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Toward an Improved Distribution of Magnetic Observatories for Modeling of the Main Geomagnetic Field and Its Temporal Change

R. A. LANGEL[1], R. T. BALDWIN[2], and A. W. GREEN[3]

[1] *Geodynamics Branch, Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.*
[2] *Hughes STX Corp., Lanham, MD 20706, U.S.A.*
[3] *U.S. Geological Survey, Golden, CO 80401, U.S.A.*

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The magnetic field from Earth's core (the main field) is a global phenomena with measurable temporal variations with periods ranging from one year to millennia. Geomagnetic studies are thus heavily dependent on the availability of data well distributed over the globe and acquired over long periods of time. Satellite data provide the best geographic coverage, but are unlikely to be available except possibly at intervals of 10 to 30 years. Accurate mapping of the main field over long periods of time is mostly dependent upon a network of geomagnetic observatories, each of which contributes continuous, three-component, data of high accuracy. The overall accuracy of knowledge of the main field depends both upon the adequacy of the geographic distribution of those observatories and on the existence of periodic surveys by satellite. Analysis of models based on the existing observatory distribution reveals large geographic regions in which their accuracy is degraded such that studies of the field, its source dynamo, etc. are seriously limited. Model accuracy is studied for three distributions of 92, 162, and 252 equally spaced observatory sites and for degradation of those distributions by a large area with no data. The 92-site distribution is the most economically realistic. Expansion of the existing network so that a subset of observatories approximates this 92-site distribution can be accomplished by a phased program of collocating magnetometers at 20 sites already established, or now planned, for other geophysical networks such as FLINN, GEOSCOPE, IDA, and IRIS, at 10 additional land or island sites, and at 8 sea bottom sites. Specific locations for these sites are proposed. While not meeting all of the needs for study of current problems in geomagnetism, if implemented, this extension of the current observatory network would form a firm foundation for most such studies. Such implementation will only be accomplished if the burden for doing so is partially shouldered by most or all of the national agencies and organizations representing data users and if such users unit in expressing their own need.

1. Introduction

It is common to represent the internal magnetic field of the Earth in terms of a potential function of the form

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

where a is the mean radius of the Earth (6371.2 km); r the radial distance from the center of the Earth; ϕ the east longitude measured from Greenwich; θ the geocentric colatitude; and $P_n^m\ (\cos\theta)$ the associated Legendre function of degree n and order m, normalized according to the convention of Schmidt (see, e.g., Langel, 1987). The g_n^m and h_n^m are called Gauss coefficients. The radial variation, $(a/r)^{n+1}$, represents fields from sources internal to the region where (1) is valid; fields originating in $r > a$ are ignored in (1). The magnetic field $\boldsymbol{B}$ is then given by

$$\boldsymbol{B} = -\boldsymbol{\nabla} V. \tag{2}$$

Using measurements from the Magsat spacecraft, such representations, or their equivalent, have been computed up to about degree 60, i.e., $n^* = 60$, before the effects of noise begin to dominate (Cain *et al.*, 1989; Arkani-Hamed and Strangway, 1986; Arkani-Hamed *et al.*, 1994). It is now generally agreed that, near the Earth's surface, the magnetic field from the core dominates for degrees 1–12 and that the magnetic field from the crust and/or lithosphere dominates for degrees above 14.

However, when deriving spherical harmonic models in the absence of Magsat-quality satellite data, the IAGA (International Association of Geomagnetism and Aeronomy) committee responsible for the International Geomagnetic Reference Field (IGRF) concluded that the data quality and, mainly, distribution, did not warrant carrying the analysis beyond degree 10 (Langel, 1992). The early IGRF models were dependent upon data from the magnetic observatories, heavily supplemented by data from repeat stations and by land, aeromagnetic, and shipborne magnetic survey data in areas between magnetic observatories. Even with the best available data distribution, differences between candidate IGRF models, indicative of model error, reached several hundreds of nT in some cases.

This highlights a growing concern of many in the geomagnetic community, i.e., the serious deficiencies in the present network of geomagnetic observatories. Figures 1 and 2 summarize the situation regarding the present and past geographic distribution of observatories. Figure 1, adapted from Malin and Gubbins (1983), shows the number of observatories as a function of time; Fig. 2 shows the observatories from which data are available for the 1980–1990 time period. The imbalance between northern and southern hemispheres and between continental and oceanic regions is obvious. Further deterioration is occurring due to closure, or impending closure, of some observatories due to economic or political pressures. This is of particular concern when such observatories are in areas where coverage is already minimal. To redress this situation, Division 5 of IAGA has initiated Program Outreach (Williams, 1993), a call for aid to, or adoption of, observatories in difficulty, by agencies or groups in countries with more adequate resources.

Spherical harmonic models of the field from the core have many uses. These extend from the production of charts for various commercial uses to sophisticated investigations of the Earth's

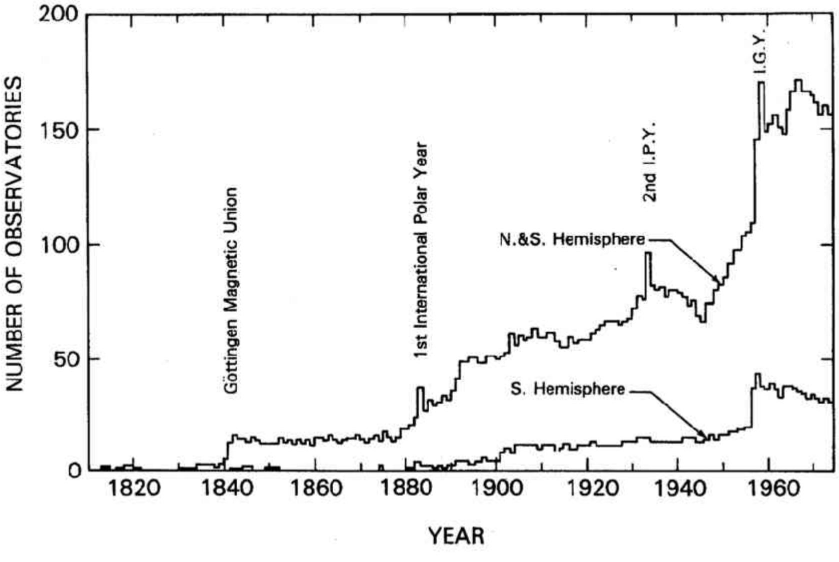


Fig. 1. Distribution of the number of magnetic observatories in time. (Malin and Gubbins, 1983).

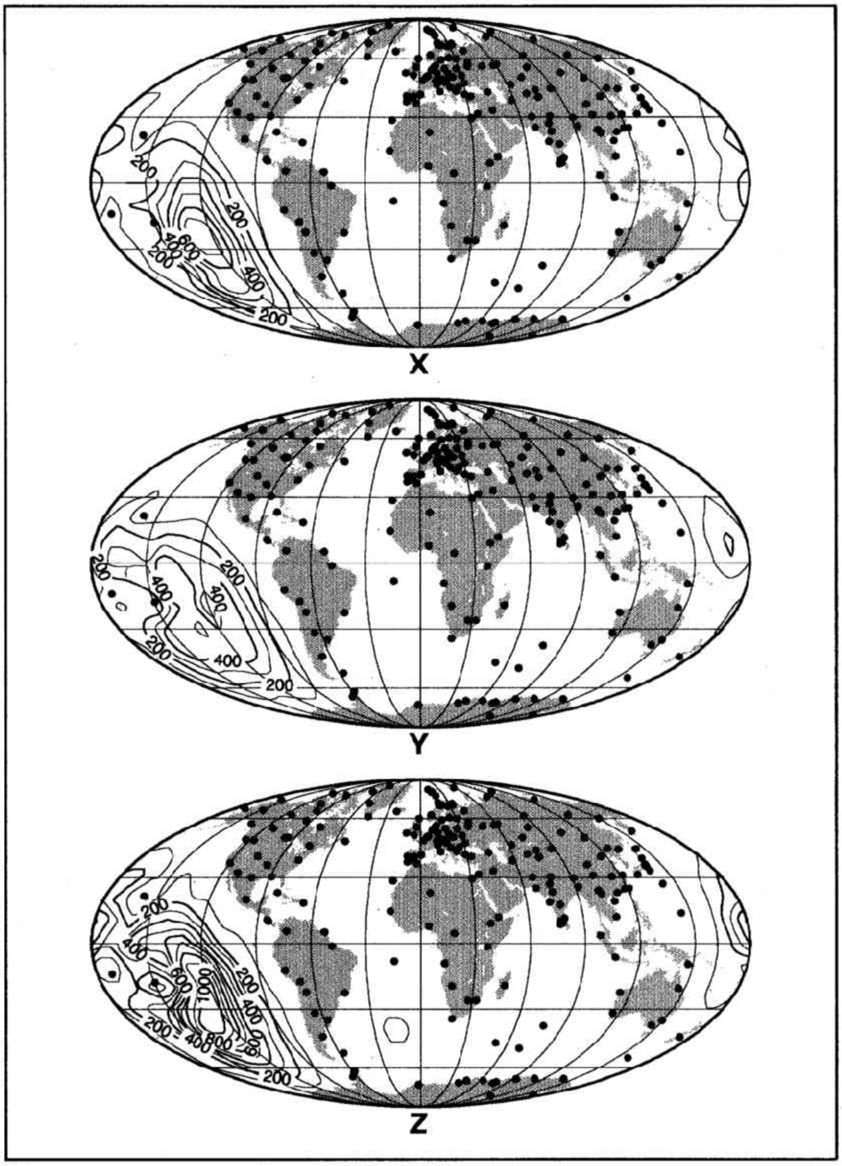


Fig. 2. Geographic distribution of magnetic observatories providing data in the 1980–1990 time period overlain by contours of estimated field model error, in nT, for this distribution.

core and mantle. The latter have been especially highlighted since the advent of satellite data. It is fair to say that main field geomagnetism has reached the point where accurate global vector data extending over a significant time span, ideally decades and more, are required for significant advances. It also seems evident that at least a portion of these data must come from periodic satellite surveys, of the quality of Magsat.

However, the list of proposed, yet unrealized, missions to measure the geomagnetic field becomes longer each year, e.g., GRM, MFE, APAFO, EOS/GOS, MFE/Magnolia, ARISTOTE-

LES, and GAMES. While we are hopeful that some sort of magnetic field measuring mission will take place in this and/or the next decade, e.g., Oersted and/or POGS/DMSP, the realities of the current economic climate appear to be such that the best that can be hoped for on a continuing basis is a mean time between missions of ten to thirty years. That is not sufficient to address the scientific issues. Therefore, it seems prudent to formulate and to try to implement a plan to bridge the gaps between satellite surveys using surface measurements. Assuming that satellite surveys will provide "anchor points", or "snap shots", at which the main field is known very accurately, such a bridge should serve two functions. First, it should provide adequate data to map the main field and its temporal change, or secular variation (which, strictly speaking, is the first time derivative), between the anchor points and, second, it should supplement the satellite data, during the satellite measurement epochs, by mapping local-time field variations on a global scale.

In our view, the best way to map temporal change is with the traditional magnetic observatory, suitably upgraded with current technology. This is not to say that other types of data are not essential. Nor is it to say that, given sufficient satellite data, observatories are not needed. Data from repeat stations are crucial in defining temporal change in regions away from magnetic observatories and land, sea, and air surveys are crucial for mapping regional field changes. Furthermore, when observatory quality measurements are not available, well-conducted repeat station measurements and periodic surveys fill some of the gaps. The particular advantage of magnetic observatory data is their ability to map the temporal change continuously at a set of fixed locations. No survey data, including that from satellites, can provide such data. Furthermore, satellite data alone cannot unambiguously distinguish between temporal and spatial variations of the field. Further, even the long period temporal change of the main field cannot be accurately measured by occasional satellite surveys since it is non-linear.

The purpose of this paper is to outline, and provide the rationale for, extending the existing observatory network into the required bridge. There will certainly be other ways to do this. But perhaps our suggestion will provide a focal point for further discussion, and, we hope, action. We will begin by suggesting an idealized geographic distribution in the sense that its locations are evenly spaced. The effect of departures from this distribution on field model errors will be documented. Then the existing observatory network will be compared to the ideal, and locations for additional stations suggested. Since other geophysical measurements (e.g., seismic, geodetic) are also acquired on a global basis, such sites that are close to our ideal sites will be noted. Co-location of instruments, where compatible, would be one method of reducing the cost of constructing our bridge. However, this will not always be an option; the establishment of observatory-quality measurement stations in remote sites, and even at the bottom of the ocean, will be required if an adequate bridge is to be realized.

