165.7	47.1	44.8	75.2
NANTES	43.8	0.3	53.5	15.8	11.9	19.0
NIEMEGK	9.0	21.5	8.3	11.2	12.6	17.0
ORCADAS DEL SUR	44.1	207.2	180.9	64.2	76.1	91.2
PANAGYURISHTE	8.6	24.1	16.2	20.7	19.9	23.5
PILAR	54.4	38.3	27.8	38.7	40.5	60.0
PRUHONICE	10.2	22.7	5.9	11.7	13.0	17.6
RUDE SKOV	2.0	14.2	24.9	11.3	13.1	16.5
SAN FERNANDO	0.8	23.0	25.3	17.6	19.2	27.1
SAN JUAN	7.6	72.7	33.0	26.8	30.9	47.6
SAN MIGUEL	75.6	8.6	47.5	34.0	30.2	48.8
SHESHAN	0.7	48.0	34.8	36.1	34.9	49.4
SITKA	6.9	40.7	99.4	34.3	29.9	42.1
SODANKYLA	38.3	18.4	54.2	15.9	15.8	22.0
SREDNIKAN	50.9	74.8	25.6	36.4	39.2	63.2
STEPANOVKA	8.6	13.2	15.9	22.1	21.1	29.1
SURLARI	18.4	15.0	151.7	20.3	19.9	24.7
SWIDER	6.6	27.5	17.8	13.2	15.5	19.8
TAMANRASSET	28.2	22.6	10.4	26.9	28.1	32.9
TANANARIVE	83.6	17.7	69.5	72.0	55.8	86.1
TEOLOYUCAN	43.9	18.7	188.1	38.3	43.1	52.2
TIKSI	126.9	29.7	64.0	34.0	38.6	56.3
TOLEDO	35.8	8.3	11.7	17.8	15.5	22.8
TOOLANGI	89.0	16.7	7.6	48.5	45.7	74.6
TROMSO	19.5	6.7	91.6	15.2	15.5	21.1
TUCSON	42.2	12.0	15.2	35.8	33.7	49.5
VALENTIA	96.8	54.0	49.4	15.6	16.5	23.7
VASSOURAS	60.6	19.9	6.6	38.8	42.1	55.1
VOYEYKOVO	23.8	27.0	14.7	18.0	17.5	23.0
VYSOKAY DUBRAVA	21.1	10.1	9.5	32.3	28.5	47.4
WATHEROO	28.9	114.3	216.8	86.2	90.8	132.3
WINGST	4.5	9.9	34.8	11.0	12.3	16.9
WITTEVEEN	16.6	10.4	7.3	11.2	11.8	17.4
YAKUTSK	31.2	2.7	175.1	31.7	42.4	55.9
YUZHNO SAKHALSK	118.4	44.2	20.6	29.3	32.2	44.0
ZAYMISHCHE	6.6	3.7	11.6	29.4	24.3	39.6
ZUY	31.9	10.7	8.8	42.3	36.5	63.4

Table 3. (continued).

Uncertainty estimates and bias differences for years: 1955 - 1960

	BIAS DIFFERENCES			UNCERTAINTY ESTIMATE		
	X	Y	Z	X	Y	Z
AGINCOURT	32.4	11.2	4.2	7.9	8.0	11.7
ALIBAG	29.7	77.6	73.0	31.9	30.3	42.9
ALMERIA	52.2	44.0	49.7	8.5	8.3	11.8
AMBERLEY	9.1	41.1	31.1	21.7	22.2	27.0
APIA	52.3	7.1	131.3	23.2	26.3	33.9
BAKER LAKE	26.4	11.8	22.3	9.8	9.0	13.4
BANGUI	18.8	15.7	7.3	18.2	19.6	24.9
BARROW	51.2	43.0	15.5	21.7	17.8	28.8
BINZA	28.3	35.9	29.0	22.2	20.5	28.9
BJORNOYA	15.7	16.2	67.2	15.2	14.8	21.0
CASTELLACCIO	24.8	1.9	108.5	7.7	7.3	9.6
CHAMBON FORET	54.0	11.7	13.5	6.6	6.5	9.1
CHELYUSKIN	91.1	6.7	13.5	21.7	23.8	35.5
COIMBRA	4.2	12.6	46.1	7.6	7.2	10.5
COLLEGE	24.6	19.5	31.5	19.5	16.5	26.5
DIKSON	69.3	40.1	42.9	23.7	21.0	33.5
DOMBAS	24.8	16.5	38.0	9.5	10.1	13.0
DOURBES	18.3	2.9	76.7	6.5	6.7	9.3
DUSHETI	0.8	7.8	28.6	22.6	17.4	32.8
EBRO	2.3	27.2	27.3	8.0	7.3	10.3
ESKDALEMUIR	38.5	20.7	33.7	7.3	7.2	10.0
FUQUENE	47.8	38.7	23.1	12.6	13.4	17.0
FURSTNFELDBRUCK	31.9	9.4	66.1	6.9	7.4	9.8
GODHAVN	5.7	25.7	72.4	10.6	9.2	14.8
HERMANUS	41.4	16.6	15.8	31.9	32.6	42.3
HONOLULU	48.4	10.3	43.8	20.3	21.8	25.8
HUANCAYO	77.2	13.0	101.7	21.6	24.9	33.1
HURBANOVO	26.8	31.1	71.8	8.6	9.6	11.3
ISTANBL KNDILLI	7.4	66.6	48.1	15.4	14.8	19.3
KAKIOKA	28.8	6.6	46.3	11.4	12.0	17.8
KELES	23.4	53.3	125.1	24.6	24.7	33.4
KODAIKANAL	61.3	52.4	28.5	29.5	30.0	55.8
KRASNAYA PAKHRA	0.7	28.2	40.3	18.0	14.4	22.5
KSARA	33.8	48.5	31.9	20.7	18.3	28.1
LA QUIACA	91.2	3.7	46.3	24.9	28.2	38.5
LERWICK	34.3	24.6	17.2	8.3	8.4	11.3
LOVO	17.9	8.1	49.0	10.4	10.9	13.7
LUANDA BELAS	3.7	40.2	84.1	22.2	22.8	36.2
M BOUR	22.3	70.6	27.0	11.6	12.6	17.6
MACQUARIE ISLND	96.5	8.7	141.6	25.5	32.6	43.1
MANHAY	36.3	1.1	70.6	6.5	6.8	9.3
MAURITIUS	47.5	185.3	18.9	46.6	37.4	51.0
MAWSON	4.5	81.2	15.9	34.8	31.8	52.6
MEANOOK	48.6	17.1	37.6	9.4	9.7	12.7
MEMAMBETSU	34.3	13.1	1.7	13.1	15.2	23.1
MUNTINLUPA	42.0	26.9	6.9	22.6	23.1	36.0
NIEMEGK	29.5	9.8	61.8	7.3	8.1	10.4
NURMIJARVI	12.2	16.2	45.8	12.6	12.4	16.7
ORCADAS DEL SUR	56.6	6.3	142.1	36.8	52.7	65.9
PANAGYURISHTE	22.6	63.6	50.6	12.7	13.0	14.8
PILAR	64.1	5.6	31.9	29.2	37.8	46.5
PRUHONICE	21.9	6.0	86.5	7.4	8.4	10.5
QUETTA	1.6	36.4	80.6	25.9	25.8	37.6
RESOLUTE BAY	72.9	11.3	134.6	13.5	11.9	18.3
RUDE SKOV	27.0	2.4	45.8	8.3	8.9	11.1
SAN FERNANDO	30.4	31.3	63.2	8.3	8.1	11.6
SAN JUAN	0.3	8.8	42.2	8.7	9.4	11.1
SAN MIGUEL	9.9	28.6	56.9	9.1	8.0	12.4
SHESHAN	50.0	1.4	2.6	20.7	21.2	27.3
SIMOSATO	33.7	2.2	19.8	11.7	12.2	17.6
SITKA	26.5	7.7	23.9	15.8	14.9	20.3
SODANKYLA	9.6	16.0	52.2	14.2	13.8	20.2
SREDNIKAN	51.1	9.0	30.1	20.8	26.8	38.7
STEPANOVKA	9.4	35.6	0.5	14.8	14.1	19.4
SURLARI	10.1	54.1	9.8	12.9	13.2	15.9
SWIDER	16.3	26.3	75.7	9.9	10.7	12.9
TAMANRASSET	63.3	58.6	81.5	12.6	14.3	20.7
TANANARIVE	22.7	39.5	171.0	39.2	26.8	48.9
TEOLOYUCAN	140.3	17.2	20.6	19.0	17.6	24.7
THULE II	72.6	16.4	58.5	14.1	11.6	19.0
TIHANY	21.2	37.1	71.4	8.7	9.6	11.2
TIKSI	67.7	18.5	16.7	20.7	28.1	38.5
TOLEDO	1.6	25.9	21.9	7.8	7.3	10.6
TOOLANGI	54.0	40.5	77.2	17.0	17.6	25.3
TROMSO	0.6	0.6	64.9	13.2	13.5	18.9
TUCSON	60.2	5.7	1.1	16.7	14.0	22.7
UELEN	88.9	1.9	48.2	25.7	19.8	34.1
VALENTIA	35.2	11.5	44.8	7.2	6.8	10.1
VASSOURAS	40.2	30.5	81.5	21.7	24.8	33.0
VOYEYKOVO	0.5	30.8	42.2	14.8	13.4	19.3
VYSOKAY DUBRAVA	60.6	19.4	8.2	23.6	19.9	33.8
WIEN KOBENZL	23.0	27.0	45.1	8.0	8.9	10.8
WINGST	33.1	0.7	55.8	7.3	7.8	10.1
WITTEVEEN	31.8	1.3	51.8	6.9	7.3	9.7
YAKUTSK	2.1	45.8	3.3	19.6	28.8	37.3
YUZHNO SAKHALSK	84.0	35.6	131.6	14.1	17.0	25.1
ZAYMISHCHE	18.0	7.1	22.9	22.4	16.6	29.1

within the expected 1σ, 2σ and 3σ limits, respectively. The same percentages for 1950–1955 are 72%, 93% and 99%; for 1955–1960 the percentages are 49%, 82% and 95%. Thus the large differences are not statistically significant. The reason that the 1955–1960 differences are somewhat larger than expected is not yet known.

7. Coefficient Uncertainties

Table 1 lists the computed standard errors of the determined models. Intercomparison of models for the same epoch (LOWES, 1974; GIBBS and ESTES, 1982; LANGEL and ESTES, 1985b) and recent simulation studies show that the computed standard errors found in the standard least squares modeling of the geomagnetic field can underestimate the actual uncertainty by factors of two to five. The uncertainty analysis formulation of LANGEL and ESTES (1988), adopted for the present models, is an attempt to derive more realistic uncertainty estimates by accounting for the presence of unmodeled fields.

A test of the uncertainty estimates was made by comparing the differences between coefficients from models at adjacent epochs with their uncertainty estimates. The coefficients of the models, and their uncertainty estimates, were first transformed to the epoch midway in time between the two model epochs, i.e., 1947.5, 1952.5 and 1957.5. This transformation used the secular variation coefficients derived with each model. The coefficient differences at these midpoint epochs should be zero within a 1σ value which is given by the square root of the sum of squares of the individual 1σ values from the two models being compared. Comparing coefficient differences at 1947.5 between the 1945 and 1950 models showed that 86.7% of the differences were within the expected 1σ value and 100% were within the expected 2σ value. In the comparison at 1952.5 of the differences between the 1950 and 1955 models, 81.7% of the differences were within the expected 1σ value, 97.5% within the 2σ value and 100% within the 3σ value. For the comparison at 1957.5 of the differences between the 1955 and 1960 models the corresponding percentages are 64.2%, 92.5% and 97.5%. By this test our uncertainty estimates are not too low and, in fact, seem a little pessimistic for the earlier epoch models.

The adopted uncertainty model has proved more realistic than those previously used. This is encouraging. However, in spite of the effort to incorporate more rigor into the models and their uncertainty estimates, there remain some shortcomings. For the best estimate of model parameters and their uncertainty, the model must account for all significant parameters. The present model does not. Three areas of needed improvement are apparent. First, the estimates of coefficient uncertainty for the Magsat model projected backward in time for use as *a priori* models were too low. This is because the GSFC(12/83) model did not account for the presence of the crustal fields and truncated terms in the spherical harmonic analysis, i.e., it did not incorporate the correlated weight matrix. Because the uncertainty in the *a priori* models was mainly due to the uncertainties in secular variation, this is not a large effect. Also, it becomes less important as the time between the projected model and 1980 increases, i.e., the 1960 accuracy estimates are affected more than the 1945 accuracy estimates. Second, the projection of GSFC(12/83) backward in time did not account for data correlations introduced by taking observatory first differences, nor did it account for truncated secular variation terms. Again, the effect is that coefficient uncertainties will be underestimated. Third, the observatory bias estimates are known to depend upon the validity of the model of temporal change. The present models included only first derivative terms up to degree eight. In fact, the actual temporal change is more complex both in terms of degree and in terms of higher derivatives. It is not known how this model deficiency affects the uncertainty estimates for the constant (main field) coefficients.

It is instructive to compare the coefficients of Table 1 with the coefficients of LANGEL and ESTES (1987) for the same epochs. Aside from the data used, the present models differ from the earlier set in two ways. The present models include the effects of correlated noise from the crust and also a more rigorous projection of the GSFC(12/83) model to the earlier epochs. The lack of the correlated weight matrix in the earlier models caused their uncertainty estimates to be too small. On the other hand, it is likely that the earlier *a priori* uncertainty estimates were too high. Comparison of the two sets of models is limited to coefficients up to degree eight, since that was the degree of the earlier models. For each epoch, differences between coefficients were compared with the square root of the sum of the squares of the individual epoch coefficient uncertainty. For 1945, 75%, 92.5% and 100% of the coefficient differences were within the expected 1σ, 2σ and 3σ limits, respectively. The same percentages for 1950 are 63.7%, 92.5% and 97.5%; for 1955: 60.0%, 83.7% and 95.0%; and for 1960: 22.5%, 46.2% and 68.8%. Except for 1960, the results are encouraging. The trend of lower percentages at later times indicates that the uncertainty estimates are less reliable at those times. As already discussed, both sets of uncertainty estimates have shortcomings. The specific reason for the breakdown of the uncertainty estimates at 1960 is not known. However, we would contend that the present models and their uncertainty estimates are the more reliable.

8. DGRF Secular Variation Uncertainty

Secular variation for the DGRF models is the linear interpolation between models of adjacent epochs. This differs from the linear secular-variation models derived here. As a measure of the difference we have computed the mean-square difference of the X, Y and Z components as computed from the derived main-field models, including their secular-variation, and from the models resulting from linear interpolation of the main-field models only. The mean-square difference is computed on the sphere $r=a$, where a is the mean radius of the earth, using the formalism given by LOWES (1966). Table 4 shows these differences. As expected from the difference between two linear models, they increase linearly with time from the epoch of the nearest model. Some of these numbers seem large but, in general, they are considerably smaller than the predicted uncertainties shown in Figs. 2–5. The major exception is the difference for Z in 1958 which is of the same order of magnitude as the predicted uncertainty.

Table 4. Mean-square differences between components computed from models using the calculated secular variation and models computed using linear interpolation between main-field terms. Units are nT^2.

Epoch	X	Y	Z
1946	20.9	19.8	30.6
1947	41.7	39.7	61.2
1948	39.3	38.3	58.4
1949	19.6	19.1	29.2
1951	22.2	18.8	31.1
1952	44.3	37.7	62.1
1953	39.4	34.7	55.9
1954	19.7	17.4	27.9
1956	15.1	13.8	23.0
1957	30.4	27.5	46.1
1958	25.8	24.6	39.2
1959	12.8	12.3	19.5

9. Temporal Change

The secular variation from each of the four epochs is displayed in Figs. 6–9. The patterns are very similar from year to year indicating that the temporal change was fairly stable. The secular variation in X is dominated by a high in the northern Atlantic and a low in the southern Atlantic. The North Atlantic high gradually increases in magnitude with time and has a tendency to move over the North American continent. There is also a positive cell over much of Antarctica which decreases in amplitude with time. The change in X over Europe is positive and relatively stable at 0–10 nT a^{-1}. A small positive cell is present over India for 1945 and 1950 but decreases in magnitude and disappears by 1960.

