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A Model of the Geomagnetic Field at Epoch 1975

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Summary

The main magnetic field at epoch 1975 is defined by 168 spherical harmonic coefficients (those representing the internal part to degree and order 12). A further 80 coefficients (degree and order 8) define the secular variation and, in addition, 26 secular acceleration coefficients (those most significantly determined) are included. Details are given of the data used and the methods of reduction.

1. Introduction

This paper presents the latest in a series of models of the geomagnetic field that have been derived in association with the World Magnetic Charts published by the British Hydrographic Office. The models are listed in Table 1 together with the epochs to which they refer. The next three columns give the number of spherical harmonic coefficients derived for the main field (MF), its first time derivative (secular variation: SV) and its second time derivative (secular acceleration: SA). An S in the final column indicates that the Earth has been assumed to be spherical; an E, that its ellipticity has been taken into account. Although responsibility for the preparation of both charts and models passed from the Royal Greenwich Observatory to the Institute of Geological Sciences in 1967, there has been continuity of experience and personnel throughout the period.

The increasing number of coefficients is partly a reflection of the increase in computing capability with time, but also indicates the improvement of our knowledge of the geomagnetic field due to the improved distribution, accuracy and quantity of data available for analysis. Significant advances have also been made in the methods of analysis.

For the present model we have determined all the coefficients up to twelfth order and degree for the main field. The data do not justify so many coefficients for the time derivatives, so the secular variation model has been truncated after eighth order and degree, and for secular acceleration only the 26 most significant coefficients are included. For any temporal extrapolation of the main field coefficients, it is appropriate to treat those coefficients not present in the SV and SA models as though they were zero, We have deliberately omitted standard deviations since these are of limited value and can be misleading.

The British World Charts for 1975 are derived from a composite spherical harmonic model that has been recommended to the International Hydrographic Organisation as the source of declination values for the International Series of Navigation Charts. By

A

Table 1

Source	Epoch	No. of coefficients MF	SV	SA	Figure of Earth
Dyson & Furner (1923)	1922·0	48	—	—	S
Jones & Melotte (1953)	1942·5	48	—	—	S & E
Finch & Leaton (1957)	1955·0	48	—	—	S
Leaton (1962)	1955·0	—	48	—	S
Leaton, Malin & Evans (1965)	1965·0	80	48	—	S
Present	1975·0	168	80	26	E

agreement with the United States Geological Survey, this composite model is defined by coefficients that are the mean of those given in Table 3 and a corresponding set derived by the US Geological Survey.

2. Main field

This section describes the production of a model of the main geomagnetic field of internal origin for epoch 1975·0. The coefficients of the model are given in Table 3 in Schmidt quasi-normalized form, in units of nT. The figure of the Earth has been assumed to be an oblate spheroid with an equatorial radius of 6378·16 km and a reciprocal flattening of 298·25 (the International Astronomical Union Ellipsoid; Pecker 1966).

2.1 *Data selection*

The available data can be conveniently divided into four categories: (a) survey data and observatory annual mean values, (b) oceanographic data, (c) ships' compass observations, and (d) satellite data:

(a) The survey data include observations made during magnetic surveys on land, at sea and in aircraft. They comprise values of one or more of the following components of the geomagnetic field: declination (D), inclination (I), horizontal intensity (H), vertical intensity (Z) and total intensity (F). The observatory annual mean values derive from records made at the 200 or so fixed magnetic observatories distributed rather unevenly over the globe (see Fig. 3). The majority are of D and H and either Z or I but there are also a few values of the north intensity (X) and east intensity (Y) measured at some high latitude stations.

(b) The oceanographic data consist of a large number of F observations made during oceanographic surveys covering most of the ocean areas of the world.

(c) The ships' compass observations are values of D (generally of rather low accuracy) selected from the compass record books of merchant vessels sailing in the less frequented parts of the oceans, for example, in the southern Indian Ocean.

(d) The satellite data are derived from observations of F made by the POGO series of satellites (OGO-2, OGO-4 and OGO-6). These data were treated differently from the surface and near-surface data of the first three categories, and the method of including them in the model is described in Section 2.6.

Categories (a), (b) and (c) included all observations made since 1955, obtained from the magnetic tape files in World Digital Data Centre C1 at Herstmonceux.

2.2 *Reduction*

Before analysis, all the data of categories (a), (b) and (c) were reduced to sea level (where necessary) and to a common epoch. Although the required epoch is 1975·0, the data reduction was started well before that date, and no reliable SV model was then available for updating the data to 1975. For this reason the common epoch was chosen to be 1965·0; this is approximately the mean date of observation of the data, so that as many data had to be extrapolated forwards as backwards, thus minimizing the effect of any errors in the adopted SV.

The post-1965 data were reduced to 1965·0 using a preliminary SV model for 1970. This was derived from the SV model of Malin & Clark (1974) for 1965, updated using the SA model of Malin (1969). Each observation was reduced to sea level and to 1965·0 in a single operation represented by the expression

$$E\,(1965, 0) = E_0\,(t, h) - [E_c\,(t, h) - E_c\,(1965, 0)].$$

Here, E_0 denotes the value of an element observed at time t and altitude h; $E_c\,(t, h)$ denotes the value of an element computed for time t and altitude h using the International Geomagnetic Reference Field (IGRF) main field coefficients and the preliminary 1970 SV coefficients, and $E\,(1965, 0)$ denotes the value of the element reduced to 1965·0 and to sea level.