2. Formalism for Error Estimation

To evaluate any particular data distribution it is convenient to have some objective estimate of the accuracy of the resulting models. In principle, we should investigate errors in the extension in time of a main field model derived from satellite data at a fixed epoch. But this would require an accurate parameterization of the temporal change, which is complicated and is debated. As a proxy error analysis, we choose to examine the errors in a main field model based only on the spatial distribution of magnetic observatories. There are various ways of looking at the error from a spherical harmonic model. The two perspectives considered are: first, to estimate the error distribution, and corresponding maximum error, for each field component over the globe, and, second, to estimate the error in specific spherical harmonic coefficients.

The formalism employed for making the error estimates is as follows (see, e.g., Langel, 1987). Bold faced symbols will represent vectors. If $\boldsymbol{C}$ is the column vector of measurements, and $\boldsymbol{p}$ the column vector of spherical harmonic coefficients, including any other parameters to be determined, then the model equation is

$$\boldsymbol{C} = A\boldsymbol{p} + \boldsymbol{e} \tag{3}$$

where A is the matrix of partial derivatives of the measurements with respect to the $\boldsymbol{p}$, and $\boldsymbol{e}$ is the column vector of measurement errors, assumed random. The formal, least squares, solution to (3) is

$$\hat{\boldsymbol{p}} = (A^T W A)^{-1} A^T W \boldsymbol{C} \tag{4}$$

where ^{T} indicates transpose, W is a suitable weight matrix reflecting data accuracy and correlations (Langel *et al.*, 1989; Langel, 1991), and $\hat{\boldsymbol{p}}$ is the estimate of $\boldsymbol{p}$. If the model is adequately parameterized, the solution covariance matrix

$$V_p = (A^T W A)^{-1} \tag{5}$$

will provide an estimate of the error and of correlation between the parameters, $\boldsymbol{p}$. Further, since for linear components, B_j, of the field, $\boldsymbol{B}$, it is possible to write

$$B_j(\boldsymbol{r}) = \boldsymbol{p}^T \boldsymbol{g}_j(\boldsymbol{r}) \tag{6}$$

where $\boldsymbol{g}_j(\boldsymbol{r})$ is a vector of geometric parameters (the vector of partial derivatives of $B_j(\boldsymbol{r})$ with respect to the $\boldsymbol{p}$ at location $\boldsymbol{r}$). The predicted error estimate for $B_j(\boldsymbol{r})$ is given by

$$\sigma_j(\boldsymbol{r}) = \boldsymbol{g}_j(\boldsymbol{r})^T V_p \boldsymbol{g}_j(\boldsymbol{r}). \tag{7}$$

To apply this formalism, the effect of truncated fields is neglected, i.e., contributions from spherical harmonics above degree n^*, and it is assumed that crustal fields at the observatories have been accounted for in some way, perhaps by subtracting a known field. Only linear data , i.e., the usual X, Y, Z components are considered. This permits W to reflect only the noise in the data. For simulation purposes, the σ of the data is taken to be 10 nT (nanoTesla), uniformly. For comparison, Langel and Estes (1985) found σ's of 16.9, 9.4 and 14.4 nT in the X, Y, and Z components, respectively, when accounting for crustal fields in the GSFC(12/83) model. The estimated errors scale directly with the chosen σ, i.e., if the reader prefers an estimate of $\sigma = 25$ nT, then all results should be multiplied by a factor of 2.5.

3. Defining An Ideal Distribution

By our definition, measurement locations in an ideal distribution are equidistantly spaced. There are several ways to estimate the spacing required. For example, if the mean radius of the Earth is $a = 6371.2$ km, then each data point will "represent" an area of $A = 4\pi a^2/N$, where N is the number of locations. Suppose the area assigned to each data point is approximated by a spherical cap of radius χ, in radians. That area is then

$$A = 2\pi a^2(1 - \cos\chi) = 4\pi a^2 \sin^2(\chi/2) = 4\pi a^2/N. \tag{8}$$

Take the diameter of the spherical cap, say d_1, as an estimate of the average distance between adjacent data points. This gives

$$d_1 = 2\chi a = 4a\sin^{-1}(N^{-1/2}). \tag{9}$$

If the minimal N is equal to the number of coefficients in Eq. (1), then

$$N = N_1 = n^*(n^* + 2). \tag{10}$$

Another spacing estimate can be made by noting that degree n in the spherical harmonic expansion of the potential includes a maximum of n wavelengths in one great circle circumference of the Earth. The mean circumference of the Earth is $c = 2\pi a = 40031.4$ km, so the minimum wavelength is c/n^* km or $2\pi/n^*$ degrees. The usual Nyquist criteria would require at least two measurements in one wavelength or a measurement every $\theta_2 = \pi/n^*$ degrees, or a distance between measurement location of

$$d_2 = 20015/n^* \text{ km}. \tag{11}$$

To derive an ideal measurement location distribution, a technique proposed by Vestine *et al.*, (1963) and adapted by Covington (1993) for dividing a sphere into symmetric, equal area sectors was used. This method, called SIM for spherical icosahedron model, utilizes the arrangement of the faces of a spherical icosahedron (20 faced polyhedron) to subdivide a sphere so that the sectors surrounding a central grid point are symmetric and are the same shape regardless of the location of the grid point on the sphere. Figure 3 shows how the grid points are arranged in the SIM. One axis of the spherical icosahedron corresponds to the axis of rotation of the Earth. The spherical triangle ABC is one of five such triangles that have a common vertex at the north pole and which have two sides (AB and AC) that lie in meridional planes. The sides AB and AC can be subdivided into m equal arcs ($m = 16$ in Fig. 3) described by their colatitude locations. The m points on AB can be joined to their corresponding points, i.e., those with the same colatitude, on AC by great circles. Each of these arcs can be subdivided once for each arc lying between it and the pole, generating the gridding pattern shown in the figure. Repeating the process for the rest of the faces produces a distribution grid of consistently shaped, nearly equal-area sectors. The shape of each sector is a hexagon, except for the 12 points where five faces join at a common

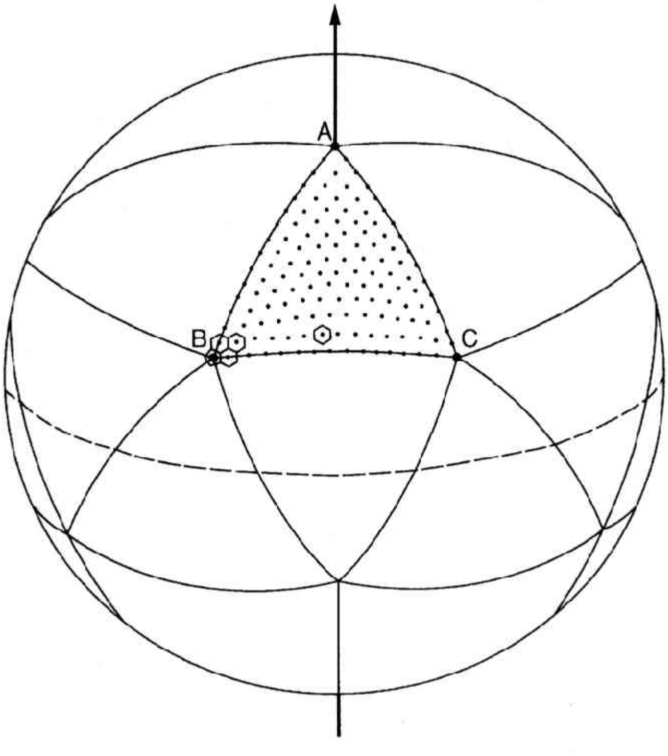


Fig. 3. SIM distribution scheme. Dashed line is the equator.

vertex to form a pentagon. An algorithm exists to generate the geographic coordinates of the grid points for any choice of m. Since m is restricted to integer values, the number of points, which is $10m(m-1)^2+2$, and their spacing is quantized.

Table 1 shows three values of n^*, and the corresponding N_1, d_1, d_2 and θ_2. Three SIM distributions were chosen, roughly corresponding to the three values of θ_2 and d_2 in the table. The number of points in each SIM distribution is given as N_s, and the distance between SIM points is given by d_s. The quantity d_s is obtained by dividing the length of a side of a spherical triangle on a icosahedron (7054 km) by m, the number of subdividing arcs for the triangle.

In Table 1, N_1 is the number of unknowns, or coefficients, in the model. At least N_1 measurements are required to obtain a solution. With N_s data locations, the Nyquist criteria, or the minimal data spacing to avoid aliasing, is met. In practice, three field components are measured at magnetic observatories. Each component constitutes a measurement when discussing N_1. Thus, it is possible to satisfy the N_1 condition and not the N_s condition. In this case a solution may be obtained in which the spherical harmonic coefficients are well-determined in a least squares sense but for which the Nyquist criteria is not satisfied. In practice, aliasing is

Table 1. Ideal measurement spacing vs. degree of model.

	Number of coefficients		Nyquist criteria		Number of SIM points		
n^*	N_1	d_1	d_2	θ_2	N_s	m	d_s
9	99.	2566.	2224.	20°	92	4	2351
12	168.	1968.	1668.	15°	162	5	1763
15	255.	1597.	1334.	12°	252	6	1411

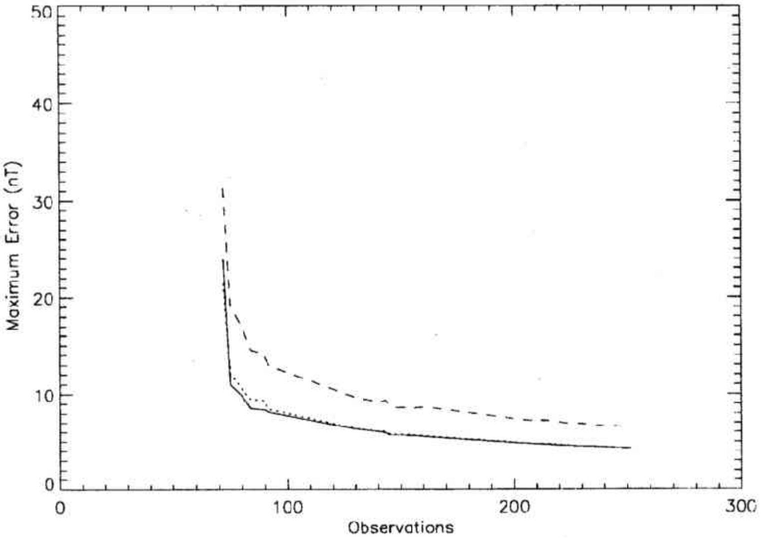


Fig. 4. Maximum error in nT of the field components computed from a degree 13 spherical harmonic model vs. number of evenly spaced, three-component, observations used to derive the model. Solid line: X component; Dotted line: Y component; Dashed line: Z component.

mitigated by three factors: (1) Additional data locations are included from observatories not part of the ideal distribution, from repeat stations, and from land, sea, and air surveys; (2) Actual models are assumed to be "anchored" at a base epoch by data from a global satellite survey; (3) The power in the geomagnetic field spectrum decreases monotonically with increasing harmonic degree.

To quantify the situation where three component measurements are available, the error formalism described in the previous section was used to compute the maximum error in each component from a series of degree-13 models. Each model assumed an equal area distribution of observatories (not SIM distributions), each measuring three components. Figure 4 shows these maximum errors as a function of the number of observatories. The error curves drop steeply as the number of observatories increases from 70 to 90, at which point the decrease in error becomes more gradual. This leads us to the conclusion that the $n^* = 9$ spacing in Table 1 is adequate, though not ideal from a Nyquist point of view, for accurate derivation of a model with $n^* = 12$ or 13. In the following Section, error analyses are presented for each of the three SIM distributions.