The secular variation in Y is dominated by a negative over South America, a positive over West Africa which extends to the North Polar region, a negative in the Southern Indian ocean, and a positive over part of Antarctica, poleward from Australia. The South American cell increases slightly in amplitude but is fairly stable, as is the West-African cell. The negative in the Southern Indian ocean decreases rapidly in amplitude from near -120 nT a^{-1} in 1945 to near -60 nT a^{-1} in 1960. The positive over Antarctica slowly decreases in magnitude.

The secular variation in Z is dominated by a negative in the mid-Atlantic which is slowly increasing in magnitude, a negative in the Southern Indian ocean which is rapidly decreasing in magnitude and a positive in the southernmost Atlantic, extending on into the South Pacific, which is decreasing in magnitude. A developing negative cell is present over New Guinea. There is also a positive cell over eastern Europe and the U.S.S.R. in the early years, which shrinks and disappears with time.

The westward drift of the geomagnetic field is a well known but little understood phenomenon whose nature and extent is debated. A common way of computing a drift rate, $\dot{\phi}$, at the Earth's surface, is to use the equation (WHITHAM, 1958; LANGEL, 1987):

$$\dot{\phi} = \frac{\sum_{n,m} [m/(2n+1)][g_n^m \dot{h}_n^m - h_n^m \dot{g}_n^m]}{\sum_{n,m} [m^2/(2n+1)][(g_n^m)^2 + (h_n^m)^2]} \,. \tag{12}$$

Equation (12) is usually applied to the non-dipole field and is limited to coefficients of lower degree. For comparison with the results of LANGEL *et al.* (1986), we computed the westward drift for coefficients of degree 2 through 5. The results, given in Table 5, agree within about 10% of the results derived by LANGEL *et al.* (1986) and show the same trend toward decreasing drift rate as time progresses.

The first approximation of the geomagnetic field is that of the field of a dipole located at the Earth's center and inclined to its axis of rotation. Approximately 90% of the field at the Earth's surface can be represented by this simple model and the approximation improves with height above the Earth's surface. The strength of that dipole is represented by Ma^{-3}, where M is the dipole moment computed from the first three harmonic coefficients and a is the mean radius of the Earth, and has been decreasing for some years (MCDONALD and GUNST, 1967; HARWOOD and MALIN, 1976; BARRACLOUGH *et al.*, 1978), resulting in speculation that we may be observing a reversal of the Earth's field. We have computed Ma^{-3} from the new models; from previously published DGRF models for 1965, 1970, 1975 and 1980; and from IGRF1985. Figure 16 shows the variation of Ma^{-3} and of the axial dipole term, g_1^0, as a function of time. Figure 17 shows the time rate of change of these quantities as a function of time. Error bars would be smaller than the size of the plotted symbols on Fig. 16 and about equal to the size of the printed symbols on Fig. 17. Both rates of change have increased from nearly 7.5 nT a^{-1} at 1945–1950 to rates above 20 nT a^{-1} since 1970. The divergence of the rates after 1965 is due to an increase in the rates of change in g_1^1 and h_1^1 at that time. The present rate of decrease of Ma^{-3} is nearly 27 nT a^{-1}. As pointed out by LANGEL *et al.* (1980), if the present rate continues the Earth's field will reverse in about 1200 years. However, it is far from certain that this rate will continue. A plot of $\dot{g}_1^0$ shows (e.g., LANGEL *et al.*, 1986; LANGEL, 1987) that its rate of change reached a minimum near 1945 after having reached a maximum of about 30 nT/yr at about 1917, i.e., the rate of change of $\dot{g}_1^0$ is fluctuating. There is some evidence (e.g., LANGEL *et al.*, 1986) that changes in $\dot{g}_1^0$ are correlated with changes in the decade fluctuations in the rate of rotation of the Earth.

Table 5. Westward drift computed from coefficients of degree 2 through 10.

Year	$\dot{\phi}$ (degrees a^{-1})
1945	-0.211
1950	-0.200
1955	-0.189
1960	-0.171

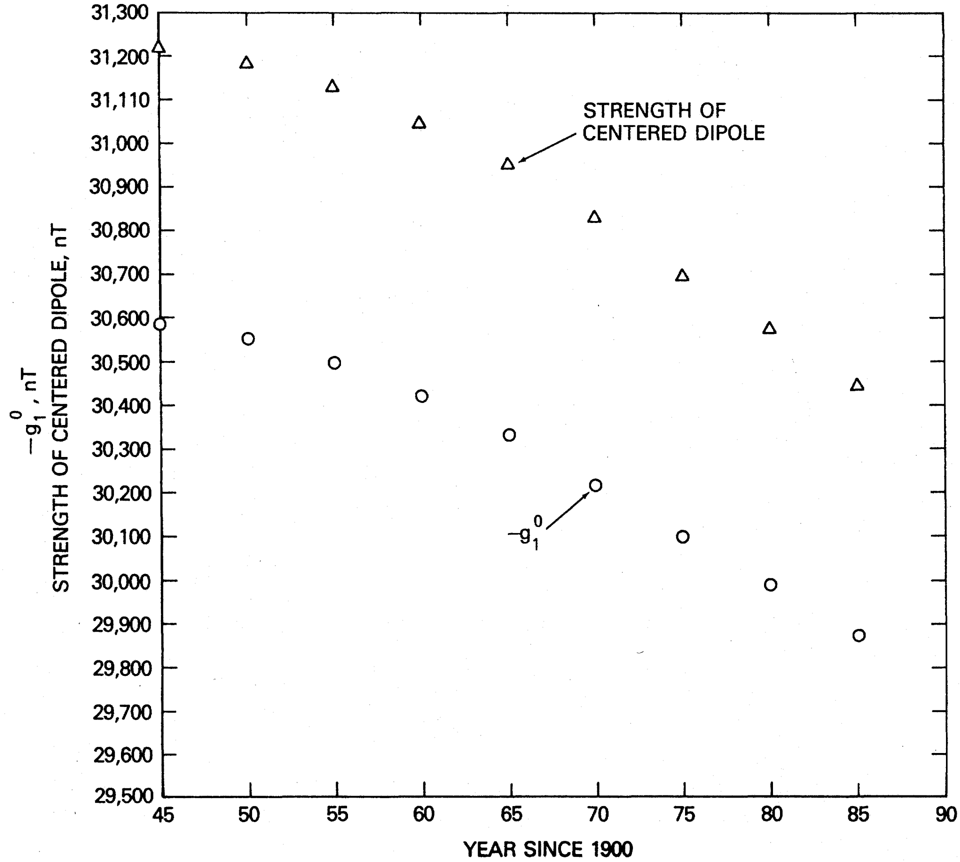


Fig. 16. Variation of g_1^0 and the strength of the centered dipole with time as determined from IGRF models. Units are nT.

10. Geomagnetic Poles

The two points where the axis of the centered, tilted, dipole cuts the surface of the Earth are known as the geomagnetic or dipole poles; they are mutually antipodal and their positions can be calculated from the values of the first three coefficients of a spherical harmonic model (see, e.g., LANGEL, 1987). The positions of the northern geomagnetic pole at five-yearly intervals from 1945 to 1990, as given by the models of the fifth generation IGRF, are given in Table 6. The variation with time of the latitude and longitude of the geomagnetic pole are shown in Fig. 18. The dipole pole remained at an essentially constant latitude of about 78.5° N from 1945 until 1955. Since then, it has been moving northwards at an increasing rate which is currently about 2.5 arcmin yr^{-1} or 4.6 km yr^{-1}. From 1945 to 1980 the geomagnetic pole moved westwards at

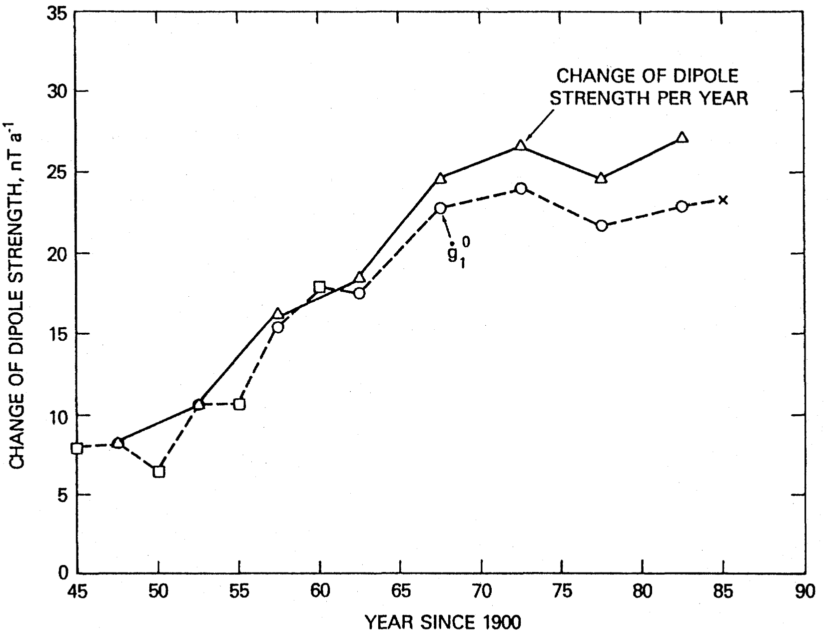


Fig. 17. Variation of $\dot{g}_1^0$ and rate of change of strength of centered dipole versus time as determined from IGRF models and associated secular-variation models. Circled points are from linear secular-variation between DGRF and candidate DGRF models; boxed points are secular-variation models solved for in association with the candidate DGRF models; the x is the 1985 IGRF secular-variation model, which is a predictive model. Points inside triangles are the yearly change of the strength of the centered dipole in nT a^{-1}.

Table 6. North geomagnetic (dipole) pole positions computed from fifth generation IGRF.

YEAR	LATITUDE (Degrees)	LONGITUDE (Degrees)
1945	78.47 (0.014)	-68.53 (0.066)
1950	78.47 (0.012)	-68.85 (0.056)
1955	78.46 (0.008)	-69.16 (0.036)
1960	78.51 (0.003)	-69.47 (0.018)
1965	78.53 (0.005)	-69.85 (0.013)
1970	78.59 (0.007)	-70.18 (0.022)
1975	78.69 (0.009)	-70.47 (0.024)
1980	78.81 (0.001)	-70.76 (0.004)
1985	78.98 (0.021)	-70.90 (0.076)
1990	79.19 (0.056)	-70.98 (0.136)

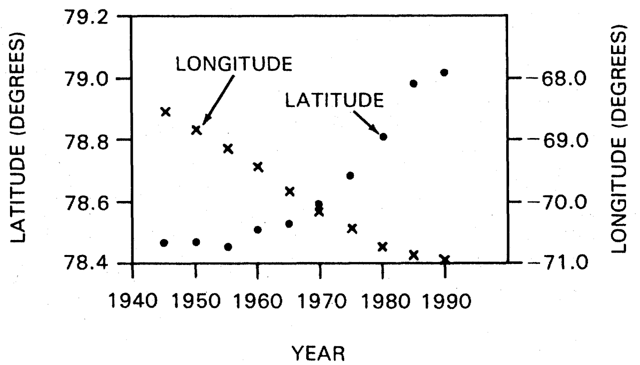


Fig. 18. Position of North Geomagnetic Pole.

about 4 arcmin yr^{-1} (1.3 km yr^{-1}) but since 1980 the drift rate has slowed to about 1.5 arcmin yr^{-1} (0.4 km yr^{-1}).

A better approximation to the geomagnetic field is given by displacing the dipole discussed above from the center of the Earth whilst maintaining its dipole moment and direction in space constant. The position of the eccentric, or offset, dipole that best fits the geomagnetic field can be calculated from the values of the first 8 coefficients of a spherical harmonic model; details are given by LANGEL (1987). (See also THOMSON, 1872; SCHMIDT, 1934.) The coordinates (x, y, z) of the eccentric dipole position (sometimes referred to as the magnetic center) are given in Table 7, together with the alternative representation in terms of geocentric distance (r), latitude and longitude. The orientation of the cartesian coordinate system is such that the z axis is parallel to the Earth's rotation axis, the x axis lies in the equatorial plane and points toward longitude 0° and the y axis lies in the same plane and points toward 90° E. The positions have been calculated from the models of the fifth generation IGRF. Figure 19 shows the variation with time of the latitude, longitude and radius of the eccentric dipole. Present velocities in the x, y, and z directions are -1.2 km yr^{-1}, 2.0 km yr^{-1} and 1.8 km yr^{-1}, respectively. The radial velocity of the eccentric dipole has been approximately constant at about 2.4 km yr^{-1} outward from the Earth's center.

The magnetic dip-poles are defined as the points on the Earth's surface where the geomagnetic field is vertical. Although the notion of the dip-poles as definite points is over-simplified (the effects of external current systems cause the instantaneous position of a dip-pole to follow a roughly elliptical path whose dimensions can reach 100 km or more), their positions are of some interest. The positions of the north and south dip poles, as computed from the models of the fifth generation IGRF at five-yearly intervals, are given in Table 8. The time variation of the latitudes and longitudes of the two poles are shown in Fig. 20.

These dip-pole positions can be compared with the latest determinations of their positions based on local surveys. NEWITT and NIBLETT (1986), using data from 7

Table 7. Eccentric dipole positions computed from fifth generation IGRF.

YEAR	M(nT)	x(km)	y(km)	(km)
1945	31224.5 (6.7)	-355.2 (0.82)	175.5 (0.90)	92.3 (0.93)
1950	31183.7 (5.6)	-359.0 (0.69)	190.7 (0.74)	101.3 (0.76)
1955	31129.2 (3.7)	-362.6 (0.48)	203.5 (0.54)	110.7 (0.55)
1960	31043.2 (1.3)	-365.9 (0.19)	214.8 (0.16)	122.4 (0.23)
1965	30951.6 (3.0)	-368.8 (0.25)	223.8 (0.25)	133.6 (0.15)
1970	30829.2 (4.0)	-373.1 (0.20)	231.0 (0.38)	146.4 (0.29)
1975	30696.4 (2.2)	-378.6 (0.18)	237.0 (0.26)	159.8 (0.43)
1980	30573.7 (0.8)	-385.4 (0.04)	247.5 (0.02)	170.2 (0.11)
1985	30438.0 (4.5)	-391.9 (0.29)	257.7 (0.40)	178.9 (0.46)
1990	30299.1 (7.5)	-398.2 (0.63)	267.3 (1.45)	187.2 (1.61)

YEAR	r(km)	Lat(°)	Long(°)
1945	406.8 (0.8)	13.12 (0.130)	153.71 (0.128)
1950	418.9 (0.7)	13.99 (0.104)	152.03 (0.103)
1955	430.3 (0.5)	14.91 (0.073)	150.69 (0.072)
1960	441.6 (0.2)	16.09 (0.029)	149.59 (0.023)
1965	451.6 (0.2)	17.20 (0.021)	148.75 (0.033)
1970	462.6 (0.3)	18.45 (0.036)	148.24 (0.044)
1975	474.4 (0.2)	19.69 (0.049)	147.95 (0.031)
1980	488.6 (0.1)	20.39 (0.013)	147.29 (0.004)
1985	502.1 (0.3)	20.88 (0.050)	146.67 (0.045)
1990	514.8 (1.1)	21.32 (0.172)	146.13 (0.150)

stations surrounding the expected position of the north magnetic dip-pole, derived its position at epoch 1983.9 as 77.0°N, 102.3°W. BARTON *et al.* (1987) used a novel technique involving a ship-borne magnetometer to determine the position of the south magnetic dip-pole and estimated its position at epoch 1986.0 to be 65° 10′S, 139° 10′E. These positions are indicated by crosses (x) on Fig. 20. The agreement between these positions and those computed from the IGRF is good.