The large number of observations was reduced to a manageable size by dividing the Earth's surface into 1654 tesserae, and taking means of all observations of each element that lie in the same tessera. The latitudinal extent of each tessera is 5° and the longitudinal dimension varies from 5° at the equator to 120° at the poles, to keep the areas approximately constant. Separate series of tesseral means were formed for each category of data.

Up to this stage, no attempt had been made to reject any erroneous or anomalous observations from the data. The method of identifying and removing these is described in the next Section 2.3.

The category (a) data for the interval 1955 to 1965 had previously been reduced in a manner similar to that described above to a set of tesseral means for epoch 1960·0. (This was done in connection with the derivation of a main field model for 1960, details of which will be presented elsewhere.) The data had been reduced to sea level and to 1960 using the IGRF main field coefficients together with the 1955 SV model of Malin (1969) for the interval 1955 to 1957·5, the 1960 SV model of Malin (1969) for the interval 1957·5 to 1962·5, and the 1965 SV model of Malin & Clark (1974) for the interval 1962·5 to 1965. The two latter SV models were used also to update the tesseral means from 1960 to 1965.

2.3 *Rejection of erroneous and anomalous values*

Residuals of the tesseral means from the corresponding IGRF values were computed. Each observation contributing to any mean whose residual exceeded 1000 nT was examined in detail. In most cases the reason for the high residual was immediately obvious and the corrected tesseral mean was computed. The other erroneous means were deleted. This resulted in the loss of 24 means derived from a total of 29 individual observations.

As a further check, the scatter of individual observations about their mean was examined. All observations were rejected that departed from the mean by more than 2·36 standard deviations. After each such rejection, the mean and standard deviation were re-computed, and the procedure was repeated until no observation satisfied the criterion for rejection. It should be noted that this procedure is not effective if the number of observations contributing to a mean is less than about 10.

In all, about 3 per cent of the original data were rejected.

2.4 *Amalgamation of tesseral means*

At this stage we had separate sets of tesseral means for the older and newer parts of category (a) and for categories (b) and (c). In combining these to form a single set of means for each element, the separate means were weighted according to the number of

Table 2

Numbers of observations used for the main field analysis

Element	Category (a) 1955–1965	(a) post-1965	(b)	(c)	Total*	No. of tesseral means
D	56888	35526		3989	64009·89	1448
I	49204	33023			57625	1352
H	24159	15062			27141·5	941
X		42			42	8
Y		42			42	8
Z	21847	13939			24862·5	865
F	72698	42401	302608		381358	1446
All	224796	140035	302608	3989	555080·89	6068

* Giving weight 0·5 to the earlier (a) data and 0·01 to the (c) data.

observations contributing to them, and by an additional weighting factor of 0·5 for the 1955–1965 data and 0·01 for the compass data. The additional factors were subjectively chosen to reflect the lower accuracy of the compass data and the relative unimportance of the older data for determining the present configuration of the main field.

The numbers of observations in each category and the weighted numbers in the combined tesseral means are summarized in Table 2. The geographical distribution of the data is shown in Figs 1 and 2.

2.5 *Spherical harmonic analysis*

The method used to produce a spherical harmonic model of the main field from this set of amalgamated tesseral means was the widely-used differential method which allows the use of data for all elements of the geomagnetic field (see, for example, Cain *et al.* 1967). This method involves solving for the corrections to the coefficients of an approximate spherical harmonic model. The approximate model used here was the IGRF. The coefficients of the unknowns and the right-hand sides of the equations of condition were computed for each tesseral mean and stored on magnetic tape. From these the normal equations matrix which results from the use of the method of least squares weas computed, weighting the equation for each tesseral mean according to the effective number of observations that contributed to the mean; i.e. counting compass observations as one hundredth and earlier survey observations as a half. Although this was not yet the final version of the normal equations matrix (as it did not incorporate any satellite data), the matrix was inverted and corrections to the IGRF were derived. By applying these corrections we obtained a twelfth order and degree main field model based on surface and near-surface data, for epoch 1965.

2.6 *Inclusion of satellite data*

Large numbers of F observations have been made by the OGO-2, -4 and -6 satellites between 1965.8 and 1970.7. Cain has derived a series of spherical harmonic models based on these data and representing the part of the geomagnetic field that has its origin within the Earth. That designated POGO (8/73) is based on observations made during magnetically quiet periods and comprises all main field and secular variation coefficients up to degree and order 14; it refers to epoch 1970. Regardless of any of its other properties, there is no doubt that this model closely reproduces F at satellite levels, including more detailed features than can be represented by a twelfth order model. Rather than repeat the reduction of all the satellite observations, we have used the POGO(8/73) model to synthesize values of F at 5-degree intervals of latitude and longitude between 85 °N and 85 °S at an altitude of 800 km (to simulate