As a criteria for selecting an ideal distribution we would note the already mentioned division of the spherical harmonic spectrum into those harmonics representing the field from the core, degree 1–12, and those harmonics representing the field from the crust/lithosphere, degree greater than 14. On this basis, one of the adopted goals of our bridge is that its geographic distribution be adequate to derive a spherical harmonic model in which, given data of adequate accuracy, coefficients of degree up to and including 12 are significant.

4. Errors When the Distribution is not Ideal

The contours on Fig. 2 show the estimated errors, from Eq. (7), in each component for the distribution of observatories shown, i.e., the existing network. As expected, the largest errors, reaching over 500 nT, occur in the south Pacific where the data gap is greatest. Table 2 summarizes the estimated error for each of the three SIM distributions described in the previous section. The error for each component is relatively uniform over the globe with all error expected to be less than 15 nT.

Table 3 gives a tabulation of the maximum coefficient standard error, or σ, by spherical harmonic degree, for each of the three idealized distributions. For comparison, the coefficients from the GSFC(12/83) model of Langel and Estes (1985), based on Magsat data, are summarized in the last column. All standard errors are between 0.17 and 0.8 nT. Those for the 20° spacing are larger by a factor that varies between about 1.7 at degree 1 and 2.0 at degree 13. All of these distributions are of marginal accuracy at degree 11 through 13. At degree 13, about half of the coefficient values in the GSFC(12/83) model are greater than the σ value in the 20° distribution.

For each of the three SIM location distributions, error estimates due to a simple departure from the ideal were derived. In particular, the errors due to simple gaps in the distribution were estimated by systematically removing points in an enlarging "circle" of radius s, as follows: (1) One location is removed, e.g., location p on the equator; (2) All nearest neighbor locations to p

Table 2. Estimated range of error for three SIM distributions.

Distribution spacing	Range of error (nT)		
	X-Component	Y-Component	Z-Component
12°	4.2–4.4	4.1–4.5	6.1–6.8
15°	5.1–5.6	5.1–5.8	7.4–8.8
20°	6.2–8.3	6.4–9.1	9.1–13.7

Table 3. Range of coefficient standard error for three ideal station distributions: 12° station spacing; 15° station spacing; and 20° station spacing and range of coefficient magnitudes from the GSFC(12/83) model.

Degree	Maximum standard error (nT) 12° Spacing	15° Spacing	20° Spacing	GSFC(12/83) coefficient range(nT)
1–5	0.44	0.55	0.74	46–30,000
6	0.24	0.30	0.41	2.2–192.0
7	0.23	0.28	0.41	0.63–72.0
8	0.21	0.27	0.37	0.44–18.5
9	0.20	0.25	0.37	1.19–20.9
10	0.19	0.24	0.35	0.27–6.1
11	0.19	0.23	0.43	0.04–3.5
12	0.18	0.23	0.44	0.01–2.55
13	0.17	0.23	0.44	0.06–1.5

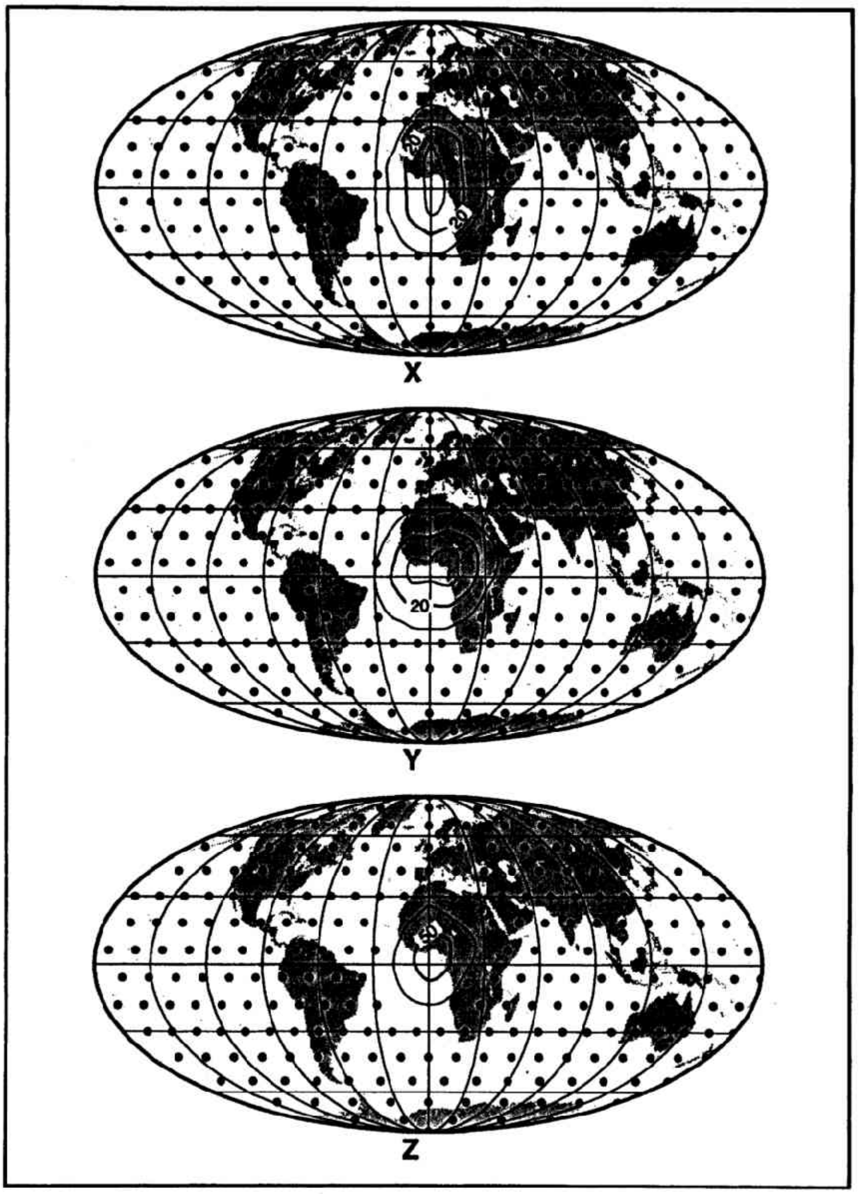
Table 4. Number of points in distribution as function of gap size.

Exclusion Radius, s: Degrees	Number of points in distribution 12° Spacing	15° Spacing	20° Spacing
None	252	162	92
5	252	161	92
10	250	161	92
15	248	161	90
20	244	155	89
25	240	155	89
30	236	146	84
35	229	146	84
40	223	143	80
45	215	141	80
50	207	130	75

are removed, i.e., the points in the "circle" of points surrounding p; (3) the process is repeated for the next "circle" of points, etc. The maximum predicted error in X, Y and Z is then plotted as a function of the exclusion radius, s. Table 4 shows the number of points remaining as a function of s, for each of the three SIM spacings.

Figure 5 shows contour plots of the resulting error estimations for a gap of radius 30°, while Fig. 6 shows the increase in maximum error as the size of the data gap increases. From Fig. 5 it is seen that, as expected, a large increase in error occurs in the data gap. However, it is also clear that the denser data distribution is more tolerant of a gap, i.e., its error is lower for a gap of the same size. The growth of the maximum error as a function of data gap is faster for the smaller ideal data set.

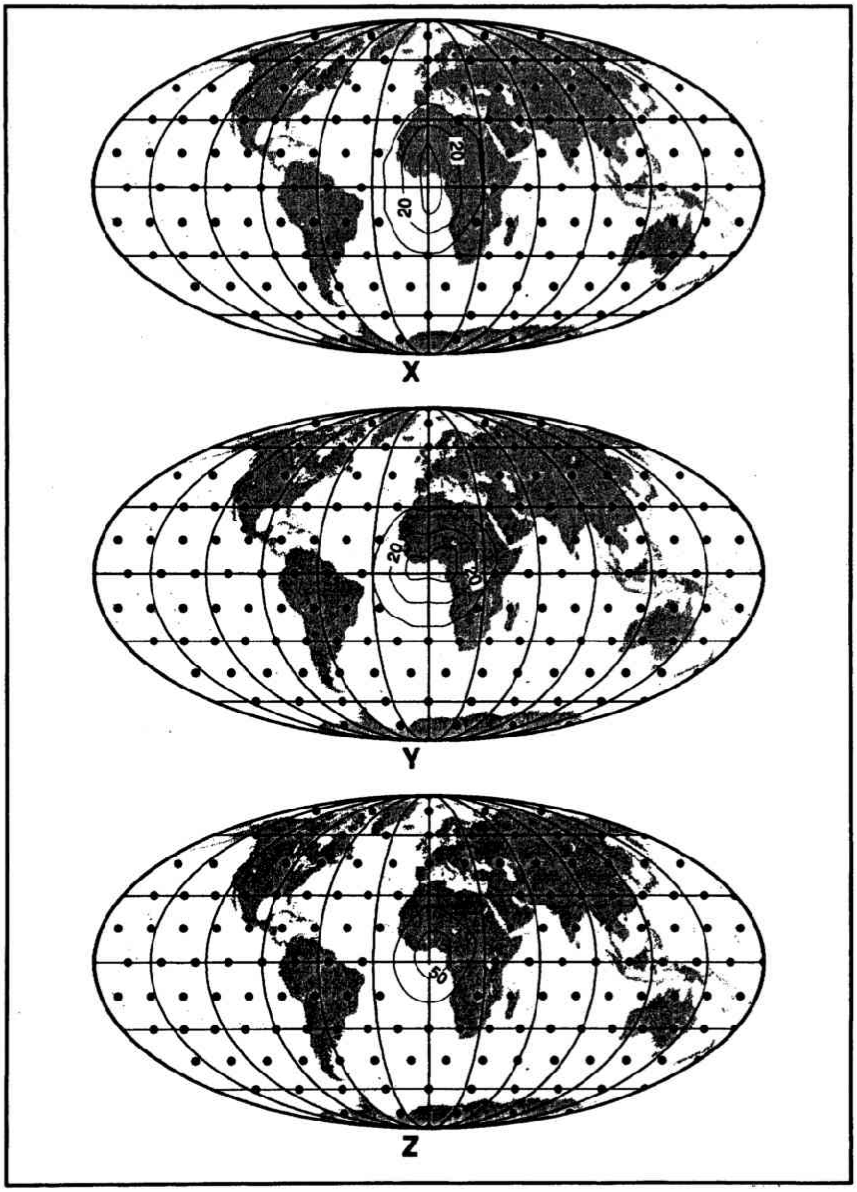
In addition to the error in the computed field, it is desirable to have some estimate of the effect of data distribution on the standard error, σ, of the estimated coefficients. It seems likely that the coefficients of higher degree and order will be most affected. Figure 7 shows the computed σ for the sectorial coefficients ($n = m$) for degree 10 through 13 as a function of the size of the



(a)

Fig. 5. Contour plots of the estimated error in components when s, the radius of exclusion, is equal to 30°. (a) When the basic location spacing is 20°; (b) When the basic location spacing is 15°; (c) When the basic location spacing is 12°. Units are nT; contour interval 10 nT for X and Y, 25 nT for Z.