Also plotted on Fig. 20 are a series of earlier dip-pole determinations based on local observations. These are plotted with a + symbol, extended to represent the uncertainty, where this is quoted. For the north dip-pole the positions are for 1945.0 (JONES, 1950); 1948.0 (DAWSON and LOOMER, 1963); 1950.0 (WHITHAM and LOOMER, 1956); 1953.0 (WHITHAM *et al.*, 1959); 1955.0 (from a Project MAGNET survey); 1960.0 and 1962.5 (DAWSON and LOOMER, 1963); 1964.0 (HAINES, 1967); 1965.0 (DAWSON and DALGETTY, 1966); 1970.9 (HAINES and HANNAFORD, 1974); 1973.5 and 1975.0 (DAWSON and NEWITT, 1978); 1980.0 (DAWSON and NEWITT, 1982b). The agreement between the IGRF values and these observed positions is generally good. These are fewer observed positions of the southern dip-pole. Those plotted are for 1952.0 (MAYAUD, 1953); 1959.0 (LARZILLIERE and LACHAUX, 1964); 1960.0 (from a Project MAGNET survey) and 1962.0 (BURROWS, 1963). The agreement is less good in the case of the latitude of the southern dip-pole.

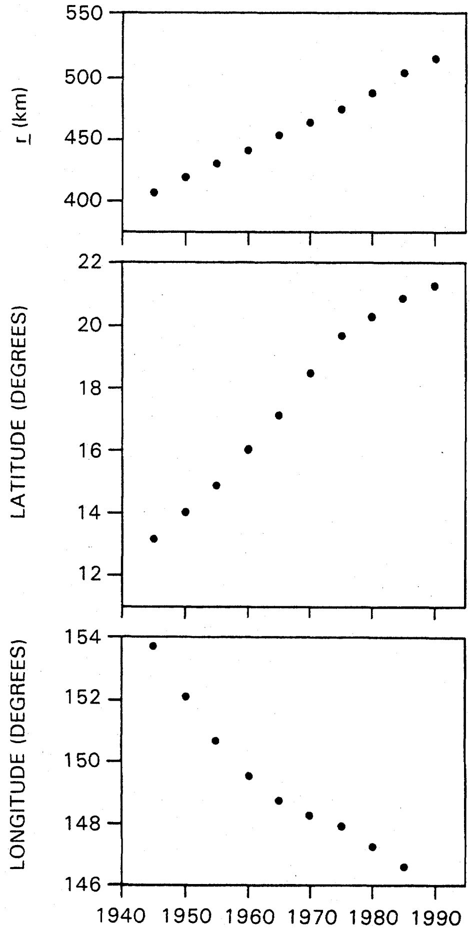


Fig. 19. Position of Eccentric Dipole.

Table 8. Magnetic dip-pole positions computed from fifth generation IGRF.

DATE	NORTH Latitude (Deg.)	NORTH Longitude (Deg.)	SOUTH Latitude (Deg.)	SOUTH Longitude (Deg.)
1945	73.93	-100.20	-68.17	144.45
1950	74.63	-100.83	-67.89	143.53
1955	75.18	-101.43	-67.20	141.53
1960	75.30	-101.06	-66.70	140.21
1965	75.63	-101.34	-66.33	139.53
1970	75.88	-100.98	-66.02	139.40
1975	76.15	-100.64	-65.74	139.52
1980	76.91	-101.68	-65.42	139.34
1985	77.38	-102.72	-65.14	139.31
1990	77.76	-103.68	-64.90	139.37

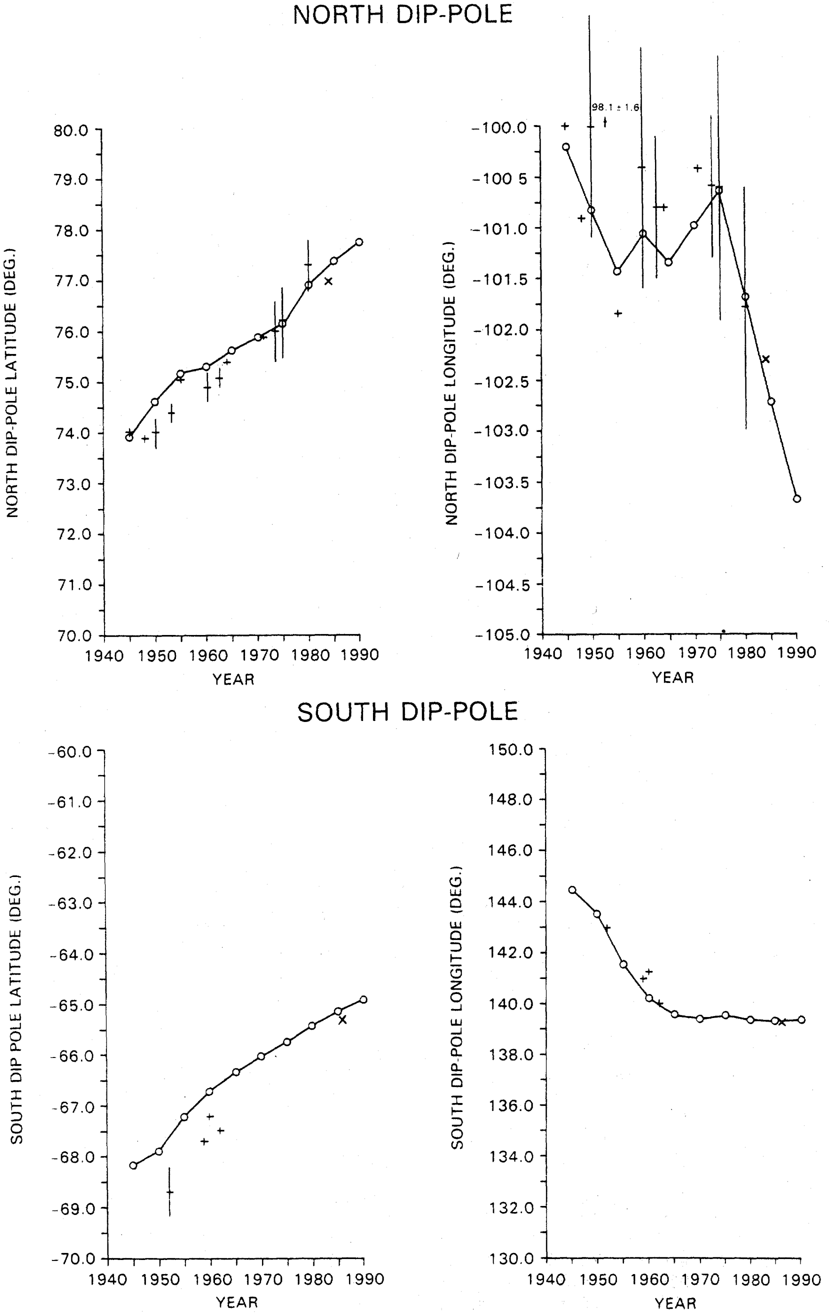


Fig. 20. Positions of North and South Dip-poles.

11. Summary and Conclusions

This paper presents results arrived at cooperatively by researchers in three countries. We believe that cooperation resulted in the collection of the most complete data sets possible. New techniques were employed to take maximum advantage of the accurate knowledge of the geomagnetic field at 1980 by projecting it backward in time and to make what we consider to be realistic uncertainty estimates on the resulting spherical harmonic coefficients.

The resulting models for 1945, 1950, 1955 and 1960 are considered to be as definitive as available data make possible. The coefficients and their uncertainty estimates were presented and discussed. Plots were presented for estimates of the field components and their secular change and of the uncertainty estimates for these quantities. A solution for bias fields at the fixed observatories was incorporated into the solution. The effect of these biases is demonstrated in plots of observatory data and the uncertainties in those biases are shown and discussed.

These models were adopted by IAGA as the definitive version of the IGRF for the epochs of the models. As DGRF's the derived secular variation models will not be used. Rather, the DGRF secular variation will be taken to be the linear interpolation between models at adjacent epochs. It was shown that the uncertainty introduced by this procedure is smaller than the estimated uncertainties of the main field models themselves.

Jeff Buck, Mike Purucker, Jeff Ridgway and Susan Simko of Science Applications Research were instrumental in making the plots and tables. We are grateful to World Data Center A, Boulder Colorado, for furnishing much of the data. This paper is published with the permission of the director, British Geological Survey. Part of this research was funded by NASA RTOP 676-40-02. Comments and criticisms by Frank Lowes, Jim Heirtzler, Coerte Voorhies, Pat Taylor, and two anonymous referees helped smooth some of the rough edges of the paper.

Appendix 1. Data Description

Table A1 lists all the observatories used, together with the time spans of the available data. Figures A1 to A4 show the geographical distribution of the observatory data used in the models for 1945, 1950, 1955 and 1960 respectively.

The majority of the survey data were selected from magnetic tapes containing all available magnetic survey observations made since 1900. These tapes were supplied by World Data Center A for geomagnetism, Boulder, Colorado. Each record contains, in general, values for the elements that were observed, together with calculated values for the other elements. Only the observed elements were used in producing the DGRF candidates. In almost all cases a maximum of three elements were observed. However, for the extensive oceanic surveys made by the Russian non-magnetic ship *Zarya*, the declination, D, horizontal intensity, H, vertical

Table A1. Observatories whose data were used in deriving the candidate DGRF models, together with the time spans of the available data and the "bias" values found in the four models.

OBSERVATORY	TIME SPAN		BIASES											
	START	STOP	1945			1950			1955			1960		
			X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
ABINGER	1943.50	1957.12	95.2	-73.7	58.9	70.9	-77.8	32.5	98.7	-91.0	8.7			
			(16.85)	(15.34)	(19.54)	(20.15)	(18.67)	(28.02)	(13.96)	(13.75)	(15.95)			
ABISKO	1948.50	1957.50				12.0	27.5	73.6	-10.3	26.3	-4.3			
						(18.17)	(18.99)	(22.42)	(20.29)	(20.35)	(26.16)			
ADDIS ABABA	1958.50	1962.50										386.1	42.6	70.1
												(17.51)	(18.93)	(25.39)
AGINCOURT	1943.50	1962.50	-12.3	171.4	-105.0	-66.5	176.3	-166.8	-28.0	181.0	-159.9	-60.3	192.3	-155.7
			(24.87)	(24.29)	(41.51)	(27.36)	(25.83)	(40.77)	(14.63)	(14.71)	(18.03)	(12.95)	(13.12)	(14.69)
ALIBAG	1943.50	1962.50	-195.5	375.8	648.6	-268.3	714.3	701.5	-152.9	549.8	554.7	-123.1	472.4	627.8
			(46.57)	(45.06)	(55.41)	(73.05)	(63.34)	(101.84)	(44.66)	(42.16)	(59.17)	(16.50)	(16.86)	(20.57)
ALMERIA	1955.50	1962.50							-64.3	7.3	-69.6	-12.1	51.2	-19.9
									(18.25)	(18.21)	(21.46)	(12.63)	(12.55)	(13.52)
AMBERLEY	1943.50	1962.50	18.7	-30.3	100.4	-0.4	-5.6	104.1	11.6	-3.3	48.4	20.7	37.5	79.6
			(28.10)	(31.66)	(68.15)	(34.29)	(36.72)	(84.71)	(29.01)	(29.77)	(34.26)	(17.82)	(17.77)	(21.55)
ANNAMALAINAGAR	1958.50	1962.50										142.6	-55.6	-267.8
												(16.64)	(17.40)	(22.72)
APIA	1943.50	1962.50	275.4	189.5	-1001.8	108.6	314.8	-831.2	-58.2	256.1	-891.2	-110.2	249.1	-1022.3
			(111.50)	(120.76)	(191.95)	(99.78)	(134.30)	(162.08)	(27.53)	(31.27)	(36.51)	(22.56)	(24.27)	(33.35)
AQUILA	1960.50	1962.50										-24.4	51.7	48.8
												(15.92)	(15.76)	(16.58)
ARGENTINE ISLND	1958.50	1962.50										126.8	-92.6	250.8
												(21.22)	(29.11)	(35.43)
BAKER LAKE	1953.50	1962.50							67.8	-66.3	-63.8	94.1	-78.1	-86.3
									(16.37)	(15.54)	(20.01)	(13.52)	(13.28)	(14.99)
BANGUI	1955.50	1962.50							-151.7	6.2	248.7	-170.5	21.9	256.0
									(25.39)	(27.00)	(29.09)	(18.75)	(19.23)	(27.35)
BARROW	1949.50	1962.50				-33.8	-104.2	55.2	-24.8	-43.8	58.5	26.6	-87.1	74.3
						(47.85)	(34.08)	(71.00)	(31.31)	(25.75)	(40.16)	(16.04)	(15.80)	(19.49)
BEIJING	1958.50	1962.50										577.0	-194.0	468.6
												(19.50)	(20.18)	(26.48)
BINZA	1953.50	1962.50							-146.6	-148.5	-2.5	-118.3	-112.7	-31.6
									(29.11)	(26.58)	(34.44)	(19.21)	(19.28)	(26.44)
BJORNOYA	1953.50	1962.50							-145.0	-2.7	-46.7	-129.1	13.6	20.5
									(22.53)	(21.33)	(28.91)	(14.97)	(15.96)	(18.52)
BUDAKESZI	1949.50	1955.50				-32.2	-2.4	-41.4	-25.1	27.1	-39.3			
						(20.77)	(21.74)	(26.74)	(18.34)	(18.97)	(20.15)			
BYRD	1958.50	1961.50										85.9	-364.8	-325.3
												(24.97)	(21.14)	(28.34)
CASTELLACCIO	1943.50	1962.50	54.4	-189.4	-248.5	13.9	-206.1	-216.4	26.5	-171.8	-188.9	1.8	-173.6	-80.4
			(21.35)	(16.51)	(22.59)	(22.20)	(18.72)	(25.80)	(16.01)	(15.65)	(17.62)	(12.41)	(12.32)	(13.24)
CHA PA	1958.50	1962.50										-70.4	-162.4	-166.9
												(19.56)	(18.29)	(26.32)
CHAMBON FORET	1943.50	1962.50	3.3	-10.6	190.8	-39.6	-21.5	180.1	-19.3	-15.1	140.4	-73.4	-3.3	153.9
			(17.46)	(13.61)	(19.59)	(21.98)	(17.08)	(26.23)	(14.00)	(13.77)	(15.92)	(12.19)	(12.29)	(13.23)
CHELTENHAM	1943.50	1956.40	-88.9	-0.4	271.9	-110.4	-8.6	346.6	-61.1	-16.0	315.6			
			(27.91)	(24.66)	(42.35)	(29.58)	(30.21)	(43.44)	(15.31)	(15.74)	(18.31)			
CHELYUSKIN	1943.50	1962.50	-80.9	-40.8	-117.8				-191.0	-26.2	-123.1	-99.6	-19.2	-108.9
			(49.60)	(43.78)	(71.87)				(30.64)	(33.42)	(47.42)	(18.40)	(18.95)	(26.36)
COIMBRA	1943.50	1962.50	-22.7	-8.3	-353.2	-15.6	-26.7	-52.9	4.0	-8.8	-13.6	8.2	3.8	32.5
			(28.15)	(25.59)	(29.61)	(29.30)	(29.21)	(31.47)	(14.65)	(14.32)	(17.39)	(12.53)	(12.57)	(13.51)
COLLEGE	1943.50	1962.50	-33.6	-40.6	-42.3	-61.4	-92.5	25.3	-76.4	-26.3	-12.4	-51.6	-45.9	-43.9
			(37.54)	(31.62)	(62.39)	(50.55)	(34.71)	(67.89)	(28.42)	(24.24)	(36.93)	(15.36)	(15.25)	(18.95)
DIKSON	1943.50	1962.50	-277.6	-134.5	-62.3	-262.6	92.1	5.0	-155.0	-35.9	-263.2	-85.1	-75.8	-306.0
			(48.84)	(38.34)	(61.08)	(42.36)	(33.17)	(52.71)	(32.58)	(28.61)	(43.85)	(19.29)	(18.89)	(26.20)

Table A1. (continued).