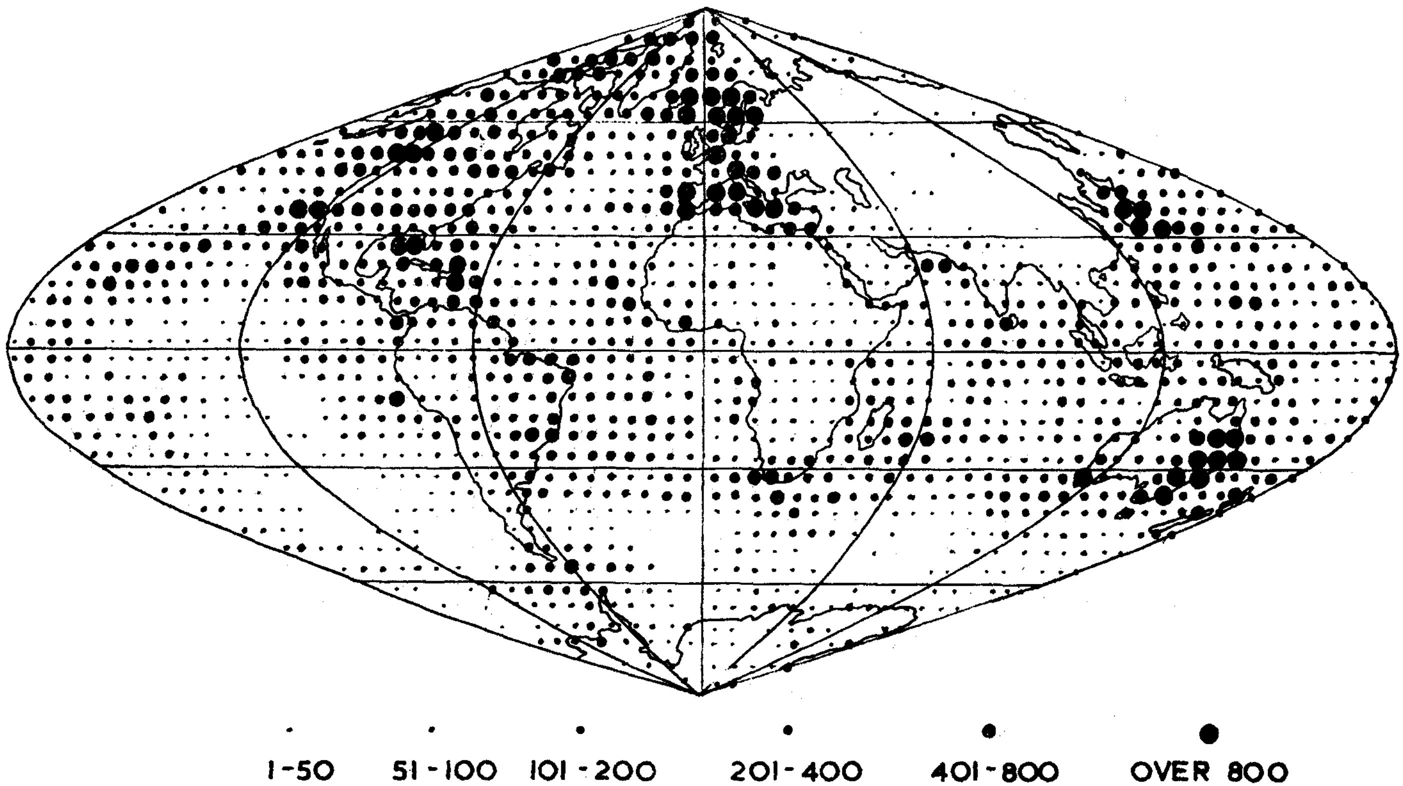

FIG. 1. Distribution of survey data used in the main field analysis. The number of observations in each tessera is indicated by the size of the symbol. Sanson–Flamsteed (equal area) projection.