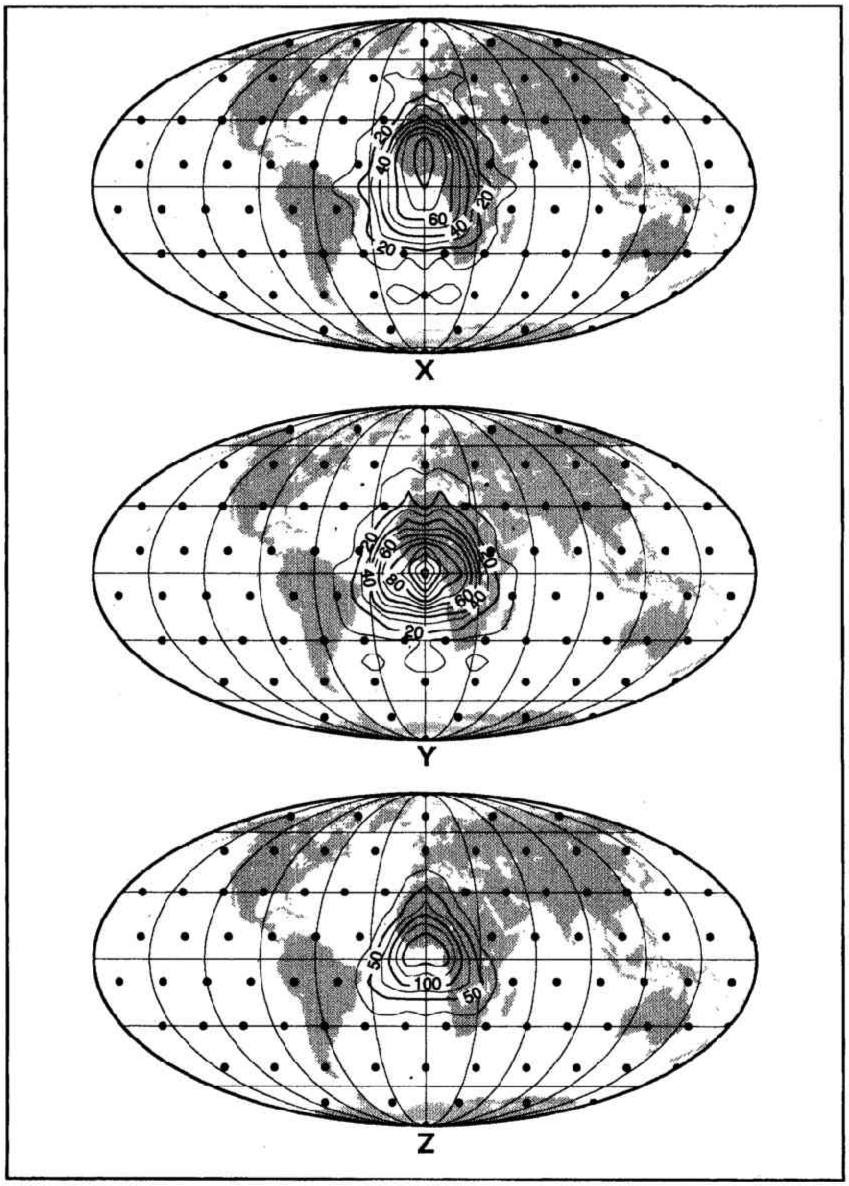
data gap. As expected, the distribution with 12° spacing has the lowest error, near 2–3 nT for an exclusion radius near 40°, while the distribution with 20° spacing has errors near 50–100 nT, for a 40° exclusion radius. For comparison, the values of these coefficients as estimated from the GSFC(12/83) model are printed on the figure. Several of the coefficients have magnitudes



(b)

Fig. 5. (continued).

of a few tenth's nT, i.e., of the same order of magnitude as their errors. For these, all of the distributions provide marginal accuracy, even with no data gaps. However, some coefficients of these degrees have magnitude greater than 1 nT. These are well above the error estimates for all three distributions. However, as the data gap radius increases beyond 30°, the errors in the 20° distribution rapidly climb above 1 nT and reach 10 nT and above for a gap radius of 40°. Again, the denser distribution is more tolerant of a data gap.



(c)

Fig. 5. (continued).

Figure 8 shows the computed σ for the higher order and degree coefficients beginning with g_{10}^{0} as coefficient 100 and continuing to h_{13}^{13} as coefficient 195. Curves are included for data spacing of 12° (top), 15° (middle), and 20° (bottom). For each of these, σ is computed for gap radii of 10, 20, 30, 40, and 50°. From this figure, it is seen that the errors for the sectorial coefficients are slightly larger than for the other coefficients. This means that, for a particular degree, n, the σ estimates of Fig. 7 are a worst case, since they are for the sectorial terms.

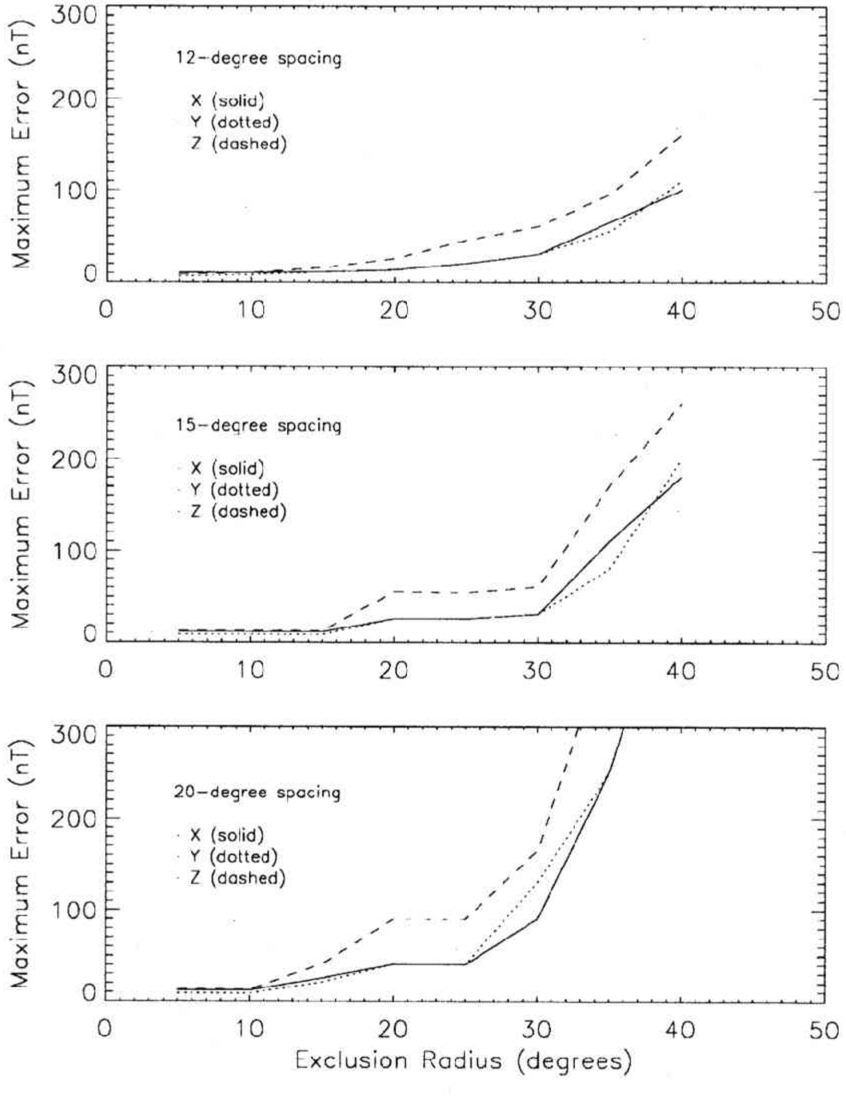


Fig. 6. Maximum estimated error versus size of s, the radius of exclusion.

5. Criteria for a Suitable Distribution

We have presented three SIM's or idealized data distributions. How shall we adopt one for our bridge? It seems to us that the criteria should include the following:

1. The data distribution be adequate for modeling to $n^* = 12$.
2. The bridge makes good use of existing facilities.
3. It is economically, politically and technically feasible.
4. It is expandable to meet needs of the future.

In our opinion, an attempt to approximate the SIM distribution with 20° spacing best meets these criteria. That it meets the first, though marginally, has been demonstrated by the discussion in the previous section.

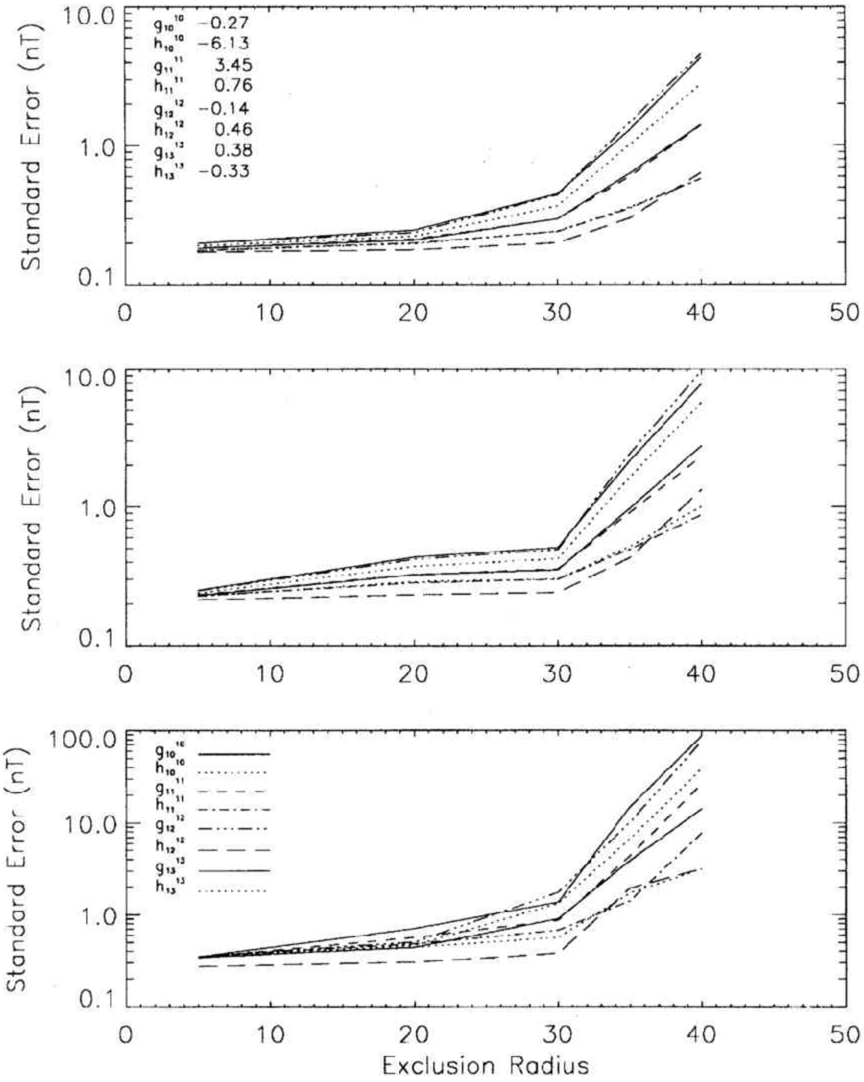


Fig. 7. Standard error of sectorial harmonics ($n = m$) of degree 10, 11, 12 and 13 as a function of exclusion radius. Top: Basic location spacing of 12°; Middle: Basic location spacing of 15°; Bottom: Basic location spacing of 20°. For reference, the values of these harmonics from the GSFC(12/83) model are printed at the left of the top plot.

To make good use of existing facilities includes making full use of all of the present magnetic observatories. It also means that when new sites are chosen, those sites should be chosen to minimize costs of installation and operation. This can be achieved by locating new observatories at locations where similar or related equipment can be shared with other facilities, e.g., sites at which other geophysical measurements are being made. Toward this end, in the next section we shall discuss an expansion of the existing network in which magnetic observatory measurements are collocated with geodetic and seismic observing sites. It will be shown that the cost of such an expansion, and subsequent operations, is reasonable, if extended over a several-year time period.