OBSERVATORY	TIME SPAN START	TIME SPAN STOP	BIASES 1945 X	1945 Y	1945 Z	1950 X	1950 Y	1950 Z	1955 X	1955 Y	1955 Z	1960 X	1960 Y	1960 Z
DOMBAS	1943.50	1962.50	-127.4	-116.7	-112.9				-90.1	-100.6	-223.7	-115.0	-84.0	-185.8
			(17.88)	(15.37)	(20.38)				(16.30)	(16.58)	(19.60)	(13.17)	(13.78)	(14.81)
DOURBES	1953.50	1962.50							10.4	-4.2	61.0	-7.9	-1.2	137.6
									(16.78)	(16.79)	(18.65)	(12.22)	(12.43)	(13.47)
DRUZHNAYA	1959.50	1962.50										70.0	-640.5	1108.7
												(18.45)	(17.92)	(23.98)
DUMONT DURVILLE	1958.50	1962.50										-158.6	-376.5	-3084.0
												(20.42)	(23.93)	(29.95)
DUSHETI	1943.50	1962.50	-145.2	-14.0	-187.7	-210.7	-4.6	-39.1	-236.9	26.2	-57.4	-235.9	34.0	-85.5
			(40.28)	(24.76)	(40.22)	(43.04)	(35.16)	(57.45)	(31.66)	(24.87)	(43.68)	(16.97)	(15.85)	(22.82)
EBRO	1943.50	1962.50	1.8	5.4	-26.2	-4.2	-7.8	34.5	5.2	-1.3	-7.0	7.5	25.9	20.3
			(21.60)	(17.15)	(24.94)	(25.84)	(20.64)	(32.17)	(15.30)	(14.73)	(17.50)	(12.31)	(12.18)	(13.10)
ELISABETHVILLE	1943.50	1957.50	-326.1	-187.2	78.0	-145.4	-121.9	20.9	-10.8	-152.7	-32.6			
			(127.36)	(118.68)	(185.36)	(56.97)	(47.03)	(77.80)	(29.79)	(38.34)	(46.76)			
ESKDALEMUIR	1943.50	1962.50	22.1	-55.9	-6.1	15.3	-35.7	-33.5	33.6	-62.2	-39.6	-4.9	-41.5	-6.0
			(17.70)	(18.42)	(20.80)	(18.92)	(20.70)	(30.00)	(14.45)	(14.02)	(16.51)	(12.51)	(12.90)	(13.90)
FREDERICKSBURG	1958.50	1962.50										-27.5	-46.6	148.4
												(13.33)	(13.53)	(14.52)
FUQUENE	1954.90	1962.50							133.6	-66.3	78.6	85.6	-104.8	101.9
									(19.81)	(19.51)	(24.02)	(14.13)	(15.85)	(16.57)
FURSTNFELDBRUCK	1943.50	1962.50	16.4	-2.1	54.6	-8.5	-16.7	21.8	-0.5	9.4	2.9	-32.4	0.2	69.1
			(16.86)	(12.50)	(19.00)	(19.36)	(18.24)	(24.37)	(14.16)	(14.40)	(16.32)	(12.35)	(12.59)	(13.65)
GNANGARA	1959.50	1962.50										-143.2	-79.8	93.6
												(20.54)	(20.07)	(25.91)
GODHAVN	1943.50	1962.50	204.3	-191.6	552.0	173.4	-201.4	480.8	198.3	-208.0	573.1	192.5	-182.2	500.5
			(46.64)	(34.12)	(61.33)	(35.26)	(29.34)	(52.23)	(16.93)	(15.80)	(20.48)	(14.21)	(13.37)	(17.10)
GORNOTAYEZHNAYA	1958.50	1962.50										-27.1	-27.5	-10.8
												(16.31)	(18.10)	(22.38)
GROCKA	1958.50	1962.50										-48.0	-66.0	-11.4
												(13.05)	(13.47)	(14.29)
GUAM	1958.50	1962.50										82.9	106.4	82.7
												(17.50)	(20.01)	(25.94)
HALLETT STATION	1958.50	1962.50										103.5	-236.2	-374.9
												(19.90)	(23.08)	(26.49)
HALLEY BAY	1958.50	1962.50										-222.8	430.2	-28.5
												(23.58)	(24.21)	(34.30)
HARTLAND	1958.50	1962.50										-42.2	19.2	97.7
												(12.37)	(12.62)	(13.53)
HEL	1958.50	1962.50										19.4	-160.9	-12.4
												(13.09)	(13.73)	(15.04)
HELWAN	1943.50	1957.50	-227.4	-39.4	-28.7	-195.8	47.2	27.3	-96.4	49.4	-27.5			
			(53.62)	(43.12)	(72.44)	(44.99)	(39.89)	(63.98)	(29.91)	(29.70)	(41.14)			
HERMANUS	1943.50	1962.50	198.4	82.5	-215.0	1.1	19.8	94.7	-9.3	47.4	18.8	-50.8	63.7	3.0
			(181.03)	(153.29)	(207.81)	(58.33)	(65.29)	(85.92)	(42.27)	(43.04)	(55.37)	(22.44)	(22.82)	(28.24)
HOLLANDIA	1958.50	1962.33										-183.3	-39.5	-382.2
												(16.88)	(19.98)	(26.17)
HONOLULU	1943.50	1960.50	10.7	-388.7	77.4	136.2	223.7	44.0	23.8	166.8	107.8	72.0	177.2	63.9
			(137.26)	(76.19)	(203.60)	(116.10)	(142.79)	(178.06)	(26.50)	(28.46)	(31.38)	(20.37)	(20.53)	(24.64)
HUANCAYO	1943.50	1962.50	102.9	73.2	-15.8	111.5	47.2	-10.3	75.0	47.3	-1.1	152.3	34.7	100.9
			(43.11)	(45.28)	(65.12)	(36.52)	(45.84)	(60.52)	(31.77)	(32.88)	(43.21)	(12.79)	(20.01)	(23.44)
HURBANOVO	1948.50	1962.50				10.9	-22.4	-96.0	18.9	2.5	-60.6	-7.8	-28.4	11.4
						(20.39)	(21.39)	(26.47)	(15.64)	(16.35)	(17.80)	(12.71)	(13.27)	(14.26)
IBADAN	1958.50	1962.50										48.0	-350.9	33.7
												(17.07)	(18.29)	(23.87)
ISLA DE PASCUA	1958.50	1962.25										424.5	29.2	-335.4
												(32.27)	(32.68)	(45.78)

Table A1. (continued).

OBSERVATORY	TIME SPAN START	STOP	BIASES 1945 X	1945 Y	1945 Z	1950 X	1950 Y	1950 Z	1955 X	1955 Y	1955 Z	1960 X	1960 Y	1960 Z
ISTANBL KNDILLI	1948.50	1962.50				124.5	143.3	-84.7	157.5	142.6	-51.8	165.1	76.1	-3.4
						(32.72)	(28.88)	(36.83)	(23.01)	(22.05)	(27.53)	(14.35)	(14.52)	(16.07)
JASSY	1943.50	1957.50	179.5	-135.5	86.8	133.7	-68.6	193.3	112.8	-50.8	105.0			
			(22.84)	(15.84)	(25.55)	(24.59)	(25.30)	(31.86)	(20.22)	(19.97)	(23.59)			
KAKIOKA	1943.50	1962.50	-19.4	51.8	-87.1	-20.6	47.3	37.0	-35.0	24.2	-15.0	-6.2	17.6	-61.3
			(37.44)	(38.86)	(51.17)	(31.20)	(32.83)	(46.72)	(16.61)	(17.20)	(22.65)	(15.56)	(15.90)	(19.43)
KANOYA	1960.50	1962.50										4.6	38.3	-21.9
												(18.78)	(19.20)	(22.44)
KANOZAN	1961.50	1962.50										-34.2	44.3	-48.9
												(21.30)	(21.67)	(24.55)
KARAVIA	1958.50	1961.30										59.7	-122.4	47.7
												(19.03)	(20.06)	(26.57)
KELES	1943.50	1962.50	-235.6	-11.6	-170.9	-219.1	37.8	-105.2	-287.5	9.3	-92.8	-264.1	-43.9	32.6
			(41.01)	(34.55)	(54.99)	(52.76)	(48.80)	(72.30)	(33.99)	(33.09)	(42.85)	(18.29)	(19.95)	(26.20)
KERGUELEN	1958.50	1962.50										101.0	294.9	739.5
												(24.97)	(26.36)	(36.55)
KIEV	1958.60	1962.50										-69.1	169.8	168.4
												(14.35)	(14.92)	(17.35)
KODAIKANAL	1950.50	1962.50				-541.8	333.7	291.9	-625.5	300.6	-36.2	-564.0	248.3	-64.5
						(70.12)	(60.29)	(124.28)	(41.20)	(41.45)	(76.66)	(16.28)	(17.44)	(22.43)
KRASNAYA PAKHRA	1946.50	1962.50	137.8	-19.9	339.9	85.8	-9.5	243.3	83.4	0.1	257.9	83.8	-28.1	298.4
			(25.12)	(21.93)	(28.65)	(26.16)	(26.27)	(35.17)	(25.73)	(20.78)	(30.22)	(16.18)	(15.70)	(19.72)
KSARA	1943.50	1962.50	-135.8	-1.9	-211.8	-126.4	65.4	-80.1	-63.0	95.1	-107.3	-28.9	46.7	-75.2
			(53.88)	(35.41)	(61.38)	(45.91)	(38.00)	(60.89)	(29.00)	(26.21)	(38.65)	(16.31)	(15.47)	(18.76)
KUYPER	1949.50	1957.50				85.6	363.8	77.7	166.3	92.3	120.9			
						(85.74)	(90.83)	(135.80)	(41.44)	(45.88)	(70.00)			
LA QUIACA	1943.50	1962.50	52.7	22.9	-0.6	12.9	28.5	-27.4	-49.4	-47.3	-56.1	42.0	-50.9	-9.7
			(38.17)	(38.54)	(52.67)	(39.30)	(33.70)	(51.17)	(35.86)	(38.74)	(51.49)	(20.43)	(23.81)	(28.64)
LANZHOU	1959.50	1961.50										-52.0	19.6	-40.5
												(22.91)	(21.68)	(32.00)
LEIRVOGUR	1958.50	1962.50										-297.1	595.6	-399.5
												(13.65)	(13.16)	(16.14)
LERWICK	1943.50	1962.50	-115.6	146.9	75.4	-101.6	172.8	67.1	-106.1	139.2	66.8	-140.5	163.8	83.9
			(18.08)	(19.07)	(21.66)	(19.69)	(21.06)	(26.31)	(15.30)	(14.91)	(17.79)	(12.82)	(13.33)	(14.30)
LHASA	1958.50	1962.50										137.0	-9.8	27.8
												(20.21)	(19.42)	(27.44)
LOGRONO	1958.50	1962.50										-4.6	28.4	57.7
												(12.21)	(12.18)	(13.10)
LOVO	1943.50	1962.50	23.6	1.1	58.9	47.1	-16.1	29.9	28.5	3.2	10.0	10.4	-4.7	59.1
			(17.75)	(14.76)	(19.63)	(17.34)	(19.12)	(21.51)	(17.16)	(17.34)	(20.14)	(13.45)	(13.99)	(15.41)
LUANDA BELAS	1954.50	1962.50							238.0	-40.2	277.8	234.3	-0.1	193.6
									(32.30)	(33.12)	(48.33)	(19.48)	(19.37)	(26.07)
LVOV	1958.50	1962.50										129.5	116.5	213.1
												(13.28)	(14.10)	(15.43)
LWIRO	1958.75	1961.77										254.8	29.0	139.1
												(19.64)	(20.22)	(26.93)
M BOUR	1953.50	1962.50							104.9	78.6	122.7	127.2	8.1	149.7
									(15.25)	(15.43)	(18.75)	(16.36)	(17.63)	(22.00)
MACQUARIE ISLND	1948.21	1962.50				86.1	48.2	425.4	189.8	-42.4	442.6	286.4	-33.9	301.1
						(75.00)	(71.08)	(87.20)	(34.85)	(44.24)	(56.91)	(18.66)	(20.20)	(26.57)
MAGADAN	1960.50	1962.50										-1342.3	288.1	1282.1
												(20.33)	(22.65)	(28.82)
MANHAY	1948.50	1962.50				4.0	-7.2	196.6	39.7	7.1	190.3	3.4	6.1	261.0
						(19.38)	(17.54)	(25.29)	(13.83)	(13.88)	(15.90)	(12.24)	(12.46)	(13.54)
MAPUTO	1958.50	1962.50										259.1	69.7	-171.8
												(19.87)	(20.85)	(23.72)

Table A1. (continued).