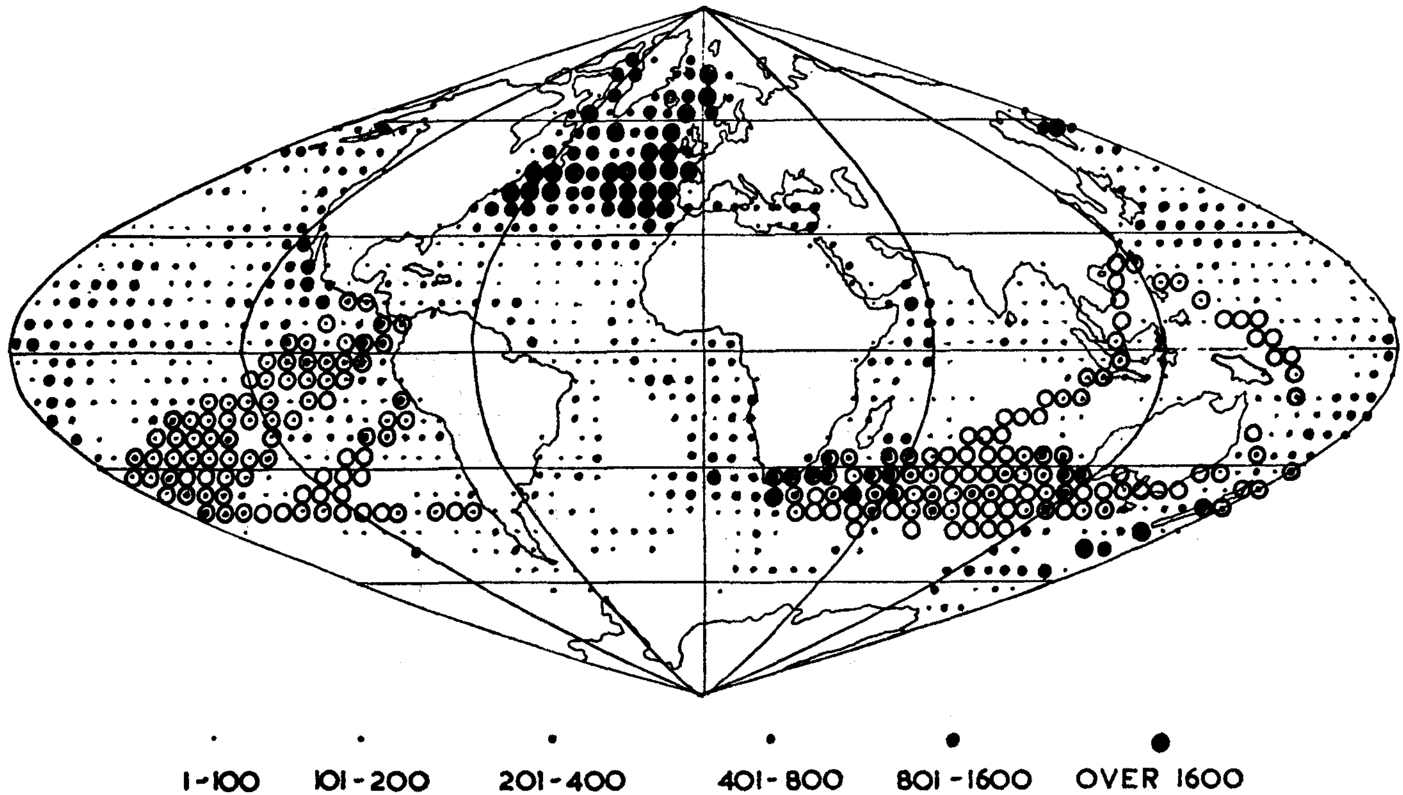

FIG. 2. Distribution of oceanographic data (filled circles) and ships' compass observations (open circles) used in the main field analysis. For the oceanographic data the number of observations is indicated by the size of the symbol plotted at the centre of the tessera.

the actual distribution of the satellite data), for epoch 1965. From these synthetic values (2520 in number) a set of normal equations was formed in the same way as that described in Section 2.5, giving unit weight to each satellite ‘observation’. The weighted sum of these equations and the normal equations derived from the surface data was formed, solved and used to derive a spherical harmonic model based on all data. In order to give the satellite data approximately the same weight as the surface and near-surface data, the satellite normal equations were multiplied by 200.

2.7 *Production of main field model for* 1975

The epoch of the main field model just described was chosen to be 1965 for the reasons given in Section 2.2; essentially that no reliable model of recent secular variation was available when the data reduction was started. By the time the 1965 main field model had been derived, a more accurate SV model had been deduced (see Section 4.1c), and this was used to up-date the 1965 coefficients to those for 1975.0 given in Table 3.

3. Secular variation

An accurate SV model is useful not only for the reduction of main field data to epoch, but also for the information it contains concerning movements in the Earth's core. Therefore, we have continued to refine the SV model even after deriving that used for correcting the main field coefficients to 1975 (referred to in Section 2.7).

The data used in previous analyses of the SV (Leaton 1962; Malin 1969; Malin & Clark 1974) have been based on annual mean values from magnetic observatories, which are unevenly distributed over the globe. In the present analysis we have improved the data distribution by including SV information from other sources, namely repeat stations, survey and satellite data. Furthermore, since the uncertainty of individual observations varies widely, we have attempted to weight them correctly relative to one another.

The final SV model for 1975.0 is defined by the spherical harmonic coefficients listed in Table 4. These are in Schmidt quasi-normalized form, in units of nT yr^{-1}. The model contains internal coefficients only, is complete up to eighth order and degree, and was derived taking account of the oblateness of the Earth.

3.1 *Data*

3.1.1. *Observatories.* The data are annual mean values for 180 observatories taken from the Herstmonceux Catalogue. This catalogue is continually updated from the literature; discontinuities and inconsistencies being resolved by direct correspondence with the observatory concerned—which also provides further unpublished information. First differences of each observed element (D, H, Z) were plotted against time and the curves extrapolated to 1975. Rather than use rigid formulae, the extrapolations were made after discussion between the authors, taking into consideration such factors as the reliability of the observations and possible correlations with trends at neighbouring observatories. For each extrapolated value an estimate was made of the range in which the actual value might reasonably be expected to fall. This uncertainty was used to weight the 532 values correctly relative to one another. The range of relative weights was from 20 to 1. Residuals from a preliminary analysis were examined for wild values, and those observations were re-examined. One observation was discarded ($\dot{D}$ at Base Baudouin) and in four cases the estimated uncertainty was revised. The distribution of the observatories used is shown in Fig. 3.