In most of the world the proposed network is easily expandable. However, for some oceanic

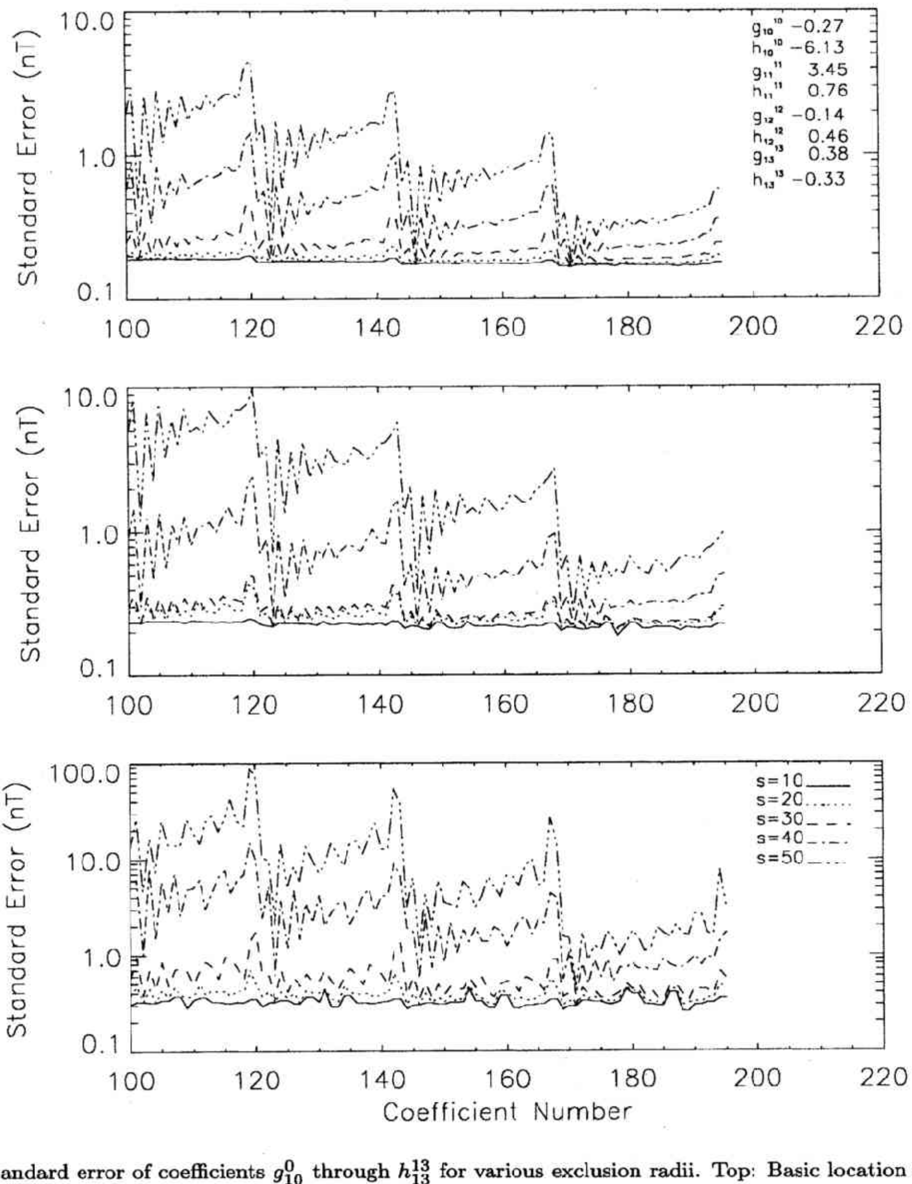


Fig. 8. Standard error of coefficients g_{10}^0 through h_{13}^{13} for various exclusion radii. Top: Basic location spacing of 12°; Middle: Basic location spacing of 15°; Bottom: Basic location spacing of 20°. The values of the sectorial harmonics from the GSFC(12/83) model are printed on the top plot.

regions expandability will depend upon the development of reasonable-cost ocean-bottom instrumentation.

6. A Suitable Site Distribution

Table 5 is a list of the 92 bin centers in the 20° SIM distribution; their locations are shown in Fig. 9. For each bin, Table 5 lists magnetic observatories, with the distance to the bin center noted. Observatories are included if they are currently in operation or seem definitely planned for the near future, to the best of our knowledge. The observatory order within each bin is strictly by

Table 5. List of bin centers for ideal distribution, 20° station spacing Magnetic observatories listed for each bin.

Bin	Stat	Latitude	Longitude	Observatory	Latitude	Longitude	Distance
1	IM	90.000	0.000	ALERT*	82.500	297.500	834.
				HEISS ISLAND	80.617	58.050	1043.
2	UG	70.000	72.000	DIKSON*	73.543	80.562	493.
				PODKAM TUNGUSKA	61.600	90.000	1234.
				CHELYUSKIN	77.717	104.283	1286.
				ARKHANGELSK	64.583	40.500	1459.
3	IM	70.000	144.000	TIKSI*	71.583	129.000	575.
				YAKUTSK*	62.017	129.717	1092.
				STEKOLINIY	60.117	151.017	1145.
4	IM	70.000	216.000	BARROW*	71.323	203.380	486.
				COLLEGE*	64.860	212.163	594.
				MOULD BAY*	76.200	240.600	1038.
				CAPE WELLEN	66.163	190.165	1143.
5	IM	70.000	288.000	GODHAVN*	69.252	306.467	717.
				THULE*	77.483	290.833	837.
				RESOLUTE BAY*	74.700	265.100	923.
				BAKER LAKE*	64.333	263.967	1202.
				CAMBRIDGE BAY*	69.200	255.000	1266.
6	IM	70.000	360.000	TROMSO*	69.663	18.948	724.
				ABISKO*	68.358	18.823	763.
				BJORNOYA*	74.500	19.200	815.
				KIRUNA*	67.833	20.417	847.
				HORNSUND*(?)	77.000	15.550	914.
				DOMBAS*	62.073	9.117	971.
				NEW ALESUND	78.917	11.933	1048.
				LERWICK*	60.133	358.817	1099.
				SODANKYLA*	67.368	26.630	1106.
				LEIRVOGUR	64.183	338.300	1131.
				LOPARSKAYA*	68.250	33.083	1308.
				LOVO*	59.345	17.827	1445.
7	IM	50.000	36.000	DYMER(?)	50.717	30.300	412.
				STEPANOVKA(?)	46.783	30.883	520.
				KRASNAYA PAKHRA*	55.478	37.312	615.
				PLESHENITZI*(?)	54.500	27.883	745.
				LVOV	49.900	23.750	876.
				BOROK	58.030	38.970	914.
				SURLARI*	44.680	26.253	942.
				ZAYMISHCHE*	55.833	48.850	1076.
				BELSK*	51.837	20.792	1083.
				DUSHETI	42.092	44.705	1105.
				ISTANBL KANDILLI	41.063	29.062	1130.
				ANKARA	39.891	32.764	1152.
				VOYEYKOVO*	59.950	30.705	1156.
				PANAGYURISHTE(?)	42.515	24.177	1230.
				HEL*	54.608	18.815	1272.
				GROCKA	44.633	20.767	1291.
				HURBANOVO*	47.873	18.190	1319.
				NURMIJARVI*	60.508	24.655	1368.

* Digital in place or to be installed.

(?) Station possibly, though not certainly, at risk of closure.

IM Bin contains INTERMAGNET observatory.

UG need to upgrade at least one observatory in this bin to intermagnet standards.

Table 5. (continued).

Bin	Stat	Latitude	Longitude	Observatory	Latitude	Longitude	Distance
8	IM	50.000	72.000	BEREZNAYKI	49.817	73.083	80.
				ALMA ATA*	43.250	76.917	839.
				NOVO KAZALINSK	45.800	62.100	872.
				KLYUCHI	55.033	82.900	924.
				YANGI-BAZAR*	41.333	69.617	981.
				ARTI*	56.433	58.567	1142.
				URUMQI	43.817	87.697	1373.
9	UG	50.000	108.000	PATRONY*	52.167	104.450	346.
				MANZAOLI	49.600	117.400	676.
				MO HE	53.500	122.400	1063.
				CHANGCHUN	44.050	125.200	1457.
10	IM	50.000	144.000	MEMAMBETSU*	43.907	144.193	678.
				PARATUNKA*	52.900	158.433	1049.
				GORNOTAYEZHNAYA	43.683	132.167	1139.
11		50.000	180.000	None			
12	IM	50.000	216.000	SITKA*	57.058	224.675	970.
13	IM	50.000	252.000	MEANOOK*	54.617	246.667	628.
				NEWPORT*	48.263	242.880	691.
				GLENLEA*	49.600	262.900	783.
				BOULDER*	40.138	254.762	1118.
				VICTORIA*	48.517	236.583	1129.
				FORT CHURCHILL*	58.767	265.900	1322.
				YELLOWKNIFE*	62.400	245.500	1435.
14	IM	50.000	288.000	OTTAWA*	45.400	284.450	576.
				POSTE-DE-LA-BAL*	55.270	282.220	703.
15	IM	50.000	324.000	ST JOHNS*	47.600	307.317	1248.
				NARSSARSSUAQ*	61.100	314.800	1360.
16	IM	50.000	360.000	CHAMBON LA FORET*	48.023	2.260	275.
				DOURBES*	50.097	4.595	328.
				HARTLAND*	50.995	355.517	336.
				MANHAY*	50.298	5.682	406.
				ESKDALEMUIR*	55.317	356.800	629.
				WINGST*	53.743	9.073	748.
				VALENTIA*	51.933	349.750	749.
				FURSTENFELDBRUCK*	48.165	11.277	845.
				NIEMEGK*	52.072	12.675	914.
				CASTELLO TESINO*	46.047	11.650	970.
				BRORFELDE*	55.625	11.672	1001.
				BUDKOV*	49.080	14.015	1015.
				EBRO*	40.820	.493	1022.
				WIEN KOBENZL	48.265	16.318	1200.
				NAGYCENK	47.633	16.717	1249.
				COIMBRA*	40.222	351.578	1271.
				AQUILA*	42.383	13.317	1326.
				TIHANY*	46.900	17.893	1360.
17	UG	30.000	24.000	MISALLAT	29.515	30.892	667.
				PENDELI	38.047	23.867	895.
				AMATSIA*	31.550	34.917	1057.
				BAR GYORA	31.730	35.21	1087.

Table 5. (continued).

Bin	Stat	Latitude	Longitude	Observatory	Latitude	Longitude	Distance
18	UG	30.000	48.000	VANNOVSKAYA*(?)	37.950	58.108	1283.
19	IM	30.000	72.000	QUETTA	30.187	66.950	486.
				JAIPUR(?)	26.917	75.800	505.
				SABHAWALA	30.363	77.798	559.
				KARACHI	24.950	67.140	738.
				UJJAIN	23.183	75.783	846.
				KASKI(?)	39.500	76.000	1117.
				ALIBAG*	18.638	72.872	1267.
20	UG	30.000	96.000	LHASA	29.700	91.150	469.
				SHILLONG	25.567	91.883	638.
				CHENGDU	31.000	103.700	746.
				TONGHAI	24.000	102.7	941.
				LANZHOU	36.087	103.845	996.
				CHA PA	22.350	103.833	1155.
21	UG	30.000	120.000	SHESHAN	31.097	121.187	167.
				WUHAN	30.528	114.559	526.
				LUNPING*	25.000	121.167	568.
				QUANZHOU	24.900	118.600	584.
				GUANGZHOU	23.093	113.343	1014.
				KANOYA*	31.420	130.882	1052.
				BEIJING*	40.040	116.175	1169.
				MING TOMBS	40.300	116.200	1196.
22	IM	30.000	144.000	CHICHIJIMA	27.083	142.167	370.
				HATIZYO*	33.122	139.802	528.
				KANOZAN*	35.253	139.960	696.
				KAKIOKA*	36.230	140.190	778.
				MIZUSAWA*	39.010	141.080	1037.
23		30.000	168.000	None			
24		30.000	192.000	None			
25		30.000	216.000	None			
26	IM	30.000	240.000	FRESNO*	37.090	240.280	789.
				TUCSON*	32.247	249.167	907.
27	IM	30.000	264.000	DEL RIO*	29.940	259.080	474.
				BAY ST LOUIS*	30.400	270.600	636.
				TULSA	35.912	264.212	658.
				TEOLOYUCAN(?)	19.747	260.818	1184.
28	IM	30.000	288.000	FREDERICKSBURG*	38.205	282.627	1037.
				HAVANA	22.983	277.683	1289.
29		30.000	312.000	None			
30	UG	30.000	336.000	CANARIAS	28.477	343.739	770.
31	UG	30.000	360.000	TIO UINE	30.930	352.740	703.
				ALMERIA(?)	36.853	357.540	795.
				SAN FERNANDO	36.462	353.795	921.
				TAMANRASSET*	22.792	5.527	972.
				SAO TEOTONIO	37.500	351.700	1132.
				SAN PABLO	39.600	355.650	1139.
32	IM	10.000	36.000	ADDIS ABABA(?)	9.030	38.765	322.
				DJIBOUTI*	11.700	43.300	819.
				BUNIA	1.530	30.02	1151.
				NAIROBI(?)	−1.327	36.815	1263.

Table 5. (continued).