OBSERVATORY	TIME SPAN START	TIME SPAN STOP	BIASES 1945 X	1945 Y	1945 Z	1950 X	1950 Y	1950 Z	1955 X	1955 Y	1955 Z	1960 X	1960 Y	1960 Z
MAURITIUS	1943.50	1962.50	546.4	-526.7	-265.9	509.1	-375.0	-312.1	508.4	-505.4	-540.1	461.1	-320.4	-521.2
			(162.37)	(113.64)	(203.41)	(109.49)	(87.86)	(139.43)	(65.55)	(52.65)	(69.25)	(21.51)	(20.92)	(28.50)
MAWSON	1955.80	1962.50							94.8	28.9	219.8	99.3	110.0	204.1
									(48.24)	(43.43)	(70.16)	(22.36)	(22.90)	(32.20)
MEANOOK	1943.50	1962.50	76.1	20.8	23.8	106.1	24.2	-78.8	126.5	-12.2	-80.3	77.9	-29.3	-42.6
			(35.03)	(30.75)	(43.38)	(30.67)	(30.56)	(42.67)	(16.29)	(16.30)	(18.76)	(12.97)	(13.40)	(15.26)
MEMAMBETSU	1953.50	1962.50							-217.5	146.8	94.3	-251.9	133.6	92.7
									(19.15)	(21.06)	(29.03)	(15.60)	(16.81)	(21.97)
MIRNYY	1958.50	1962.50										50.0	0.4	-484.6
												(21.93)	(22.45)	(28.38)
MISALLAT	1960.58	1962.50										-73.3	12.8	81.4
												(18.67)	(18.67)	(21.62)
MOCA	1958.50	1962.50										-121.6	10.2	253.6
												(18.00)	(19.05)	(25.16)
MONTE CAPELLINO	1958.75	1962.50										-50.9	-35.8	-490.8
												(12.40)	(12.33)	(13.25)
MUNTINLUPA	1951.50	1962.50				-167.3	-93.9	157.7	-99.7	-36.5	0.3	-57.7	-9.8	7.4
						(62.43)	(59.36)	(97.75)	(31.04)	(31.18)	(47.48)	(16.99)	(18.17)	(23.47)
MURMANSK	1958.80	1960.50										210.1	120.4	-412.2
												(18.12)	(18.16)	(21.67)
NANTES	1943.50	1957.50	46.5	19.7	73.5	15.6	15.1	244.6	59.3	14.7	298.7			
			(19.00)	(15.86)	(20.69)	(23.96)	(18.74)	(27.00)	(14.16)	(13.77)	(16.12)			
NIEMEGK	1943.50	1962.50	-12.3	7.4	-18.1	-25.2	-6.3	-73.1	-16.3	15.1	-80.9	-45.9	5.5	-19.0
			(15.42)	(12.43)	(17.82)	(17.43)	(18.94)	(24.01)	(14.41)	(14.84)	(16.65)	(13.68)	(14.10)	(15.20)
NORWAY STATION	1960.50	1962.00										-11.7	100.4	32.3
												(28.66)	(29.43)	(37.93)
NURMIJARVI	1953.50	1962.50							251.4	-91.1	110.4	239.1	-107.2	156.2
									(19.38)	(18.87)	(23.48)	(14.28)	(14.65)	(16.75)
ORCADAS DEL SUR	1943.50	1962.50	133.2	-276.9	-489.0	101.1	-122.0	-268.4	130.9	83.2	-444.7	74.6	94.6	-302.6
			(125.09)	(144.77)	(172.92)	(79.17)	(83.66)	(98.92)	(51.46)	(73.47)	(88.64)	(25.80)	(29.60)	(40.99)
PANAGYURISHTE	1948.50	1962.50				-196.4	-157.5	-239.7	-187.8	-133.4	-223.0	-210.3	-196.8	-172.2
						(27.10)	(25.65)	(29.90)	(19.99)	(20.08)	(22.12)	(13.57)	(13.88)	(14.78)
PARAMARIBO	1958.50	1962.50										46.7	93.5	4.4
												(14.79)	(17.53)	(21.46)
PATRICK	1954.83	1956.20							156.7	-47.2	119.2			
									(17.80)	(17.74)	(20.37)			
PATRONY	1959.50	1962.50										-0.2	127.9	-138.4
												(22.27)	(21.74)	(31.98)
PILAR	1943.50	1962.50	60.5	39.4	-51.4	24.0	4.6	-29.5	-31.4	-33.4	2.3	32.5	-27.8	-29.6
			(38.80)	(40.94)	(48.73)	(39.07)	(27.48)	(57.08)	(41.82)	(52.72)	(64.32)	(18.30)	(21.06)	(23.99)
PORT MORESBY	1958.79	1962.50										51.6	93.3	211.6
												(17.23)	(20.68)	(25.49)
PRUHONICE	1946.50	1962.50	-28.5	29.9	-90.8	-39.9	9.7	-123.2	-29.6	32.2	-116.7	-51.5	26.4	-30.0
			(21.54)	(19.01)	(23.79)	(18.10)	(19.20)	(24.58)	(14.52)	(15.09)	(16.85)	(12.50)	(12.97)	(14.10)
QUETTA	1953.90	1962.50							-0.4	94.1	-87.6	1.3	57.8	-7.0
									(36.29)	(35.74)	(51.70)	(17.06)	(17.58)	(20.95)
REGENSBERG	1958.50	1962.50										-7.9	48.1	19.6
												(12.27)	(12.39)	(13.42)
RESOLUTE BAY	1953.50	1962.50							-43.4	37.3	107.4	29.7	25.9	-27.6
									(21.52)	(19.55)	(26.14)	(14.34)	(14.21)	(17.51)
RUDE SKOV	1943.50	1962.50	25.8	-6.8	36.5	37.1	-19.2	4.9	34.8	-5.1	-19.7	7.7	-7.3	26.1
			(15.53)	(13.04)	(17.34)	(16.89)	(19.16)	(22.82)	(15.25)	(15.49)	(17.34)	(12.76)	(13.25)	(14.45)
SAN FERNANDO	1943.50	1962.50	-21.2	-39.8	-35.8	-5.4	-45.6	-0.1	-4.4	-23.4	-25.4	26.0	7.8	-88.5
			(28.07)	(25.60)	(34.40)	(25.45)	(27.83)	(37.65)	(15.14)	(15.09)	(18.52)	(13.88)	(13.88)	(14.72)
SAN JUAN	1943.50	1962.50	107.2	-42.2	286.4	131.2	-26.6	222.8	125.5	46.0	186.4	125.1	37.4	228.6
			(38.98)	(48.16)	(66.66)	(38.02)	(43.62)	(66.49)	(14.40)	(14.12)	(16.39)	(13.76)	(14.79)	(14.64)

Table A1. (continued).

OBSERVATORY	TIME SPAN START	TIME SPAN STOP	BIASES 1945 X	1945 Y	1945 Z	1950 X	1950 Y	1950 Z	1955 X	1955 Y	1955 Z	1960 X	1960 Y	1960 Z
SAN MIGUEL	1943.50	1962.50	582.4	516.2	1528.4	595.6	443.7	1701.7	670.3	433.9	1656.6	660.5	405.3	1713.6
			(53.09)	(48.76)	(68.18)	(49.15)	(44.20)	(69.67)	(13.94)	(14.05)	(16.59)	(15.09)	(13.87)	(17.34)
SHESHAN	1943.50	1962.50	-286.8	87.0	200.5	-279.9	130.3	304.1	-283.6	83.4	268.3	-233.6	82.0	270.9
			(31.49)	(28.77)	(43.30)	(45.45)	(43.25)	(62.47)	(28.35)	(28.39)	(34.92)	(17.59)	(18.36)	(22.64)
SIMOSATO	1954.84	1962.50							-84.9	36.6	44.6	-51.1	34.4	24.8
									(17.70)	(18.17)	(23.37)	(15.69)	(15.93)	(19.31)
SITKA	1943.50	1962.50	-11.8	-21.4	-76.4	-8.6	-34.7	-65.3	1.2	6.6	37.8	-25.3	14.3	13.8
			(43.30)	(32.07)	(59.94)	(46.14)	(40.12)	(55.75)	(23.49)	(22.24)	(28.33)	(14.71)	(14.70)	(17.37)
SODANKYLA	1943.50	1962.50	-189.3	-85.9	-517.5	-160.1	-133.3	-557.4	-198.3	-114.4	-611.0	-207.8	-130.5	-558.8
			(25.91)	(17.74)	(27.14)	(18.21)	(18.95)	(22.30)	(21.16)	(20.34)	(27.72)	(14.88)	(15.28)	(18.28)
SOUTH POLE	1959.50	1962.50										-1300.1	-3332.3	168.1
												(20.36)	(21.33)	(28.60)
SREDNIKAN	1943.50	1960.50	119.8	47.1	114.6	118.6	21.6	216.5	72.2	-54.0	238.6	123.6	-63.0	268.8
			(51.14)	(45.70)	(73.50)	(46.29)	(45.92)	(77.00)	(28.99)	(36.41)	(51.08)	(19.95)	(22.29)	(28.56)
STEPANOVKA	1948.50	1962.50				-111.4	-673.2	60.6	-103.0	-686.8	76.8	-112.4	-722.3	77.8
						(27.50)	(26.85)	(35.55)	(22.32)	(21.01)	(27.01)	(14.27)	(14.86)	(17.29)
STONYHURST	1961.50	1962.50										0.6	42.5	-20.7
												(18.80)	(19.02)	(19.94)
SURLARI	1949.50	1962.50				-21.3	-4.3	81.2	-3.1	-19.5	-70.1	-13.0	-73.4	-79.5
						(28.09)	(27.39)	(32.66)	(20.19)	(20.19)	(23.12)	(13.62)	(14.23)	(15.50)
SWIDER	1943.50	1962.50	-294.3	-114.5	308.5	-315.3	-110.3	232.7	-308.7	-83.1	250.9	-325.1	-109.3	326.8
			(16.54)	(12.95)	(19.45)	(18.22)	(21.25)	(26.44)	(16.78)	(17.18)	(19.14)	(13.13)	(13.88)	(15.17)
SYOWA BASE	1958.50	1962.50										-32.7	57.0	-121.0
												(23.67)	(23.70)	(33.83)
TAMANRASSET	1948.50	1962.50				-28.9	-225.2	-67.3	-1.4	-247.5	-76.4	61.9	-189.1	5.1
						(39.91)	(41.10)	(45.21)	(18.32)	(19.95)	(26.85)	(15.15)	(16.01)	(19.62)
TANANARIVE	1943.50	1962.50	381.0	-58.9	-255.7	365.9	57.8	-340.6	284.6	38.0	-277.5	307.4	-1.5	-448.3
			(169.77)	(116.83)	(176.29)	(87.18)	(71.26)	(103.08)	(53.53)	(36.29)	(64.89)	(20.33)	(18.97)	(27.19)
TATUOCA	1958.50	1962.50										153.7	-109.8	147.3
												(17.09)	(18.21)	(24.15)
TEHRAN	1960.50	1962.50										-122.0	67.3	-185.1
												(20.15)	(18.79)	(25.37)
TENERIFE	1959.50	1962.50										-598.7	87.7	-1143.3
												(15.91)	(16.35)	(18.39)
TEOLOYUCAN	1943.50	1962.50	-24.3	20.7	-100.9	-28.6	-19.6	-170.5	16.4	0.1	18.9	-123.8	-17.1	39.7
			(40.96)	(43.33)	(55.62)	(50.28)	(58.37)	(68.57)	(26.29)	(24.15)	(31.36)	(16.59)	(16.52)	(21.59)
THULE I	1948.50	1952.50				105.8	58.2	-152.4						
						(38.02)	(32.05)	(51.41)						
THULE II	1955.84	1962.50							-128.0	158.2	11.1	-55.0	174.6	-47.7
									(23.30)	(20.93)	(27.85)	(14.90)	(14.02)	(18.61)
TIHANY	1955.50	1962.50							-15.6	12.1	-52.8	-36.8	-24.8	18.7
									(18.39)	(18.91)	(20.28)	(12.71)	(13.18)	(14.12)
TIKHAYA BAY	1943.50	1957.50	72.2	-48.8	-176.7				42.1	-22.8	-289.0			
			(43.71)	(37.01)	(61.62)				(29.83)	(25.13)	(39.25)			
TIKSI	1944.50	1962.50	-75.7	-116.1	211.7	-84.6	-150.7	68.5	-209.0	-179.8	5.9	-140.9	-161.1	-10.2
			(43.78)	(50.30)	(74.20)	(43.38)	(43.96)	(65.91)	(28.53)	(38.49)	(50.52)	(18.30)	(20.51)	(28.30)
TOLEDO	1948.50	1962.50				-24.3	-9.7	16.9	11.8	-2.1	5.3	10.2	23.8	27.3
						(25.69)	(23.09)	(31.88)	(15.05)	(14.61)	(17.69)	(12.35)	(12.31)	(13.27)
TOMSK	1958.50	1962.50										-24.2	-48.1	-331.9
												(20.78)	(21.55)	(29.53)
TOOLANGI	1943.50	1962.50	-48.7	-72.4	-56.7	85.8	-17.9	-2.2	7.6	-35.5	-15.9	-46.5	-75.7	61.3
			(49.34)	(46.62)	(88.88)	(67.01)	(62.65)	(100.01)	(22.97)	(23.91)	(33.60)	(16.01)	(16.03)	(18.18)
TRELEW	1958.50	1962.50										145.7	-35.5	5.4
												(18.71)	(21.71)	(20.31)
TRIVANDRUM	1958.50	1962.50										158.4	151.3	115.0
												(16.20)	(17.60)	(22.60)

Table A1. (continued).

OBSERVATORY	TIME SPAN START	TIME SPAN STOP	BIASES 1945 X	1945 Y	1945 Z	1950 X	1950 Y	1950 Z	1955 X	1955 Y	1955 Z	1960 X	1960 Y	1960 Z
TROMSO	1943.50	1962.50	35.4	-415.0	164.7	49.1	-426.1	242.1	29.5	-432.3	150.8	29.0	-431.6	215.7
			(27.35)	(17.94)	(29.26)	(18.01)	(18.76)	(22.14)	(20.12)	(20.00)	(26.38)	(14.40)	(15.23)	(17.41)
TUCSON	1943.50	1962.50	-112.6	-69.8	217.8	-83.1	-96.5	192.2	-125.5	-85.2	178.0	-185.7	-79.5	179.1
			(40.68)	(36.60)	(50.55)	(47.23)	(45.78)	(64.00)	(24.66)	(20.69)	(32.98)	(13.92)	(14.21)	(13.37)
UELEN	1953.50	1962.50							-196.4	25.8	-185.5	-107.1	23.8	-137.1
									(37.15)	(28.71)	(47.25)	(16.85)	(16.77)	(22.14)
VALENTIA	1943.50	1962.50	137.6	-30.1	-53.4	74.9	-8.8	-34.0	170.9	-62.1	15.4	135.6	-50.6	60.1
			(22.41)	(24.28)	(25.20)	(27.43)	(28.65)	(36.42)	(15.39)	(14.93)	(17.72)	(12.64)	(12.84)	(14.06)
VANNOVSKAYA	1959.50	1962.50										154.3	116.1	97.1
												(18.66)	(18.68)	(24.90)
VASSOURAS	1943.50	1962.50	2.1	22.1	-77.2	58.7	-40.6	-74.6	-4.8	-58.0	-65.7	35.4	-27.4	-147.1
			(56.11)	(60.30)	(75.52)	(48.46)	(51.25)	(66.61)	(29.12)	(33.05)	(41.96)	(18.18)	(19.23)	(25.11)
VICTORIA	1958.50	1962.50										6.4	-30.7	-260.0
												(13.42)	(14.24)	(15.87)
VOROSHILOV	1953.50	1957.50							-20.8	228.8	-42.8			
									(19.73)	(24.59)	(26.46)			
VOSTOK	1958.50	1961.50										-30.0	89.2	-55.5
												(20.56)	(20.11)	(25.67)
VOYEYKOVO	1948.50	1962.50				34.0	7.1	-285.2	10.6	33.9	-270.4	9.9	3.0	-228.1
						(21.25)	(22.31)	(25.72)	(21.81)	(19.83)	(26.43)	(15.16)	(15.17)	(18.03)
VYSOKAY DUBRAVA	1943.50	1962.50	-216.0	-181.7	-415.5	-298.9	-159.3	-521.3	-277.1	-149.0	-512.6	-338.0	-168.5	-521.0
			(30.89)	(29.69)	(43.14)	(37.29)	(34.82)	(54.61)	(32.00)	(26.76)	(43.74)	(19.48)	(18.83)	(26.30)
WATHEROO	1943.50	1957.50	-179.9	-262.5	158.3	-173.4	-395.7	264.4	-174.5	-274.0	64.8			
			(64.31)	(64.52)	(114.63)	(116.81)	(124.05)	(179.23)	(34.21)	(35.89)	(56.36)			
WIEN AUHOF	1943.50	1950.50	73.9	4.7	144.5	44.1	-3.8	110.2						
			(17.52)	(12.88)	(19.72)	(21.00)	(21.70)	(26.67)						
WIEN KOBENZL	1955.50	1962.50							29.8	24.3	41.4	6.9	-2.6	86.6
									(17.76)	(18.28)	(19.82)	(12.58)	(13.06)	(14.09)
WILKES	1958.50	1962.50										773.7	-375.7	-42.6
												(20.86)	(21.58)	(28.82)
WINGST	1943.50	1962.50	66.2	55.1	4.6	66.7	43.6	-20.2	70.9	53.4	-54.5	37.8	52.8	1.3
			(15.27)	(12.80)	(17.52)	(17.26)	(18.72)	(24.00)	(14.36)	(14.56)	(16.41)	(12.46)	(12.85)	(14.02)
WITTEVEEN	1943.50	1962.50	23.3	18.9	-52.6	23.8	5.1	-66.4	40.0	15.6	-73.2	8.2	17.1	-21.4
			(15.39)	(12.92)	(17.87)	(17.84)	(18.34)	(24.90)	(14.07)	(14.18)	(16.11)	(12.35)	(12.68)	(13.81)
YAKUTSK	1948.50	1962.50				66.1	-1124.4	40.9	35.9	-1128.5	214.2	38.1	-1174.3	211.0
						(40.19)	(49.91)	(66.39)	(26.59)	(38.59)	(47.83)	(18.44)	(21.94)	(28.82)
YUZHNO SAKHALSK	1948.50	1962.50				-62.0	-90.0	5.9	54.1	-135.4	26.5	-30.0	-171.0	-105.1
						(40.19)	(42.83)	(56.47)	(20.06)	(23.23)	(31.48)	(16.08)	(17.44)	(23.12)
ZAYMISHCHE	1943.50	1962.50	-230.8	-352.4	-117.5	-314.5	-338.9	-212.5	-307.4	-335.4	-225.2	-325.7	-342.6	-202.1
			(24.81)	(24.07)	(29.64)	(32.95)	(30.63)	(45.13)	(30.83)	(23.01)	(38.23)	(18.29)	(17.10)	(23.28)
ZUY	1943.50	1957.50	36.9	94.3	-51.5	-33.5	78.4	-60.2	-1.4	89.3	-68.2			
			(39.66)	(41.88)	(61.51)	(50.28)	(44.67)	(74.19)	(37.37)	(31.45)	(54.90)			

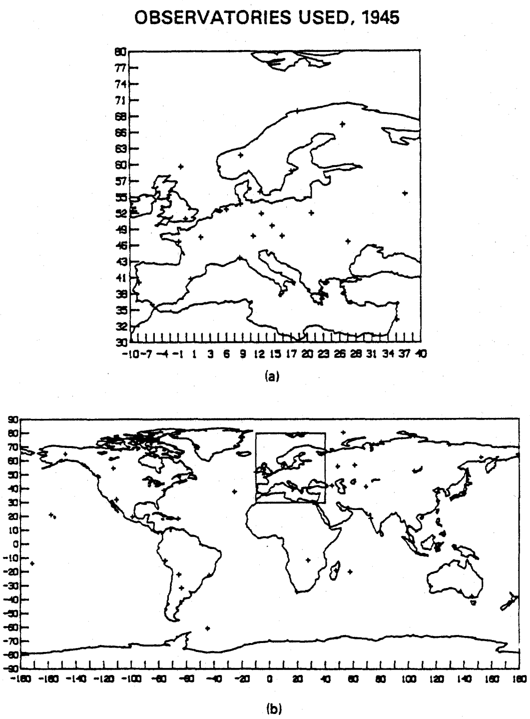


Fig. A1. Distribution of observatory data, 1945. (a) Europe, (b) Rest of the world.