3.1.2 *Repeat stations.* Observations from repeat stations form a valuable supplement to observatory data, particularly in the Southern Hemisphere and other regions

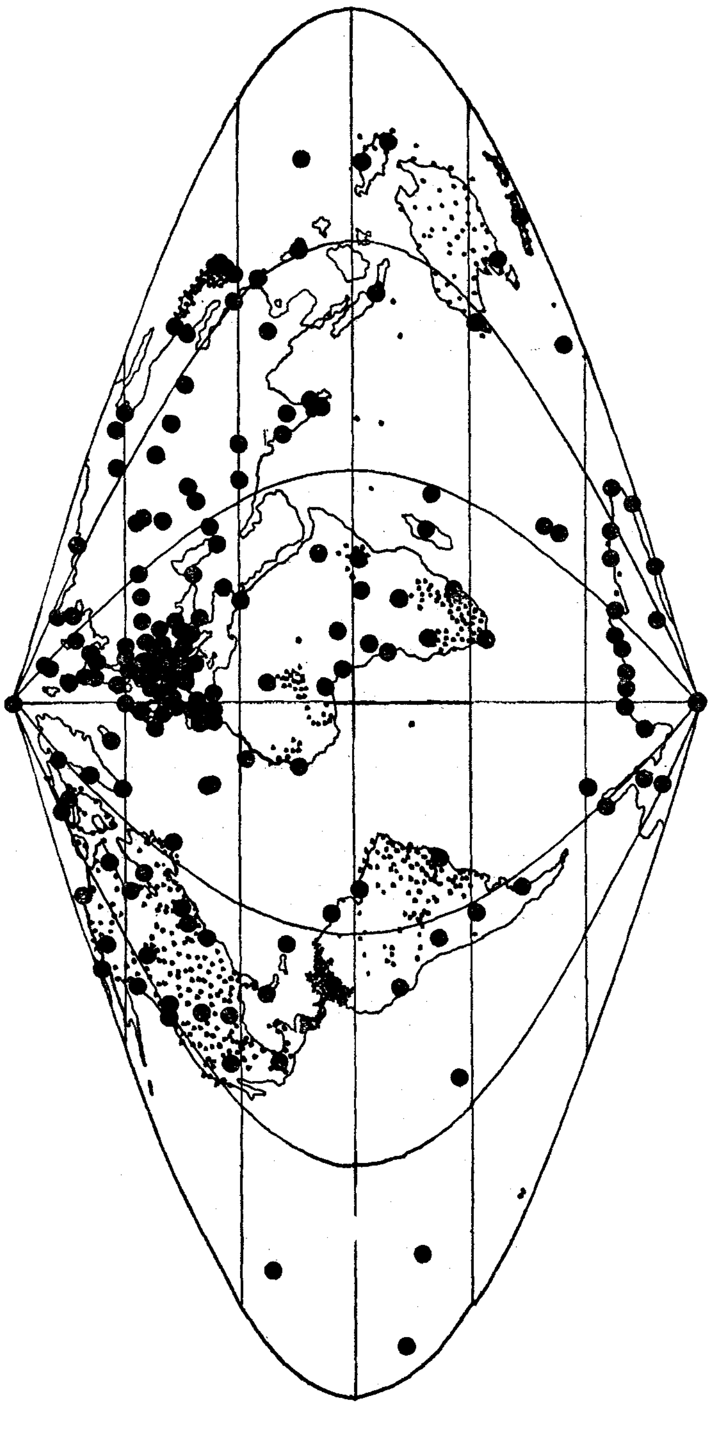

FIG. 3. Distribution of observatories (●), and repeat stations (•), used in the secular variation ayalysis.

where observatories are sparsely distributed. With this in mind, 656 repeat stations were selected from the literature and from the World Digital Data Centre tapes. Their distribution is indicated by the smaller symbols in Fig. 3. Only observations made since 1955 were considered.

From the best linear fit to these observations at each repeat station, values of $\dot{D}$, $\dot{H}$, $\dot{Z}$ (1877 in all) were estimated at the mean epoch of observation. An approximate measure of the relative uncertainties of these estimates was deduced from the expression $f. t^{-1}. n^{-\frac{1}{2}}$, where n denotes the number of occupations of the station, t the time span of the observations, and f a 'local factor' being the uncertainty of the SV estimate of that element at nearby observatories. The residuals from the preliminary models were individually examined. In this way some digitizing errors were discovered and corrected, and 32 anomalous observations were discarded.

3.1.3 *Survey data.* In order to make full use of the secular change information contained in land, sea and air surveys an interpolating function is required. Here we have synthesized $\dot{X}$, $\dot{Y}$, $\dot{Z}$ from the difference between two eighth order spherical harmonic representations of the main field for 1960 and 1970. The first was derived from the survey observations made between 1955 and 1965; and the second from the post-1965 data which have been described in Section 2.1 (categories (a) and (b)). The uneven coverage of the observations was allowed for by considering the common features of the local density of observations at each main field epoch. Values were synthesized for the centre of each tessera (as defined in Section 2.2) and weighted according to the number of main field observations in that tessera for one of the two main field epochs; where the number differed for the two epochs, the *lower* value was chosen. The distribution of SV values and their weights are shown in Fig. 4; these data are of particular value in enhancing the coverage over the oceans.