Bin	Stat	Latitude	Longitude	Observatory	Latitude	Longitude	Distance
33		10.000	60.000	None			
34	UG	10.000	84.000	ANNAMALAINAGAR	11.367	79.683	496.
				ETTAIYAPURAM	9.000	78.000	667.
				KODAIKANAL	10.230	77.463	716.
				TRIVANDRUM	8.483	76.950	792.
				HYDERABAD*	17.413	78.555	1012.
35	UG	10.000	108.000	DALAT*	11.917	108.417	218.
				BACLIEU	9.283	105.733	261.
				SANYA	18.200	109.500	926.
				QIONGZHONG	19.000	109.800	1019.
				PHOTHUY	21.033	105.967	1246.
				TUNTUNGAN(?)	3.510	98.560	1267.
36	UG	10.000	132.000	MANADO	1.297	124.925	1244.
				MUNTINLUPA	14.375	121.015	1289.
37	IM	10.000	156.000	GUAM*	13.583	144.870	1275.
38		10.000	180.000	None			
39	IM	10.000	204.000	HONOLULU*	21.320	201.998	1277.
40		10.000	228.000	None			
41		10.000	252.000	None			
42	UG	10.000	276.000	COSTA RICA(?)	9.913	276.043	11.
				CHIRIPA	10.440	275.089	111.
				FUQUENE(?)	5.470	286.263	1238.
43	IM	10.000	300.000	KOUROU*	5.100	307.400	981.
				SAN JUAN*	18.113	293.850	1119.
44		10.000	324.000	None			
45	IM	10.000	348.000	M'BOUR*	14.392	343.042	727.
46	IM	10.000	12.000	ILE-IFE*	7.550	4.567	861.
				BANGUI*	4.437	18.565	952.
47	IM	−10.000	48.000	TANANARIVE*	−18.917	47.550	993.
48		−10.000	72.000	None			
49	UG	−10.000	96.000	TANGERANG(?)	−6.167	106.633	1246.
50		−10.000	120.000	None			
51	IM	−10.000	144.000	CHARTERS TOWERS*	−20.100	146.300	1150.
				KAKADU	−12.7	132.5	1289.
52		−10.000	168.000	None			
53	UG	−10.000	192.000	APIA	−13.807	188.225	590.
54	IM	−10.000	216.000	PAMATAI*(?)	−17.568	210.425	1034.
55		−10.000	240.000	None			
56		−10.000	264.000	None			
57	UG	−10.000	288.000	ANCON (HUANCAYO)	−12.045	284.660	430.
				PATACAMAYA(?)	−17.250	292.050	917.
58	UG	−10.000	312.000	TATUOCA	−1.205	311.487	980.
59	IM	−10.000	336.000	ASCENSION ISLAND*	−8.000	345.600	1077.
60		−10.000	360.000	None			
61	UG	−10.000	24.000	LUANDA BELAS	−8.917	13.167	1194.
				TSUMEB*	−19.217	17.700	1228.
62		−30.000	60.000	None			
63	IM	−30.000	84.000	MARTIN DE VIVIES*	−37.833	77.567	1053.

Table 5. (continued).

Bin	Stat	Latitude	Longitude	Observatory	Latitude	Longitude	Distance
64	IM	−30.000	108.000	GNANGARA*	−31.783	115.950	784.
				LEARMONTH*	−22.220	114.100	1058.
65	UG	−30.000	132.000	ALICE SPRINGS	−23.762	133.883	718.
66	IM	−30.000	156.000	CANBERRA*	−35.315	149.363	857.
67		−30.000	180.000	None			
68		−30.000	204.000	None			
69		−30.000	228.000	None			
70		−30.000	252.000	None			
71		−30.000	276.000	None			
72	UG	−30.000	300.000	PILAR	−31.667	296.117	414.
				LAS ACACIAS	−35.007	302.310	597.
				LA QUIACA	−22.103	294.395	1041.
73	IM	−30.000	324.000	VASSOURAS*	−22.400	316.350	1138.
74		−30.000	348.000	None			
75	IM	−30.000	12.000	HERMANUS*	−34.425	19.225	839.
76	UG	−30.000	36.000	MAPUTO(?)	−25.917	32.583	565.
				HARTEBEESTHOEK*	−25.882	27.707	934.
77	IM	−50.000	72.000	PORT-AUX-FRANCA*	−49.350	70.200	148.
78		−50.000	108.000	None			
79	UG	−50.000	144.000	MACQUARIE ISLAND*	−54.500	158.950	1131.
80	UG	−50.000	180.000	EYREWELL*	−43.417	172.350	935.
81		−50.000	216.000	None			
82		−50.000	252.000	None			
83	UG	−50.000	288.000	TRELEW(?)	−43.248	294.685	907.
				PORT STANLEY	−51.750	303.077	1074.
84		−50.000	324.000	None			
85		−50.000	360.000	None			
86	IM	−50.000	36.000	PORT-ALFRED*	−46.433	51.867	1238.
87	IM	−70.000	108.000	CASEY*	−66.283	110.533	426.
				MIRNYY	−66.550	93.017	723.
				VOSTOK	−78.450	106.867	940.
				DAVIS*	−68.583	77.967	1179.
				ZHONG SHAN	−69.400	76.400	1207.
				DUMONT DURVILLE*	−66.665	140.007	1348.
88	UG	−70.000	180.000	SCOTT BASE(?)	−77.850	166.783	958.
89		−70.000	252.000	None			
90	IM	−70.000	324.000	ARGENTINE IS.*(?)	−65.245	295.742	1293.
				ARCTOWSKI*(?)	−62.160	301.522	1323.
				GREAT WALL	−62.200	301.00	1337.
				KING GEORGE IS.	−62.220	301.25	1350.
91	UG	−70.000	36.000	SYOWA BASE*	−69.007	39.590	178.
				MOLODEZHNAYA	−67.667	45.850	472.
				MAWSON*	−67.605	62.882	1103.
92		−90.000	.000	None			

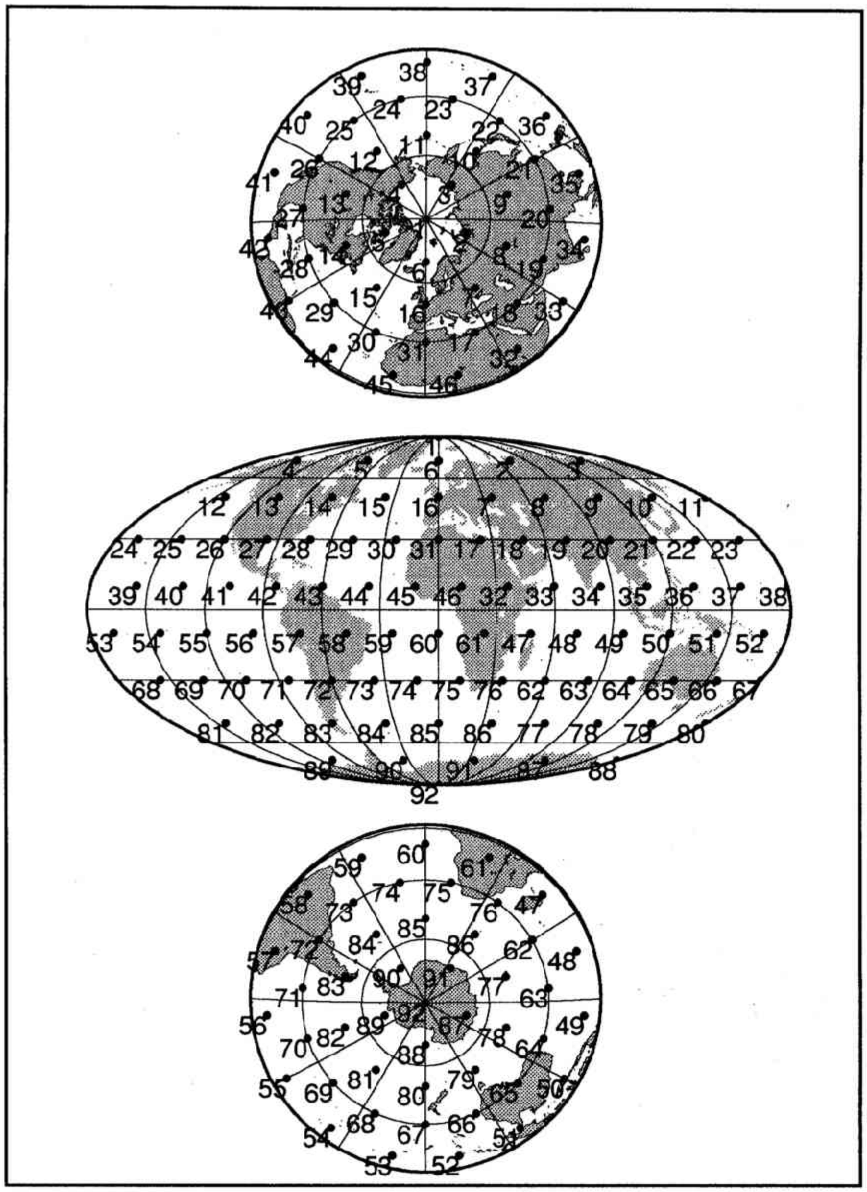


Fig. 9. Location of bin centers for ideal 20° SIM observatory distribution.

distance from the bin center. No inferences regarding quality or importance of any observatory should be drawn, except where less than three observatories are located within a bin, in which case those observatories contribute data which is vital.

Sixty two bins include at least one magnetic observatory, many include several. For the present discussion, it will be assumed that all of these observatories provide equal quality data and that all will continue to operate for the foreseeable future. In practice, this is not true. The existence of some observatories is threatened by political and/or economic conditions; some obtain only analog measurements; some have quality control problems. These situations will be

Table 6. Bins without magnetic observatories: possible network sites for magnetometers.

Bin #	Latitude	Longitude	Candidate Station	Latitude	Longitude	Type	Status	Magnetometer proposed
11	50.000	180.000	Adak Island	51.880	183.320	6	P	N
			Dutch Harbor	53.900	193.470	6	X	N
23	30.000	168.000	Wake	19.320	166.630	6	X	N
24	30.000	192.000	Midway	28.210	182.670	6	P	N
25	30.000	216.000	None					
29	30.000	312.000	None					
33	10.000	60.000	Socotra Is.	13.0	54.0	N		
38	10.000	180.000	Majuro Atoll	7.100	171.400	4	P	Y
			Tarawa	2.000	173.000	6	X	N
40	10.000	228.000	None					
41	10.000	252.000	Cape Verde	18.2	245.5	N		
			Isla Socorro	18.730	249.050	6	P	N
			Zihuatanejo	17.510	258.590	6	P	N
			Chamela	19.500	254.960	6	P	N
			Tetitlan	17.160	259.370	6	P	N
			Pinotepa Nacion	16.390	261.870	6	P	N
			Islas Marias	21.620	253.420	6	P	N
			Iguala	18.380	260.530	6	P	N
44	10.000	324.000	None					
48	−10.000	72.000	Diego Garcia Is.	−7.300	72.400	2	P	N
			Diego Garcia	−6.600	72.400	4	P	Y
			Diego Garcia	−7.300	72.400	6	X	N
50	−10.000	120.000	Sulawesi, Indon	−4.000	120.000	2	P	N
			Sulawesi	−4.000	120.000	6	X	N
			Fitzroy Crossing	−18.110	125.660	6	X	N
			Marble Bar	−21.160	119.450	6	X	N
52	−10.000	168.000	Honiara	−9.430	159.950	6	P	N
55	−10.000	240.000	None					
56	−10.000	264.000	Galapagos Is.	−1.000	269.000	4	P	Y
			Galapagos Is.	−.700	269.700	6	X	N
60	−10.000	360.000	St. Helena Is.	−16.0	355.0	N		

Table 6. (continued).