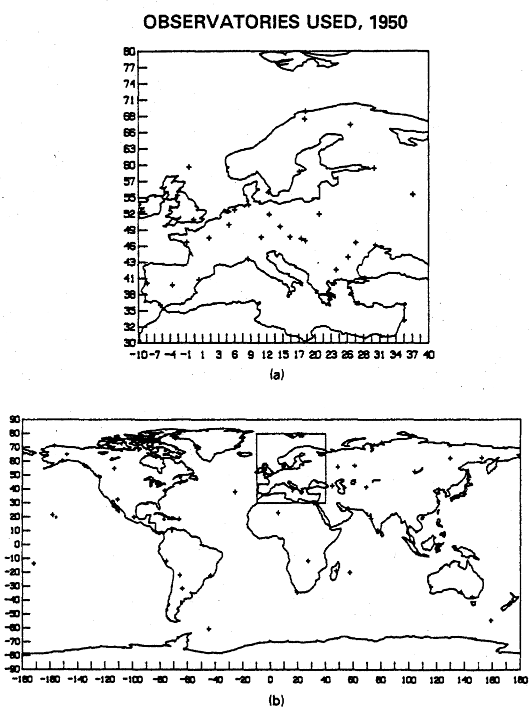


Fig. A2. Distribution of observatory data, 1950. (a) Europe, (b) Rest of the world.

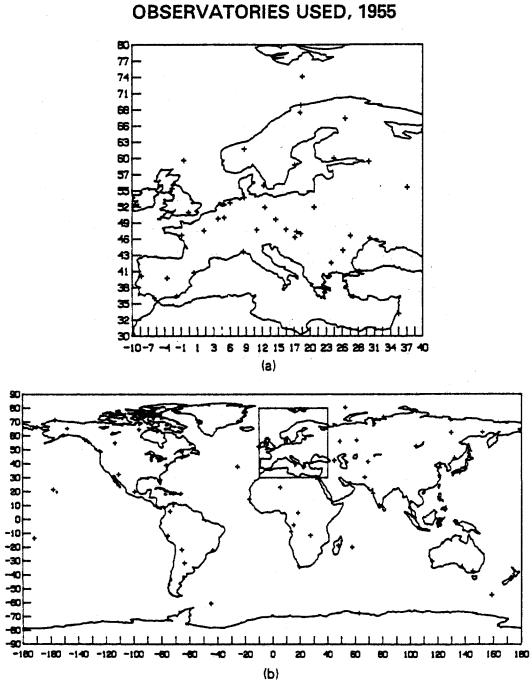


Fig. A3. Distribution of observatory data, 1955. (a) Europe, (b) Rest of the world.

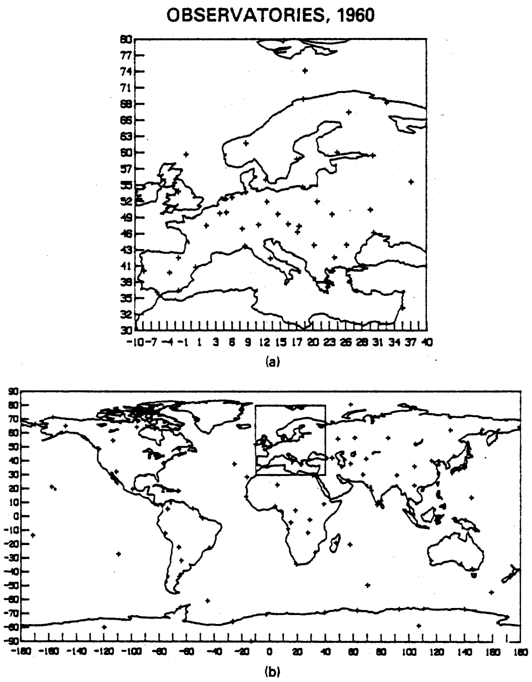


Fig. A4. Distribution of observatory data, 1960. (a) Europe, (b) Rest of the world.

component, Z and total intensity, B were observed, D with a magnetic compass, H and Z with a fluxgate magnetometer and B with a proton magnetometer. Values of D, H and B were used from this source, since B measured by proton magnetometer is more accurate than Z from a fluxgate magnetometer, especially when measured on board ship.

The data from the WDCA tapes were supplemented by values from over 100 repeat stations distributed over the territory of the USSR. These data had been adjusted to 1945, 1950, 1955 and 1960 by plotting the original observations and fitting smooth curves to them by eye.

All survey data within a given 5-year interval were compared with values computed from the preliminary IGRFs. Observations that differed by more than 1000 nT from the IGRF value were investigated, where possible, by comparing the values from the tape with the original source of the data. Where such a comparison was possible, and the data were found to have been incorrectly transcribed, the appropriate corrections were made. Where no transcription error had been made, all

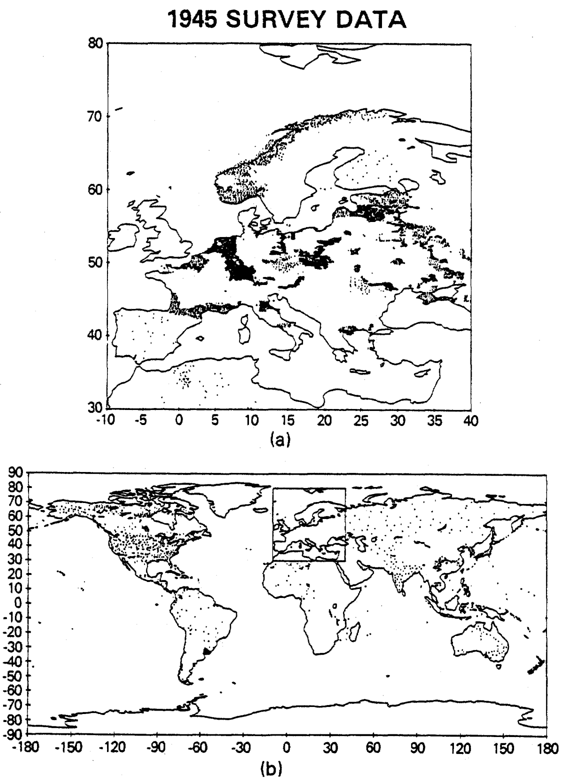


Fig. A5. Distribution of survey data, 1945. (a) Europe, (b) Rest of the world.

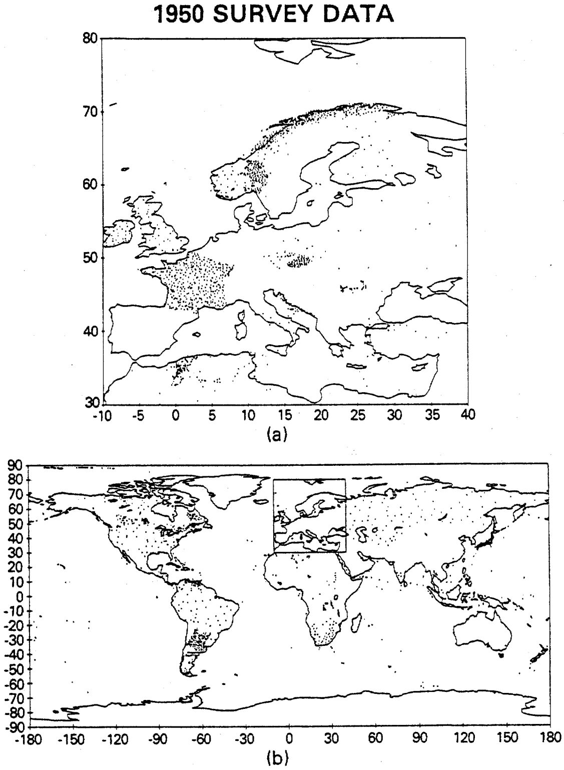


Fig. A6. Distribution of survey data, 1950. (a) Europe, (b) Rest of the world.

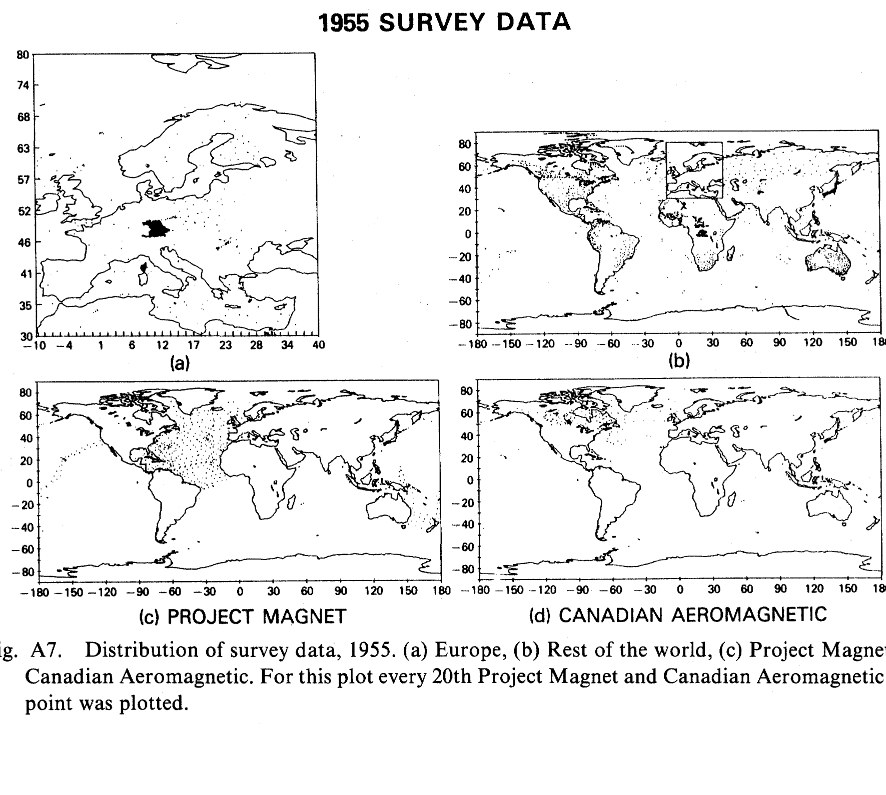


Fig. A7. Distribution of survey data, 1955. (a) Europe, (b) Rest of the world, (c) Project Magnet, (d) Canadian Aeromagnetic. For this plot every 20th Project Magnet and Canadian Aeromagnetic data point was plotted.

data differing by more than 1500 nT from the IGRF value were flagged as being anomalous and were not used further in the analysis. In the cases where it was not possible to refer to the original source of the data, it was often possible to detect and correct gross errors such as the wrong sign or transcription of latitude instead of colatitude; otherwise values differing by more than 1500 nT from the IGRF values were again flagged as anomalous.

A further rejection of gross outliers took place during the analysis of the data. For each 5-year interval residuals of the survey data from the preliminary IGRF were formed. For declination (D) and inclination (I) all data with residuals greater in absolute magnitude than 2° were flagged as anomalous; for H the critical value of the residual was 300 nT; for X, Y, Z and B it was 600 nT.

The survey data are divided by source, each survey having an identifying source number. Under the assumption that each survey is relatively homogeneous, a statistical analysis was performed, by year (from mid year to mid year), on the

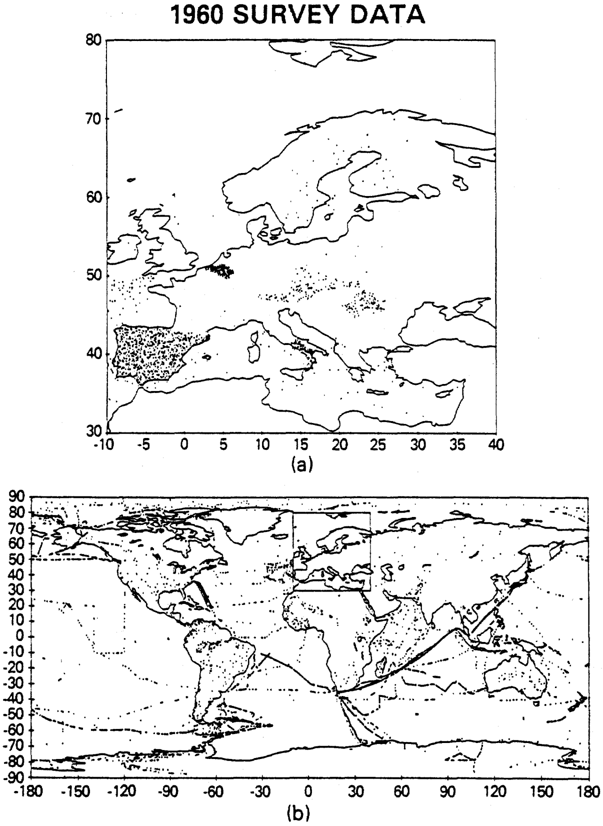
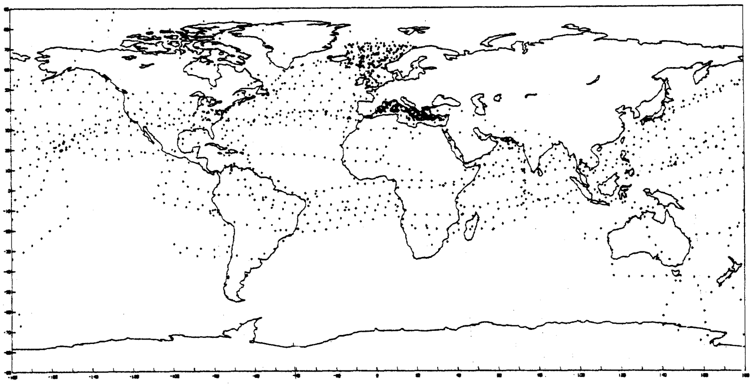
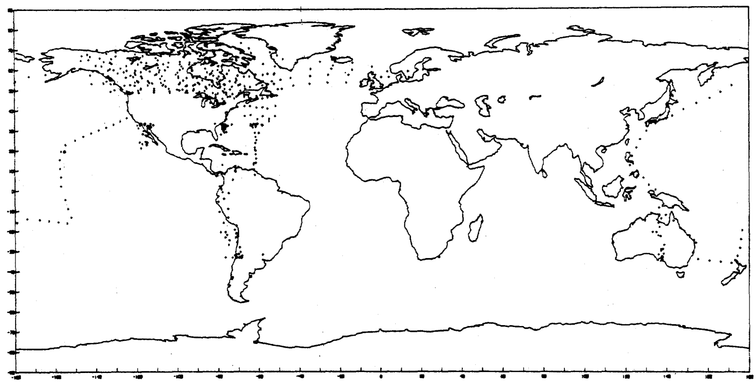


Fig. A8.