3.1.4 *Satellite data.* As in the case of survey data, an interpolating function is necessary for the extraction of SV information. The POGO(8/73) model referred to in Section 2.6 was used. This model should provide a good representation of $\dot{F}$ at satellite altitude, although, due mainly to lack of directional information, it may be less reliable for components at the surface of the Earth. From this model values of $\dot{F}$ were synthesized on the grid described in Section 2.6.

Of these four independent data sets only the first refers to epoch 1975. The others were updated to 1975 using the secular acceleration model described in Section 4. Each data set was then analysed independently to produce a spherical harmonic model, the similarity of these models serving as a final check on the observational equations—8704 in all.

3.2 *Analysis*

The secular variation is assumed to result from a potential field, $\dot{V}$, of purely internal origin. The orthogonal components, $\dot{X}$, $\dot{Y}$, $\dot{Z}$, are respectively the north, east and vertically downward gradients of $\dot{V}$. The SV of the non-orthogonal elements may be represented by linear combinations of the orthogonal elements as follows:

$$\dot{D}\,H = \dot{Y}\cos D - \dot{X}\sin D$$

$$\dot{H} = \dot{X}\cos D + \dot{Y}\sin D$$

$$\dot{I}\,F = \dot{X}\cos D\sin I + \dot{Y}\sin D\sin I + \dot{Z}\cos I$$

$$\dot{F} = \dot{X}\,X/F + \dot{Y}\,Y/F + \dot{Z}\,Z/F.$$

(The un-dotted symbols represent main field values, which may be supplied from the IGRF if observed quantities are not available.) Thus each SV observation gives a

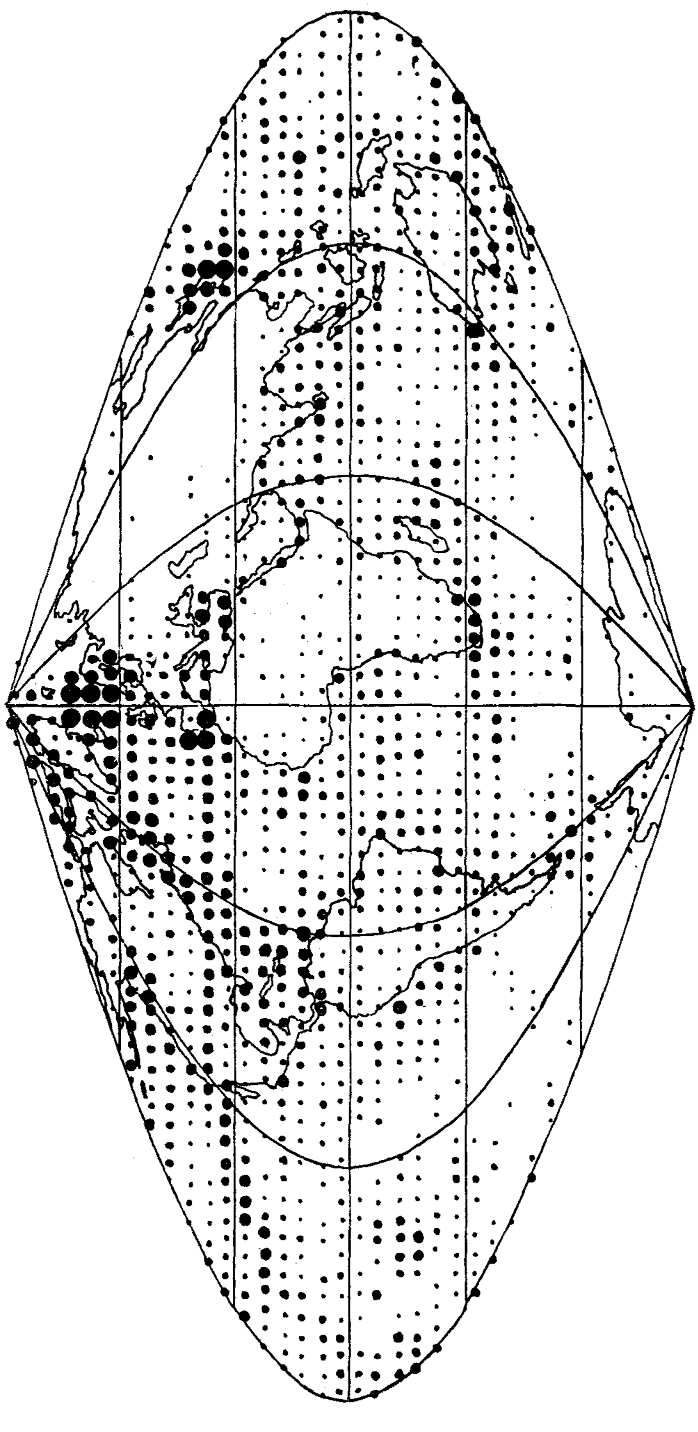

FIG. 4. Distribution of weights assigned to the synthesized secular variation values based on land, sea and air survey data. The scale of the symbols is that used in FIG. 1