Bin #	Latitude	Longitude	Candidate Station	Latitude	Longitude	Type	Status	Magnetometer proposed
62	−30.000	60.000	Mauritius	−20.100	57.600	4	P	Y
			Plaine des Cafr	−21.200	55.580	6	E	N
67	−30.000	180.000	Monasavu, Fiji	−18.080	178.250	2	P	Y
			Monasavu	−18.080	178.250	6	P	N
68	−30.000	204.000	Rarotonga	−21.210	200.230	6	E	N
69	−30.000	228.000	Rikitea	−23.070	225.430	6	X	N
70	−30.000	252.000	Easter Island,	−27.158	250.566	2	E	N
			Easter Island	−27.140	250.620	3	E	N
			Easter Island	−27.200	250.600	4	P	Y
			Rapa Nui	−27.130	250.670	6	E	N
71	−30.000	276.000	Juan Fernandes Is.	−33.0	280.0	N		
74	−30.000	348.000	Tristan-da-Cuhna	−37.000	347.500	4	P	Y
			Trindade Island	−29.500	330.700	6	X	N
78	−50.000	108.000	None					
81	−50.000	216.000	None					
82	−50.000	252.000	None					
84	−50.000	324.000	S. Georgia Is.	−54.000	324.000	6	X	N
85	−50.000	360.000	Bouvet Is.	−55.0	4.0	N		
89	−70.000	252.000	Russkaya	−74.800	223.100	4	P	N
92	−90.000	.000	SOUTH POLE	−90.000	360.000	4	E	Y
			South Pole	−90.000	115.000	6	E	N

KEY

Status:
E = Existing
P = Planned
X = Proposed

Type:
Geoscope = 1
IDA = 2
Flinn = 3
Step 6.4 = 4
Repeat = 5
IRIS = 6
None = N

addressed in a later section.

There are 30 bins in the suggested distribution that are without observatories. When considering the feasibility of placing new observatories, cost and logistics are major factors. Other geophysical communities are also establishing observing stations, notably NASA's FLINN network for geodetic measurements (National Academy of Sciences, 1991), the IRIS Consortium for seismic measurements (Smith, 1986), and STEP Project 6.4 for magnetometers at special locations for ionospheric and magnetospheric studies (Papitashvili *et al.*, 1992, 1993). Magnetic measurements are already planned, or have been implemented, in connection with some of the French Geoscope sites (a network for seismic measurements), e.g., at Tamanrasset, Antananarivo, Kourou, Djibouti and Hanoi, with plans for others in Chile and Russia (LeMouel, personal communication, January, 1993). The first four of these are included in Table 5. It has been proposed (S. Constable, personal communication) that magnetometers be placed at strategic Project IDA (International Deployment of Accelerometers) sites, a subset of IRIS. Co-locating instrumentation at single, or nearby, sites could result in cost saving in some of the logistical aspects of establishing an observatory. Preliminary discussions (personal communication) with John LaBrecque of NASA Headquarters, Rhett Butler of IRIS, Steve Constable of IDA, and Michael Teague of STEP indicate interest on their part. Accordingly, in the following, sites are identified from these networks that are close to the locations of bin centers in our ideal network.

Table 6 shows the SIM bins that are presently without magnetic observatories, with a list of potential sites within that bin. Some of the potential sites are locations, or proposed locations, for sites of geophysical stations by specific networks - either seismic, geodetic, or geomagnetic. Further, geomagnetic measurements are proposed at some of the seismic and geodetic network sites. The network, the status of the site, and whether a magnetometer is proposed are all indicated in Table 6. We propose instrumentation at one site from each of these bins, preferably, but not crucially, the first in the list because it is closer to the bin center. Of these 30 bins, there are only 12 for which no proposed instrumentation exists; each of the other 18 bins contains at least one proposed site for one or more of the networks listed. Further, one or more of the networks are presently entertaining plans to install magnetometers at 8 of these sites, as listed in the Table: STEP 6.4 in bins 38, 48, 56, 62, 70, 74, 92; and IDA in bins 48, and 67. It should be noted that, in most cases, funding is not in hand, or even promised, for these proposed sites; these are locations at which magnetic measurements are *desired* not *assured*. This means that cooperative effort may be necessary to implement the existing plans. In particular, although STEP 6.4 is planning magnetometers at Diego Garcia and Easter Island, these are only in the planning stages and, further, it is not certain that absolute measurements would be obtained at STEP sites, as necessary for observatory quality data. IDA is also in the planning stages for these two sites, while FLINN has an established site at Easter Island. Clearly interagency coordination would be profitable.

Table 7. Bins in which sea-bottom stations are proposed.

Bin #	Latitude	Longitude
25	30.000	216.000
29	30.000	312.000
40	10.000	228.000
44	10.000	324.000
55	−10.000	240.000
78	−50.000	108.000
81	−50.000	216.000
82	−50.000	252.000

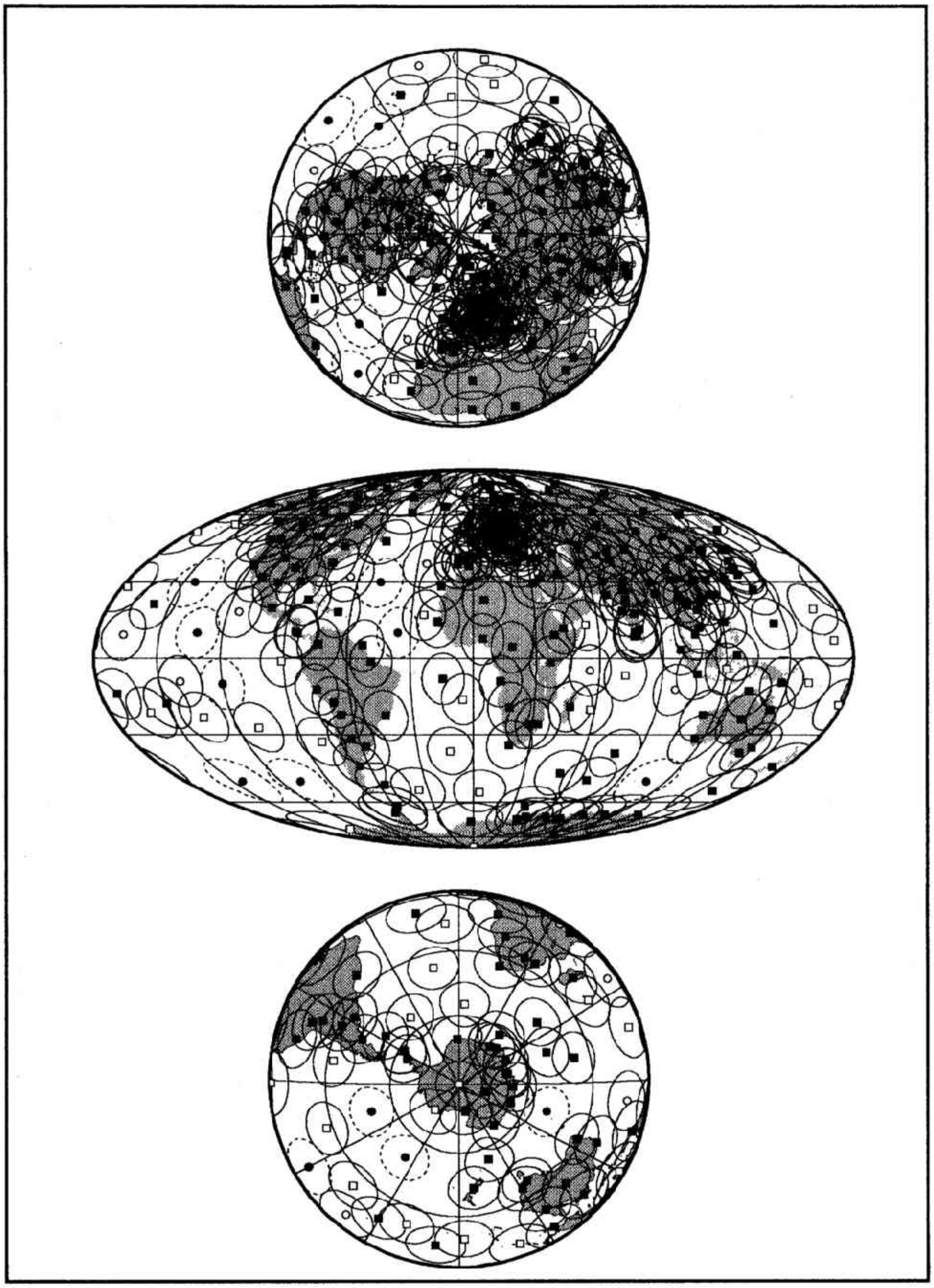


Fig. 10. Locations of existing observatories, filled squares, proposed new land/island observatory sites, open squares and open circles, and proposed sea-bottom observatories, filled circles. Open circles correspond to Table 8. Lines surrounding each site are drawn at a distance of 1000 km from that site.

The sites for which some type of geophysical station is planned, though without magnetometers, should be considered prime candidates for inclusion of magnetometers. Eight bins, listed in Table 7, are in open ocean (or ice) and would require deployment of magnetometers able to function on the sea bottom while still acquiring observatory quality data.

One difficulty with the binning scheme used above is that it is rare that an observatory site is located near the bin center. In fact, several are located near bin boundaries. This leads to unacceptable gaps in the coverage. A plot of site locations with a surrounding line drawn at 1000 km, Fig. 10, quickly shows the locations of such gaps. In the Figure, existing observatories are indicated by the solid square symbol; proposed land and island sites, from Table 6, by open square symbols; and proposed sea-bottom sites, from Table 7, by the solid circle symbol surrounded by a dashed line. An additional 9 sites, indicated by the open circle symbol, and listed in Table 8, are chosen to fill remaining gaps. These 9 sites are in bins that would then contain more than one observatory.

Table 8. Proposed sites for magnetometers in bins already occupied.

Bin #	Latitude	Longitude	Candidate Station	Latitude	Longitude	Type	Status	Magnetometer
12	50.0	216.0	Sand Point	55.35	199.5	3	E	N
28	30.000	228.000	Bermuda	32.35	295.35	N		
30	30.000	336.000	Azores	37.75	334.34	N		
			Clarion	17.0	336.00	N		
37	10.0	156.0	Kwajalein	9.38	167.47	3	E	N
47	−10.0	48.0	Mahe	−4.61	55.49	4/2	P	Y
49	−10.0	96.0	Cocos Keeling	−12.2	96.8	2	P	N
54	−10.000	216.000	Marquesas Is.	−9.0	220.000	N		

7. The Outlook for Existing Magnetic Observatories

As already noted, the existence of some of the observatories listed in Table 5 is threatened. In bins with a single observatory, closure of such observatories would create the need for a replacement. In fact, we note that 4 of the bins that are now without magnetometers (62, 70, 84, and 92) once contained fully operating magnetic observatories.

Kerridge *et al.* (1993), in a report given to the 1993 assembly of IAGA, presented tables of observatories recently closed, observatories at risk, and new observatories under consideration. Excerpts from those tables, with modifications from Kerridge (personal communication, 1994) are included here as Tables 9, 10 and 11. Instances were noted where observatories at risk had appealed for help and where that help was forthcoming. Many observatories in the Former Soviet Union (FSU) are in imminent danger of abandonment. Since about 1990, the situation has worsened - salaries of observatory personnel have not been paid (resulting in volunteer part-time manning), sensing and recording equipment have broken down and not been repaired, and, at many sites, absolute measurements have ceased or are of very poor quality (Belov and Papitashvili, 1993). The INTERMAGNET organization plans to make limited funds available to help rescue selected, long existing FSU observatories; but much more support is needed. Bins 2, 3, 8, and 18 contain only FSU observatories, so there is a very real threat to data availability from these bins. Since bins 2, 3, 8, and 18 are adjacent, there is the possibility for an exclusion radius of up to 40 degrees, which would result in modeling errors of several hundred nanoteslas or more.

Table 9. Observatories that have closed in recent years (from Kerridge *et al.* 1993; Kerridge, personal communication, 1994).

Observatory	Country	Last annual mean	Bin	Comments
Easter Is.	Chile	1968	70	
Grahamstown	S. Africa	1980	76	
Grytviken	S.Georgia (UK)	1982	84	
Ibadan	Nigeria	1975	46	Not far from Ile Ife
Ksara	Lebanon	1970	17	
Lwiro	Zaire	1970	61	Possibly still operating?
Marion Is.	S. Africa	1980	86	
Moca	Equatorial Guinea	1971	46	
Nairobi	Kenya	1980	32	Closed temporarily due to electricity supply problems. Post 1980 data exists?
Nampula	Mozambique	1984	47	Closed 1987, lack of supplies
Orcadas del Sur	Argentina	1962	90	
Paramaribo	Suriname	1974	43	
Plaisance	Mauritius	1976	62	
San Miguel	Portugal (Azores)	1977	30	
South Pole	Antarctic (USA)	1971	92	
Tate's Cairn	Hong Kong	1978	21	
Ulan Bator	Mongolia	1977	9	Possible to rehabilitate with assistance?