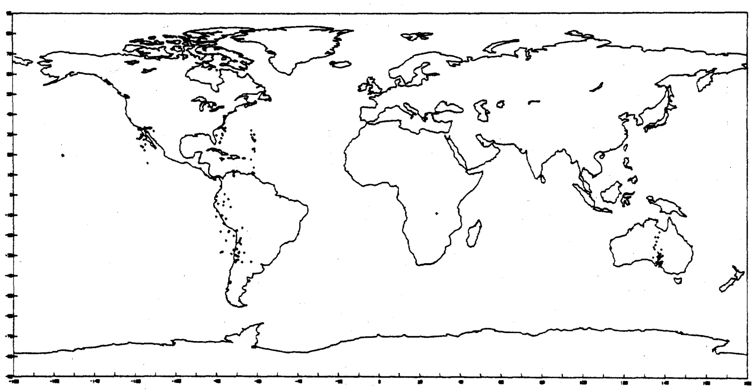
1960 SURVEY DATA



(c) PROJECT MAGNET



(d) CANADIAN AEROMAGNETIC



(e) VANGUARD 3

Fig. A8. Distribution of survey data, 1960. (a) Europe, (b) Rest of the world, (c) Project Magnet, (d) Canadian Aeromagnetic, (e) VANGUARD 3. For this plot every 3rd survey, every 20th Project Magnet, every 20th Canadian Aeromagnetic, and every 20th Vanguard data point was plotted.

residuals of each survey to the appropriate preliminary IGRF model. In each case the mean, standard deviation about the mean (σ), skewness (s) and kurtosis (k) were computed. Surveys with less than 12 data points were not included in this step. It was intended to use the resulting $1/\sigma^2$ as the weight in the fitting process. However it was found that often the distribution deviated considerably from normal and we wished to modify the weight in some appropriate, albeit somewhat subjective, fashion. To this end a modified "standard deviation", σ', was computed as follows:

$$(\sigma')^2 = \sigma^2[1 + \alpha s - \beta(k - 3)]. \tag{A.1}$$

The reasoning behind (A.1) is, first, that skewness is a measure of the departure from symmetry of a distribution: the difference between the mean and the mode, measured in units of σ. The term αs then reflects our judgement that the mean of a skewed distribution should be viewed as proportionately less reliable than the σ indicates. Second, kurtosis measures the degree of peakedness of a distribution, relative to a normal distribution. Since $k=3$ for a normal distribution, we used an adjusting term proportional to $(k-3)$. The result is that a highly peaked distribution, $k>3$, will be treated as having less scatter than a normal distribution while a broadened distribution, $k<3$, will be treated as having more scatter. The factors α and β were chosen to be 1 and .01, respectively, after trying several values. Admittedly this is subjective, but we consider it to give a more reliable weighting scheme than simply using the normal σ.

During this phase of the analysis, each data point whose individual residual differed by more than 2σ (not σ') from the mean residual for that survey was flagged as anomalous, except that for project Magnet and Vanguard data a cutoff of 1σ was used. The computation was then repeated, using only the non-flagged data, after which each non-rejected data point was assigned the value of σ' appropriate to its year and source (σ_s').

The procedure was then repeated but now collecting together data for each year and for each element into approximately equal-area bins whose size was 10° by 10° at

Table A2. Average σ_m for each data type. Units are nT for H, X, Y, Z, and B and degrees for D and I.

DATA TYPE	D	I	H	X	Y	Z	B
1945 Survey	0.43	0.23	109	---	---	---	---
1950 Survey	0.45	0.23	110	23	69	217	---
1955 Survey	0.39	0.23	95	---	---	119	287
1960 Survey	0.35	0.26	90	26	74	131	138
1955 Canadian Aeromag.	0.59	---	84	---	---	126	---
1960 Canadian Aeromag.	0.50	---	87	---	---	151	---
1955 Project Magnet	0.34	0.21	---	---	---	---	118
1960 Project Magnet	0.46	0.23	---	---	---	---	134
1960 Vanguard-3	---	---	---	---	---	---	16.1

Table A3. *A priori* model coefficients.

	N	M	1945 G,H	1945 SIG	1945 GT,HT	1945 SIG	1950 G,H	1950 SIG	1950 GT,HT	1950 SIG	1955 G,H	1955 SIG	1955 GT,HT	1955 SIG	1960 G,H	1960 SIG	1960 GT,HT	1960 SIG
G	1	0	-30585.0	(7.5)	7.8	(0.8)	-30552.0	(6.2)	6.3	(0.5)	-30511.0	(5.1)	10.3	(0.5)	-30439.0	(4.4)	17.2	(0.4)
G	1	1	-2296.6	(8.4)	7.9	(0.9)	-2252.6	(6.8)	8.8	(0.6)	-2208.9	(5.5)	8.8	(0.5)	-2164.3	(4.6)	9.1	(0.4)
H	1	1	5806.0	(8.8)	2.4	(0.9)	5812.6	(7.3)	0.8	(0.6)	5812.6	(6.0)	-0.6	(0.5)	5804.1	(5.1)	-2.5	(0.4)
G	2	0	-1253.6	(7.4)	-18.7	(0.8)	-1346.0	(6.0)	-18.5	(0.6)	-1442.2	(5.0)	-19.9	(0.5)	-1548.4	(4.3)	-22.1	(0.3)
G	2	1	2989.5	(7.3)	2.7	(0.7)	2998.8	(6.1)	1.1	(0.5)	2999.8	(5.1)	-0.3	(0.4)	2996.1	(4.3)	-0.9	(0.4)
H	2	1	-1708.5	(8.6)	-23.1	(0.9)	-1810.9	(7.0)	-18.3	(0.6)	-1891.1	(6.0)	-14.9	(0.5)	-1959.0	(5.2)	-12.7	(0.4)
G	2	2	1578.1	(7.7)	-1.2	(0.7)	1574.8	(6.6)	0.0	(0.5)	1579.6	(5.8)	1.6	(0.5)	1591.0	(5.1)	2.7	(0.4)
H	2	2	476.3	(7.9)	-17.2	(0.8)	385.3	(6.5)	-18.9	(0.6)	289.7	(5.4)	-19.0	(0.5)	197.7	(4.6)	-17.9	(0.4)
G	3	0	1281.2	(6.7)	5.4	(0.7)	1298.9	(5.5)	2.2	(0.5)	1302.7	(4.7)	0.1	(0.4)	1300.7	(4.1)	-0.6	(0.3)
G	3	1	-1828.5	(6.2)	-11.7	(0.5)	-1888.8	(5.4)	-12.1	(0.4)	-1946.3	(4.7)	-10.9	(0.4)	-1996.0	(4.1)	-9.4	(0.3)
H	3	1	-489.8	(7.6)	3.4	(0.7)	-472.7	(6.3)	3.3	(0.5)	-456.1	(5.4)	3.5	(0.4)	-435.3	(4.8)	4.7	(0.3)
G	3	2	1258.3	(6.4)	3.7	(0.5)	1276.5	(5.7)	3.5	(0.4)	1290.7	(5.1)	2.3	(0.4)	1296.5	(4.6)	0.4	(0.3)
H	3	2	187.6	(7.0)	4.1	(0.5)	204.1	(6.1)	2.9	(0.4)	216.3	(5.3)	2.2	(0.4)	226.5	(4.5)	2.0	(0.3)
G	3	3	912.8	(6.8)	-3.6	(0.6)	897.8	(6.0)	-2.5	(0.5)	887.3	(5.4)	-2.0	(0.4)	875.7	(4.7)	-2.6	(0.4)
H	3	3	-5.8	(6.2)	-7.3	(0.6)	-42.8	(5.4)	-7.6	(0.4)	-82.4	(4.7)	-8.1	(0.4)	-123.6	(4.2)	-8.2	(0.3)
G	4	0	948.6	(6.1)	1.7	(0.5)	954.0	(5.1)	0.7	(0.4)	955.6	(4.4)	0.1	(0.3)	954.9	(3.8)	-0.3	(0.3)
G	4	1	773.5	(5.3)	3.9	(0.4)	789.2	(4.5)	2.6	(0.3)	798.3	(3.7)	1.3	(0.3)	801.5	(3.2)	0.2	(0.3)
H	4	1	141.0	(6.4)	-2.6	(0.5)	131.4	(5.6)	-1.4	(0.4)	128.8	(5.0)	0.1	(0.3)	134.4	(4.4)	1.8	(0.3)
G	4	2	546.6	(5.6)	-3.7	(0.5)	528.5	(5.0)	-3.5	(0.4)	510.6	(4.5)	-3.7	(0.3)	490.9	(4.0)	-4.1	(0.3)
H	4	2	-279.9	(6.8)	-0.6	(0.5)	-278.0	(5.9)	0.8	(0.4)	-273.1	(5.2)	1.0	(0.4)	-268.7	(4.6)	0.7	(0.3)
G	4	3	-421.8	(6.1)	2.3	(0.4)	-410.2	(5.4)	2.2	(0.4)	-400.9	(4.7)	1.5	(0.3)	-396.1	(4.2)	0.5	(0.3)
H	4	3	-55.7	(5.3)	3.7	(0.4)	-37.9	(4.7)	3.5	(0.3)	-21.7	(4.1)	3.1	(0.3)	-7.3	(3.6)	2.8	(0.3)
G	4	4	303.6	(5.8)	1.6	(0.6)	303.7	(5.0)	-1.0	(0.4)	292.8	(4.3)	-2.9	(0.4)	275.4	(3.7)	-3.8	(0.3)
H	4	4	-186.0	(5.9)	-5.8	(0.4)	-212.8	(5.1)	-5.0	(0.4)	-235.4	(4.5)	-4.2	(0.3)	-253.8	(4.0)	-3.4	(0.3)
G	5	0	-255.6	(5.4)	2.2	(0.5)	-242.2	(4.6)	2.8	(0.3)	-228.8	(4.0)	2.5	(0.3)	-218.7	(3.6)	1.6	(0.2)
G	5	1	343.8	(4.8)	0.8	(0.5)	350.4	(4.0)	1.6	(0.3)	358.2	(3.3)	1.4	(0.3)	363.6	(2.9)	0.8	(0.2)
H	5	1	-13.2	(5.5)	3.9	(0.4)	3.8	(4.7)	3.1	(0.3)	16.7	(4.2)	2.2	(0.3)	25.3	(3.7)	1.4	(0.3)
G	5	2	190.9	(4.7)	3.2	(0.4)	210.5	(4.0)	4.2	(0.3)	231.5	(3.4)	4.1	(0.3)	249.4	(3.0)	3.2	(0.2)
H	5	2	99.2	(5.6)	1.2	(0.4)	105.2	(4.9)	1.3	(0.3)	112.5	(4.2)	1.6	(0.3)	121.8	(3.7)	2.0	(0.3)
G	5	3	-23.9	(6.4)	0.8	(0.5)	-20.5	(5.6)	0.6	(0.4)	-19.2	(4.9)	0.0	(0.3)	-21.6	(4.4)	-0.8	(0.3)
H	5	3	-70.3	(4.9)	-4.1	(0.4)	-86.5	(4.2)	-2.8	(0.3)	-99.0	(3.6)	-2.4	(0.3)	-110.7	(3.1)	-2.4	(0.3)
G	5	4	-139.4	(5.1)	-1.6	(0.4)	-145.6	(4.3)	-1.0	(0.3)	-149.9	(3.6)	-0.8	(0.3)	-153.2	(3.0)	-0.6	(0.3)
H	5	4	-122.2	(5.5)	0.0	(0.4)	-120.9	(4.9)	0.5	(0.3)	-116.9	(4.5)	1.0	(0.3)	-110.1	(4.0)	1.6	(0.3)
G	5	5	-84.0	(5.5)	1.2	(0.4)	-78.6	(4.7)	1.0	(0.4)	-73.6	(4.0)	1.0	(0.3)	-68.3	(3.5)	1.1	(0.3)
H	5	5	83.4	(5.4)	-0.4	(0.4)	79.1	(4.5)	-1.0	(0.3)	74.3	(3.8)	-0.8	(0.3)	72.1	(3.2)	-0.1	(0.3)
G	6	0	59.6	(4.0)	-0.9	(0.3)	54.5	(3.4)	-1.1	(0.3)	48.8	(3.0)	-1.1	(0.2)	43.7	(2.7)	-0.9	(0.2)
G	6	1	57.6	(3.9)	0.2	(0.4)	56.9	(3.3)	-0.2	(0.3)	56.7	(2.9)	0.1	(0.2)	58.5	(2.5)	0.5	(0.2)
H	6	1	6.7	(4.1)	-1.4	(0.3)	0.0	(3.6)	-1.3	(0.3)	-6.5	(3.3)	-1.2	(0.2)	-11.7	(3.0)	-0.9	(0.2)
G	6	2	7.0	(3.8)	-0.4	(0.3)	4.7	(3.2)	-0.4	(0.3)	3.5	(2.8)	-0.1	(0.2)	5.0	(2.5)	0.6	(0.2)
H	6	2	98.6	(4.3)	-0.3	(0.3)	97.5	(3.7)	-0.2	(0.3)	96.8	(3.3)	-0.1	(0.2)	96.7	(2.9)	0.0	(0.2)
G	6	3	-241.6	(4.7)	-1.2	(0.3)	-245.3	(4.2)	-0.4	(0.3)	-244.1	(3.8)	0.7	(0.2)	-237.1	(3.5)	1.8	(0.2)
H	6	3	15.4	(3.7)	3.5	(0.3)	32.5	(3.2)	3.3	(0.3)	47.6	(2.8)	2.8	(0.2)	59.4	(2.4)	2.0	(0.2)
G	6	4	-24.5	(4.7)	1.7	(0.4)	-17.6	(4.1)	1.2	(0.3)	-12.3	(3.7)	1.0	(0.3)	-7.7	(3.2)	0.9	(0.3)
H	6	4	-3.8	(4.7)	-1.0	(0.3)	-10.7	(4.3)	-1.5	(0.3)	-18.5	(4.0)	-1.6	(0.2)	-25.9	(3.6)	-1.4	(0.2)
G	6	5	20.7	(4.4)	-1.6	(0.3)	13.2	(4.0)	-1.4	(0.3)	8.0	(3.6)	-0.8	(0.2)	5.8	(3.2)	-0.2	(0.2)
H	6	5	-16.1	(4.5)	0.2	(0.3)	-14.0	(4.0)	0.5	(0.3)	-12.3	(3.5)	0.2	(0.2)	-11.6	(3.0)	0.1	(0.2)
G	6	6	-103.1	(4.8)	-0.2	(0.4)	-103.8	(4.0)	-0.2	(0.4)	-106.2	(3.5)	-0.7	(0.3)	-110.1	(3.0)	-0.8	(0.3)
H	6	6	-38.8	(5.1)	2.3	(0.4)	-30.3	(4.3)	1.4	(0.4)	-25.0	(3.7)	0.9	(0.3)	-20.3	(3.2)	1.1	(0.3)
G	7	0	64.7	(34.4)	0.2	(14.7)	65.6	(19.0)	0.2	(9.8)	66.6	(6.9)	0.2	(4.8)	67.6	(1.8)	0.2	(1.8)
G	7	1	-56.3	(36.0)	0.0	(15.4)	-56.2	(19.9)	0.0	(10.2)	-56.3	(7.3)	0.0	(5.0)	-56.7	(1.9)	-0.1	(1.9)
H	7	1	-28.6	(31.1)	-1.7	(13.3)	-37.6	(17.2)	-1.9	(8.8)	-47.6	(6.4)	-2.1	(4.4)	-58.2	(1.7)	-2.1	(1.7)
G	7	2	7.1	(29.4)	-0.1	(12.5)	6.3	(16.5)	-0.3	(8.4)	3.8	(6.3)	-0.7	(4.2)	-0.1	(1.8)	-0.8	(1.8)
H	7	2	-21.6	(41.4)	-0.3	(17.8)	-23.0	(22.7)	-0.2	(11.7)	-23.7	(8.1)	-0.1	(5.7)	-24.0	(2.0)	-0.1	(2.0)
G	7	3	10.7	(38.4)	0.3	(16.4)	11.8	(21.3)	0.1	(10.9)	11.4	(7.9)	-0.2	(5.4)	10.8	(2.1)	0.0	(2.1)
H	7	3	-2.2	(38.8)	-0.1	(16.7)	-3.3	(21.3)	-0.3	(11.0)	-5.4	(7.7)	-0.5	(5.3)	-7.8	(1.9)	-0.4	(1.9)
G	7	4	-47.0	(48.2)	1.1	(20.7)	-42.2	(26.5)	0.8	(13.7)	-39.3	(9.6)	0.4	(6.6)	-37.5	(2.4)	0.4	(2.4)
H	7	4	9.7	(37.1)	-0.5	(15.8)	7.7	(20.6)	-0.2	(10.5)	9.1	(7.7)	0.6	(5.2)	12.5	(2.1)	0.6	(2.1)
G	7	5	-15.9	(46.7)	0.4	(20.0)	-14.1	(25.8)	0.3	(13.3)	-12.7	(9.5)	0.2	(6.5)	-11.5	(2.5)	0.2	(2.5)
H	7	5	35.7	(47.4)	-0.4	(20.3)	34.0	(26.3)	-0.3	(13.5)	32.1	(9.7)	-0.4	(6.6)	29.7	(2.6)	-0.5	(2.6)
G	7	6	15.1	(47.6)	-0.2	(20.5)	14.1	(26.2)	-0.3	(13.5)	12.1	(9.5)	-0.4	(6.6)	10.5	(2.4)	-0.2	(2.4)
H	7	6	-17.0	(44.9)	-0.8	(19.2)	-20.2	(24.8)	-0.5	(12.7)	-21.6	(9.2)	-0.1	(6.3)	-21.6	(2.4)	0.0	(2.4)
G	7	7	19.8	(56.4)	-0.8	(24.3)	15.6	(30.9)	-0.9	(16.0)	11.3	(11.1)	-0.9	(7.7)	6.9	(2.8)	-0.9	(2.8)
H	7	7	-22.8	(53.3)	-0.1	(22.9)	-23.0	(29.2)	0.1	(15.1)	-21.6	(10.5)	0.4	(7.3)	-18.9	(2.6)	0.5	(2.6)
G	8	0	14.5	(21.2)	0.1	(9.0)	15.0	(11.8)	0.1	(6.0)	15.2	(4.5)	0.0	(3.0)	15.5	(1.2)	0.1	(1.2)
G	8	1	3.3	(22.7)	0.2	(9.7)	4.1	(12.6)	0.2	(6.5)	4.7	(4.7)	0.1	(3.2)	5.2	(1.3)	0.1	(1.3)
H	8	1	3.7	(21.3)	-0.1	(9.1)	3.8	(11.9)	0.1	(5.1)	5.6	(4.5)	0.5	(3.0)	8.3	(1.2)	0.5	(1.2)
G	8	2	-7.7	(20.6)	0.2	(8.8)	-6.4	(11.5)	0.3	(5.9)	-4.9	(4.4)	0.3	(3.0)	-3.2	(1.2)	0.3	(1.2)
H	8	2	-16.7	(23.3)	0.1	(10.0)	-16.3	(12.9)	0.1	(6.6)	-16.0	(4.8)	0.0	(3.3)	-15.8	(1.3)	0.0	(1.3)
G	8	3	-12.9	(22.8)	-0.1	(9.7)	-13.3	(12.8)	0.0	(6.5)	-12.9	(4.9)	0.1	(3.3)	-12.0	(1.4)	0.2	(1.4)
H	8	3	4.5	(22.4)	-0.2	(9.6)	3.8	(12.4)	-0.1	(6.4)	3.9	(4.6)	0.1	(3.1)	4.4	(1.2)	0.1	(1.2)
G	8	4	20.5	(28.2)	-0.8	(12.1)	16.5	(15.7)	-0.8	(8.0)	12.6	(5.8)	-0.8	(4.0)	9.1	(1.6)	-0.7	(1.6)
H	8	4	-18.3	(24.8)	0.3	(10.6)	-17.2	(13.8)	0.1	(7.1)	-17.5	(5.2)	-0.2	(3.5)	-18.7	(1.4)	-0.2	(1.4)
G	8	5	24.9	(27.9)	-0.9	(11.9)	20.9	(15.5)	-0.7	(7.9)	18.4	(5.8)	-0.4	(4.0)	16.6	(1.6)	-0.4	(1.6)
H	8	5	0.8	(28.3)	0.1	(12.1)	1.3	(15.7)	0.1	(6.0)	1.8	(5.9)	0.1	(4.0)	2.5	(1.6)	0.2	(1.6)
G	8	6	-19.1	(28.8)	0.7	(12.3)	-15.5	(16.1)	0.8	(8.2)	-11.1	(6.1)	0.9	(4.1)	-6.5	(1.7)	0.9	(1.7)
H	8	6	26.2	(29.3)	-0.3	(12.5)	25.1	(16.3)	-0.2	(8.3)	24.9	(6.1)	0.0	(4.2)	25.5	(1.7)	0.1	(1.7)
G	8	7	11.4	(30.7)	-0.2	(13.2)	10.7	(17.0)	-0.1	(8.7)	10.7	(6.3)	0.1	(4.3)	11.0	(1.6)	0.0	(1.6)
H	8	7	8.4	(31.5)	-0.2	(13.5)	7.3	(17.5)	-0.3	(8.9)	5.3	(6.5)	-0.5	(4.4)	2.2	(1.7)	-0.7	(1.7)
G	8	8	18.3	(38.8)	-1.1	(16.6)	13.4	(21.4)	-0.8	(11.0)	11.4	(7.9)	-0.2	(5.4)	11.3	(2.0)	-0.1	(2.1)
H	8	8	-20.3	(34.8)	0.2	(14.9)	-19.6	(19.2)	0.0	(9.9)	-20.5	(7.0)	-0.3	(4.8)	-22.0	(1.8)	-0.2	(1.8)