Table 3

Spherical harmonic coefficients of the main field for 1975·0

m	n	g_n^m (nT)	h_n^m (nT)	m	n	g_n^m (nT)	h_n^m (nT)
0	1	−30103·6		1	9	10·0	−19·6
1	1	−2016·5	5682·6	2	9	1·6	15·7
0	2	−1906·7		3	9	−11·4	4·9
1	2	3009·9	−2064·7	4	9	10·6	−3·1
2	2	1633·0	−58·1	5	9	0·6	−4·2
0	3	1278·2		6	9	−0·2	9·7
1	3	−2142·0	−329·8	7	9	0·6	12·2
2	3	1254·7	265·9	8	9	0·5	−0·2
3	3	831·0	−227·0	9	9	0·5	0·3
0	4	946·9		0	10	−5·0	
1	4	792·5	193·4	1	10	−3·3	1·3
2	4	443·8	−265·8	2	10	2·4	2·0
3	4	−403·9	53·0	3	10	−6·0	2·6
4	4	212·5	−285·2	4	10	−1·4	2·8
0	5	−220·6		5	10	6·6	−3·6
1	5	351·4	24·5	6	10	4·6	−0·2
2	5	262·3	148·4	7	10	1·2	0·3
3	5	−63·8	−161·3	8	10	−1·8	3·2
4	5	−157·5	−83·4	9	10	3·4	3·0
5	5	−40·2	92·3	10	10	−1·0	−3·4
0	6	44·1		0	11	2·8	
1	6	69·9	−11·2	1	11	−1·9	0·5
2	6	27·7	100·4	2	11	−4·5	0·7
3	6	−194·3	77·6	3	11	2·9	−0·9
4	6	−0·9	−40·3	4	11	−1·2	−1·5
5	6	3·8	−7·9	5	11	1·3	0·3
6	6	−108·7	15·6	6	11	−0·8	0·6
0	7	71·5		7	11	1·9	−2·1
1	7	−53·3	−76·6	8	11	3·4	0·9
2	7	2·3	−24·7	9	11	−1·6	−2·5
3	7	13·4	−4·5	10	11	1·7	−0·7
4	7	−6·4	7·0	11	11	2·5	0·3
5	7	3·2	24·5	0	12	−0·5	
6	7	17·0	−21·8	1	12	0·8	0·1
7	7	−5·9	−12·9	2	12	−1·3	−0·5
0	8	11·0		3	12	0·1	0·4
1	8	5·1	4·9	4	12	−0·6	0·0
2	8	−2·6	−13·9	5	12	0·0	0·8
3	8	−12·6	5·0	6	12	−1·8	−0·1
4	8	−13·8	−18·0	7	12	−1·6	−0·2
5	8	−0·1	5·7	8	12	−0·7	−0·5
6	8	−2·4	14·5	9	12	−0·9	0·3
7	8	12·3	−11·1	10	12	0·4	−2·0
8	8	4·9	−16·7	11	12	0·0	1·4
0	9	9·3		12	12	1·1	−0·2

linear equation in the spherical harmonic coefficients $\dot{g}_n^m$, $\dot{h}_n^m$. From these equations values of $\dot{g}_n^m$, $\dot{h}_n^m$ were directly determined by the method of least squares. In this analysis the oblateness of the Earth was taken into account (see Barraclough & Malin 1971).

A feature of this analysis is that an attempt has been made to weight the observations realistically. Within each set, the relative weights of the observations are readily assigned (i.e. inversely as the square of the uncertainties for the observatories and repeat stations, and according to the distribution of the information from which the models were derived for the other two sets), but no similarly straightforward rule can be used to indicate relative weights of the sets themselves. We found, after considerable experimentation, that the final model was, within a wide range, insensitive to this weighting.

The repeat stations had been selected so that their distribution would complement that of the observatories. These two sets were combined in such a way that the repeat stations were equivalent to about 80 observatories. In the final analysis this combined set was given a weight of two, while the survey data and satellite data sets were each given unit weight.

4. Secular acceleration

A reliable estimate of the secular acceleration (SA) is necessary in order to reduce to epoch the SV information derived from repeat stations and surveys. We know that the SA coefficients of Malin (1969) are reasonably good, since Malin & Clark (1974) showed that they predicted the changes in SV from 1952 to 1965 tolerably well. The SA coefficients can be better determined by including more recent SV models.

4.1 *Data*

We have various spherical harmonic models of SV based on observatory data. These are:

(a) 1942.5–1947.5, 1947.5–1952.5, 1952.5–1957.5, 1957.5–1962.5, all based on 5-year means of X, Y and Z from the *same* set of 80 observatories (Malin 1969). Equal weight was given to each observatory. The sets of coefficients are complete up to sixth order and degree. Also included is a set of SA coefficients.