the equator. Surveys with less than 12 points are now included. Only data not previously flagged were used. Each data point was then also assigned the value of σ' appropriate to its equal-area bin (σ_b'). In this step no data were rejected. Figures A5 to A8 show the geographical distribution of the survey data for the four epochs.

During the fitting procedure, each survey data point was assigned a weight of $1/\sigma_m^2$, where $\sigma_m = \max(\sigma_s', \sigma_b')$. The observatory X, Y and Z values were assigned a σ of 25 nT, and the corresponding weight. When biases were not solved for at a particular observatory, the data from that observatory were included with the survey data, and weighted accordingly. Because of the procedure used to assign weights, there is no single weight for any data type, and component, except for observatory data. To give a general idea of the weights used, the average σ_m for each data type and component was computed for each model. The results are given in Table A2.

Appendix 2. *A Priori* Model Coefficients

Section 3 describes the derivation of a set of *a priori* models, one at each epoch, used in deriving the DGRF models. Table A3 lists both the main field coefficients and the secular variation coefficients together with their standard deviations.

Appendix 3. Main Field and Secular Variation Contributions to the Correlated Weight Matrix

Section 4 described the notion of a weight matrix which takes into account the presence of unmodeled fields. Spherical harmonic models are seeking to describe the field from the Earth's core, up to degree and order n^*. Unmodeled fields include those due to crustal sources, and those due to core fields above degree n^*. When time changes are present in the data, unmodeled changes also contribute to the correlated weight matrix. The following Tables, A4 and A5, list the contribution of neglected core and neglected secular variation terms to the Q matrix used in deriving the correlated weight matrix.

Table A4. Contribution of the neglected core field to diagonal elements of Q corresponding to vertical field measurements.

n*	Contribution to Q (nT)^2
8	7404
9	1990
10	535
11	144
12	39
13	10

n* is the maximum degree and order of the model.

Table A5. Contributions of neglected secular variation to diagonal elements of Q corresponding to vertical field measurements.

n*	Contribution to Q $(nT)^2$
6	29 $(\Delta t)^2$
7	13 $(\Delta t)^2$
8	6 $(\Delta t)^2$
9	3 $(\Delta t)^2$
10	1 $(\Delta t)^2$

n* is the maximum degree of the secular variation model.
Δt is the time difference, in years, between the measurement and the epoch of the field model.

REFERENCES

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

BARRACLOUGH, D. R. and D. J. KERRIDGE, BGS candidate models for the 1985 revision of the International Geomagnetic Reference Field, *Phys. Earth Planet. Int.*, **48**, 306–312, 1987.

BARRACLOUGH, D. R., J. M. HARWOOD, B. R. LEATON, and S. R. C. MALIN, A definitive model of the geomagnetic field and its secular variation for 1965—I. Derivation of model and comparison with the IGRF, *Geophys. J. Royal Astr. Soc.*, **55**, 111–121, 1978.

BARTON, E. E., R. HUTCHINSON, P. QUILTY, K. SEERS, and T. STONE, Quest for the magnetic poles: relocation of the South Magnetic Pole at sea, 1986, *Bureau Min. Resources, Geol. Geophys. Record* 1987/3, 1987.

BURROWS, A. L., Location of the south magnetic pole, *N. Z. J. Geol. Geophys.*, **6**, 454–464, 1963.

CAIN, J. C., S. J. HENDRICKS, R. A. LANGEL, and W. V. HUDSON, A proposed model for the International Geomagnetic Reference Field—1965, *J. Geomag. Geoelectr.*, **19**, 335–355, 1967.

DAWSON, E. and L. C. DALGETTY, Magnetic charts of Canada for epoch 1965.0, *Publ. Dominion Obsy., Ottawa*, **31**, No. 9, 379–405, 1966.

DAWSON, E. and E. I. LOOMER, The north magnetic dip-pole, *Publ. Dominion Obsy., Ottawa*, **28**, No. 5, 195–208, 1963.

DAWSON, E. and L. R. NEWITT, An analytical representation of the geomagnetic field in Canada for 1975, Part III: The north magnetic pole, *Can. J. Earth Sci.*, **15**, 994–1001, 1978.

DAWSON, E. and L. R. NEWITT, Comparison of IGRF models with North American Magnetic Data, *J. Geomag. Geoelectr.*, **34**, 393–400, 1982a.

DAWSON, E. and L. R. NEWITT, The magnetic poles of the Earth, *J. Geomag. Geoelectr.*, **34**, 225–240, 1982b.

GIBBS, B. P. and R. H. ESTES, Geomagnetic modeling by optimal recursive filtering, Final Report NASA Contract NAS5-26250, prepared by Business and Technology Systems, Inc., 1982.

GUBBINS, D., Geomagnetic field analysis—I. Stochastic inversion, *Geophys. J. R. Astr. Soc.*, **73**, 641–652, 1983.

HAINES, G. V., A Taylor expansion of the geomagnetic field in the Canadian Arctic, *Publ. Dominion Obsy., Ottawa*, **35**, No. 2, 115–140, 1967.

HAINES, G. V. and W. HANNAFORD, A Three-component aeromagnetic survey of the Canadian Arctic, *Publ. Earth Phys. Branch*, **44**, No. 8, 213–234, 1974.

HARWOOD, J. M. and S. R. C. MALIN, Present trends in the Earth's magnetic field, *Nature*, **259**, 469–471, 1976.

JENKINS, G. M. and D. G. WATTS, *Spectral Analysis and Its Applications*, Holden-Day, San Francisco, 1968.

JONES, H. S., Where are the Earth's magnetic poles?, *Discovery*, **11**, 127–132, 1950.

LANGEL, R. A., Chapter Four: Main Field, in *Geomagnetism*, edited by J. Jacobs, Academic Press, 1987.

LANGEL, R. A. and R. H. ESTES, The near-earth magnetic field at 1980 determined from Magsat data, *J. Geophys. Res.*, **90**, 2495–2509, 1985a.

LANGEL, R. A. and R. H. ESTES, Large-scale, near-earth magnetic fields from external sources and the corresponding induced internal field, *J. Geophys. Res.*, **90**, 2487–2494, 1985b.

LANGEL, R. A. and R. H. ESTES, Derivation of proposed International Geomagnetic Reference Field models for 1945, 1950, 1955 and 1960, *Phys. Earth and Planet. Int.*, **48**, 293–305, 1987.

LANGEL, R. A. and R. H. ESTES, Uncertainty estimates in geomagnetic field modeling, to be submitted, 1988.

LANGEL, R. A., R. H. ESTES, G. D. MEAD, E. B. FABIANO, and E. R. LANCASTER, Initial geomagnetic field model from magsat vector data, *Geophys. Res. Letr.*, **10**, 793–796, 1980.

LANGEL, R. A., R. H. ESTES, and G. D. MEAD, Some new methods in geomagnetic field modeling applied to the 1960–1980 epoch, *J. Geomag. Geoelectr.*, **34**, 327–349, 1982.

LANGEL, R. A., D. J. KERRIDGE, D. R. BARRACLOUGH, and S. R. C. MALIN, Geomagnetic temporal change: 1903–1982, a spline representation, *J. Geomag. Geoelectr.*, **38**, 573–597, 1986.

LARZILLIERE, H. and R. LACHAUX, Reoccupation du Cap Denison, Terre du Roi George V, *Ann. Inst. Phys. Globe, Paris*, **32**, 139–141, 1964.

LOWES, F. J., Mean-square values on sphere of spherical harmonic vector fields, *J. Geophys. Res.*, **71**, 2179, 1966.

LOWES, F. J., Spatial power spectrum of the main geomagnetic field, and extrapolation to the core, *Geophys. J. R. Astr. Soc.*, **36**, 717–730, 1974.

LOWES, F. J., Perpendicular error effect in the DGRF model proposals, *Phys. Earth Planet. Int.*, **37**, 25–34, 1985.

MAYAUD, P. N., Le pole magnetique en 1952 et les deplacements compares des poles nord et sud de 1842 a 1952, *Ann. Geophys.*, **9**, 266–276, 1953.

MCDONALD, K. L. and R. H. GUNST, An analysis of the Earth's magnetic field from 1835 to 1965, ESSA Technical Report IER46-IES1, Institute for Earth Sciences, Boulder, July 1967.

NEWITT, L. R. and E. R. NIBLETT, Relocation of the north magnetic pole, *Can. J. Earth Sci.*, **23**, 1062–1067, 1986.

PEDDIE, N. W. and E. B. FABIANO, Assessment of models proposed for the 1981 revision of the IGRF, *J. Geomag. Geoelectr.*, **34**, 387–392, 1982.

SCHMIDT, A., Der magnetische mittlepunkt der erde und seine bedeutung, *Gerlands Beitrage fur Geophysik*, **41**, 346–358, 1934.

TARANTOLA, A. and B. VALETTE, Generalized nonlinear inverse problems solved using the least squares criterion, *Rev. Geophys. Space Phys.*, **20**, 219–232, 1982.

THOMSON, Sir W. (Lord Kelvin), A mathematical theory of magnetism, *Proc. Roy. Soc. London*, 483–497, 1849 with remarks added 1872.

WHITHAM, K., The relationship between the secular change and the non-dipole fields, *Can. J. Phys.*, **36**, 1372–1396, 1958.

WHITHAM, K. and E. I. LOOMER, The diurnal and annual motions of the north magnetic dip pole, *J. Atmos. Terr. Phys.*, **8**, 349–351, 1956.

WHITHAM, K., E. I. LOOMER, and E. DAWSON, Recent studies of the north magnetic dip pole, *Arctic*, **12**, 28–39, 1959.