Table 4

Spherical harmonic coefficients of the secular variation field for 1975·0

m	n	$\dot{g}_n^m$ (nT yr^{-1})	$\dot{h}_n^m$ (nT yr^{-1})	m	n	$\dot{g}_n^m$ (nT yr^{-1})	$\dot{h}_n^m$ (nT yr^{-1})
0	1	26·8		2	6	2·3	−0·2
1	1	10·0	−10·1	3	6	3·5	0·2
0	2	−25·0		4	6	0·0	−1·6
1	2	0·3	−2·8	5	6	0·8	0·4
2	2	5·5	−18·9	6	6	−0·4	2·0
0	3	−3·8		0	7	−0·4	
1	3	−10·5	7·2	1	7	−0·2	−1·2
2	3	−4·7	2·8	2	7	−0·5	−0·2
3	3	−4·7	−6·4	3	7	0·3	0·0
0	4	−0·9		4	7	0·8	0·3
1	4	−2·2	5·4	5	7	0·6	−0·6
2	4	−4·0	0·7	6	7	0·5	0·0
3	4	−2·1	2·6	7	7	−0·8	1·2
4	4	−4·6	−0·7	0	8	0·4	
0	5	0·2		1	8	0·3	−0·2
1	5	−1·0	0·9	2	8	0·0	−0·3
2	5	1·3	2·6	3	8	0·4	−0·3
3	5	−2·1	−2·7	4	8	−0·2	−0·3
4	5	−0·6	1·3	5	8	−0·4	0·5
5	5	1·3	1·1	6	8	0·6	−0·5
0	6	0·6		7	8	−0·3	−0·6
1	6	0·9	−0·3	8	8	0·0	0·5

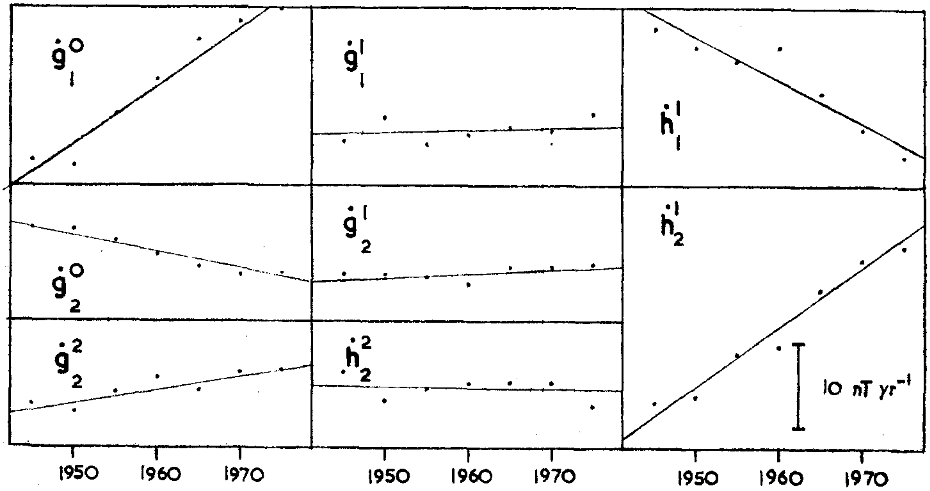

FIG. 5. The first eight spherical harmonic coefficients of secular variation plotted against time.

(b) 1962.5–1967.5, based on 5-year means of X, Y and Z from 118 observatories (Malin & Clark 1974). Equal weight was given to each observatory. The set of coefficients is complete up to sixth order and degree.

Table 5

Spherical harmonic coefficients of the secular acceleration

m	n	$\ddot{g}_n^m$ (nT yr^{-2})	$\ddot{h}_n^m$ (nT yr^{-2})
0	1	0·70	
1	1	—	−0·49
0	2	−0·20	
1	2	—	0·68
2	2	0·16	—
0	3	−0·28	
1	3	—	0·13
2	3	−0·32	—
3	3	—	—
0	4	—	
1	4	−0·17	0·30
2	4	—	—
3	4	−0·14	—
4	4	−0·17	0·16
0	5	−0·13	
1	5	−0·14	−0·14
2	5	−0·14	0·10
3	5	−0·10	—
4	5	—	—
5	5	—	0·10
0	6	0·07	
1	6	0·04	—
2	6	0·12	—
3	6	0·11	−0·10
4	6	—	—
5	6	0·09	—
6	6	—	—

(c) 1970, 1975, based on values of D, H, Z read from plots of first differences of annual mean values from 180 observatories (see Section 3.1.1). The data were weighted according to the confidence limits of the data. The models comprise 48 and 46 coefficients, respectively, fairly complete up to fifth order and degree, then including various coefficients up to eighth degree. The numbers and distribution of coefficients were chosen after numerous experiments to find the most efficient representation of the data.

In the past it has been feared that SA derived from SV models might be seriously contaminated by the effects of changes in geographical distribution of data between the models. However, from an examination of the SV coefficients plotted against time (the first 8 plots are shown in Fig. 5) it appears that SV is not particularly sensitive to the changes in data distribution that occur between (a), (b) and (c), since the first four points are not noticeably less scattered than the last three points. The linearity of the plots also suggests that higher time derivatives are of little importance compared with SA.

Thus our data set consists of 7 SV models uniformly spaced between 1945 and 1975.

4.2 *Analysis*

The SA coefficients were calculated from a least-squares linear fit to coefficients of the 7 SV models. Equal weight was given to each model. Standard deviations were calculated from the scatter of the points about the best straight line.

The final SA model comprises the 26 coefficients that exceed their standard deviations by a factor greater than 2·5. These are presented in Table 5. To adjust the main field coefficients to an epoch T years after 1975.0, the following formula applies:

$$\text{MF (new epoch)} = \text{MF} + \text{SV}\ T + \tfrac{1}{2}\ \text{SA}\ T^2.$$

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