Table 12 has been compiled by combining information in previous Tables, and from personal communication with S. McLean of the National Geophysical Data Center in Boulder, Colorado, and with D. Barraclough, S. Macmillan and D. Kerridge of the British Geological Survey. The table lists bins either with single observatories, and those possibly at risk, or with few observatories, most of which are at risk. These are bins which may become empty and require either aid for re-establishing an observatory at an old site or establishment of a replacement.

Another consideration is that not all operating observatories have digital capability. In these cases, the calculation of monthly and annual mean values must await hand scaling or digitization of analog records. Our information, which may be out of date, indicates that there are 8 single station bins where this is true, namely: 20, 30, 42, 49, 53, 57, 58, and 72. Note that 3 of these are also listed as at risk in Table 10.

Thus, bringing the bridge observatory network into existence must include finding ways to support failing observatories, particularly those observatories whose failure would leave an empty bin, and upgrading existing analog observatories with digital equipment.

We propose that each bin should contain at least one digital observatory capable of relatively rapidly reporting data. One way of accomplishing this is to upgrade existing observatories to the status of INTERMAGNET stations. The second column of Table 5 indicates, by an IM, that at least one observatory in that bin is now, or soon will be, part of INTERMAGNET. If that column contains UG, then there is a necessity to upgrade at least one of the observatories in that bin to INTERMAGNET standards. There are 25 such bins. The choice of which observatories to upgrade, and, indeed, the locations for new observatories, should be made based on

Table 10. Observatories at risk or requesting assistance (Kerridge *et al.* 1993; Kerridge, personal communication, 1994).

Country	Observatories	Bin	Comments
Algeria	Tamanrasset	31	Receiving assistance from France
Antarctica	Arctowski (Poland)	90	
	Argentine Is. (UK)	90	Will close in 1995, possibly replaced by automatic station
	Scott Base (NZ)	88	
	SANAE (S. Africa)	90	
Arctic	Hornsund (Poland)	6	
Argentina	Trelew	83	D/I Flux theodolite and digital variometer from Belgium
Bolivia	Patacamaya	57	Spare parts from Germany
Bulgaria	Panagyuriste	7	Digital recording system from Germany (Furstenfeldbruck)
Columbia	Fuquene	42	
Ethiopia	Addis Ababa	32	
Hungary	Nagycenk	16	More secure in 1993, INTERMAGNET
Indonesia	Tangerang	49	
	Tuntungan	35	
Iran	Teheran	18	
Kenya	Nairobi	32	
Mexico	Teoloyucan	27	
Mozambique	Maputo	76	Re-established in June, 1993
Mongolia	Ulan Bator	9	Funds from Royal Society of London for training in UK
Nigeria	Ile-Ife	46	Digital system from UK
Papua New Guinea	Port Moresby	51	Data-processing, maintanance, and possibly new digital system from Australia
Peru	Huancayo	57	
Philippines	Baguio	46	Required photographic paper in 1989
	Muntinlupa	36	Received equipment from Japan
Spain	Almeria	31	Urban site
Western Samoa	Apia	53	Digital system, data processing and training from New Zealand
Zaire	Binza	61	
	Karavia	61	

extensive consultation with the observatory community. This can be done through IAGA and INTERMAGNET.

8. Costs of New Observatories

A modern geomagnetic observatory, meeting INTERMAGNET standards, usually consists of a vector fluxgate magnetometer, a scalar proton magnetometer, and a Data Collection Platform (DCP) with satellite and telephone communication capability. Absolute measurements with independent instruments are made often enough (usually weekly) to insure baseline accuracies of

Table 11. New and possible observatories (Kerridge *et al.* 1993; Kerridge, personal communication, 1994).

Country	Observatories	Bin	Comments
China	Mohe	9	
	Zhong Shan*	87	
	Great Wall* (Antarctic)	90	
Portugal	San Teotonio*	31	Interested in establishing
Spain	San Fernando*	31	Re-established at new site
UK	Ascension Is.*	59	Variometer station installed, 1992 Future INTERMAGNET obs.?
	Port Stanley*	83	Installed February, 1994
Uruguay		72	Expressed interested an observatory
Zambia		61	Expressed interested an observatory

*Included in Table 5.

Table 12. Bins at risk or status unknown.

Bin	Existing observatory	Status
17	Amatsia	Last data in 1988, possibly being replaced by Bar Gyora
18	Vannovskaya	?
32	Addis Ababa	At risk
	Nairobi	Closed, hopefully temporarily
35	Tuntungan	At risk
49	Tangerang	At risk
53	Apia	At risk, but receiving aid from New Zealand
54	Pamatai	?
57	Huancayo	Being replaced by Ancon
	Patacamaya	At risk, but receiving aid
76	Maputo	Closed but re-established, receiving aid from UK
83	Trelew	At risk, but receiving aid from Belgium
88	Scott Base	At risk
90	Sanae	At risk
	Argentine Is.	At risk
	Arctowski	At risk

5 nT or better. The independent instrument suite usually consists of a Declination-Inclination Magnetometer (DIM), also known as a "DI-Flux", and a scalar magnetometer (usually a proton precession magnetometer). The DCP should be able to store a few weeks of 1-minute digital samples of 3 magnetic components and 1-minute samples of scalar measurements from the proton magnetometer. Data return is normally by satellite or telephone link; lacking these, data are periodically retrieved on diskettes.

The cost of basic observatory equipment is approximately $60,000, U.S. This includes $10,000 for a 3 component magnetometer, $8,000 for a proton precession (scalar) magnetometer, $11,000 for the DCP, $2,000 for a PC (computer), $4,000 for miscellaneous cables and interfaces, plus $25,000 for the absolute instrument, i.e., theodolite with fluxgate sensing element. Small, remote, insulated shelters are required for the magnetometer sensing elements. A larger shelter is required for the magnetometer electronics and the DCP. (The sensing elements are usually located 50 to 100 meters from the electronics). If shelters are not available they must be constructed at additional cost. Cost saving by collocation with other geophysical sites should be possible for shelter construction and, possibly, the data collection and communication equipment.

The quality of accommodation for observatory magnetometers is very important. Temperature changes and tilting of instrument piers are important sources of data error. Modern fluxgates have lower temperature coefficients than older ones and tilt-compensating suspensions have been devised, but the ideal remains an isothermal environment (for sensors, cabling and electronics), and stable piers. A simple shelter may be all that is possible in some cases but it should be recognized that data quality will suffer. It is easy to install a 3-axis fluxgate variometer which will be satisfactory for studies requiring field variation data only; it requires an order of magnitude greater effort and care to achieve observatory-standard data from the same equipment.

To achieve observatory quality data one must employ an independent absolute instrument such as the DIM. The DIM consists of a single fluxgate element mounted on the telescope tube of a non-magnetic theodolite. It is used to find the declination and inclination of the Earth's magnetic field. At the same times that the Declination and Inclination angles are determined, the total field (modulus of the Earth field vector, F) is measured with a proton precession magnetometer. This procedure provides enough information to determine instantaneous absolute values of the three components of the Earth field vector (D, H, Z, or X, Y, Z). These absolute values are compared to those measured with the observatory 3 component magnetometer for the same times, thus establishing the offsets and the baselines of the observatory magnetometer. INTERMAGNET recommends that these absolute measurements be made at least weekly, because the magnetometer baselines can and do change due to temperature, electronic instability, component aging, etc. The DIM costs about $25,000, but, at least in principle, may be shared by several observatories if there is someone available to travel between observatories making absolute measurements at appropriate intervals.

As rough estimates, the cost for upgrading an existing observatory is probably the same as for installing a new one.

True ocean bottom geomagnetic observatories do not exist today, although many magnetic variation stations have been operated successfully on the sea bottom. To be useful for field modeling, ocean bottom observatories, just as land observatories, must have the means of making periodic absolute measurements with independent instruments. Absolute magnetic measurements require a vertical reference, a horizontal reference to geographic North, and a total field measurement based on an atomic standard (proton magnetometer). At land observatories, the vertical reference is obtained from bubble levels and the horizontal reference to geographic North is obtained by celestial observations. One attractive candidate for performing these measurements on the ocean bottom is to use an "earth seeking gyro" on the ocean bottom to provide both references to an automatically operated DIM. A prototype system using an earth seeking gyro has been built and operated on land; in principle, such a system can be adapted to the ocean bottom.

Costs for an automatic ocean bottom geomagnetic observatory are extremely speculative at this time, but will clearly be much greater than for land-based instruments. Installation and operation costs depend on costs of ship time and such factors as distance and sharing of ship time costs with other projects.

9. Discussion

In terms of the number of bins needed for adequate measurement of the main field, the proposed network of 92 observatories in equally spaced bins is minimal. Sixty two of these bins are filled by existing observatories; thirty are not. Not all of the existing observatories meet modern observing standards. We propose implementation of thirty nine new observatories, eight of which are to be located on the ocean bottom, and upgrading of at least twenty five existing observatories to INTERMAGNET standards. Cost-wise, this is equivalent to 56 new land/island observatories and 8 sea-bottom observatories. Allowing \$20K per observatory for installation and logistical costs, and assuming that 4 observatories can share a single absolute instrument, the estimated cost for both the new and upgraded observatories, not including the cost of operations, is about \$4.3M. Once the network is in place, the operational cost will be about \$1.2M per year. A better evaluation of costs will require detailed investigation of the environmental conditions and logistical situation at each individual site.

Figure 11 gives the resulting error distribution when magnetometer measurements are available from all existing observatories plus observatories at all proposed sites, except those on the ocean bottom. Comparing with the error distribution from the existing observatory network (Fig. 2), the magnitude of the maximum error is reduced by over an order of magnitude while the areal size of the regions of largest error is substantially reduced. This is in spite of the fact that the observatory distribution is still not complete. The obvious conclusion is that an order of magnitude improvement over present-day capabilities is possible without sea-bottom observatories.

Figure 12 shows the error distribution if additional measuring sites are added in the 8 bins requiring sea bottom measurements. Maximum errors are now less than 15 nT for the Z component and less than about 8 nT for the X and Y components. Comparing with Table 2, this is commensurate with the expected error distribution for the 20° SIM distribution and, in fact, in continental regions, is considerably more accurate.

It must be kept in mind that what is proposed is a bridge. The assumption is that periodic satellite surveys will be available to enable determination of crustal field biases at the observatories and to anchor the surface measurements to a model of maximum accuracy at a series of fixed epochs. Without such satellites, a network of much greater density is required to avoid severe limitations on modeling capability. Separation of ionospheric, magnetospheric, induced, and main field contributions cannot be fully accomplished without measurements above the ionosphere and below the major magnetospheric sources. Determination of crustal contributions at observatories is difficult, perhaps impossible, without high quality satellite data.

The proposed distribution makes use of existing and proposed facilities and is the minimal distribution, i.e., the one with largest spacing. It therefore approximates to the most economical distribution capable of meeting the stated measurement requirements.

However, the proposed distribution still has shortcomings. Of the three SIM models discussed, it is by far the most sensitive to the existence of data gaps. This means a nearly complete implementation is necessary to meet the measurement requirements. Further, the objectives as stated are not comprehensive. For example, studies of secular variation over more localized regions can at present be conducted only with the dense network of observatories available in Europe. Again, it should be emphasized that all of the existing observatories are needed to address the full range of geomagnetic studies, as are repeat stations and surveys.

It is also noted that the requirements considered are derived only from considerations of modeling the main geomagnetic field. At the Geomagnetic Initiative Workshop held in Washington D.C. in March of 1992, the working group dealing with ionospheric and magnetospheric fields expressed a need for much closer observatory spacing: 10° in equatorial and mid-latitudes and 3° at higher latitudes. The proposed network will not meet that requirement, although it could be expanded to do so and thus may be regarded as a step in the desired direction. Filling the gaps with variometers, i.e., instruments measuring the variation of the field, but not its absolute level, might satisfy the closer-spacing requirements and should be investigated.

At this point we would like to re-emphasize the need, not only for the "bridge" observatories, but for all of the existing observatories, for repeat station measurements, for survey measurements

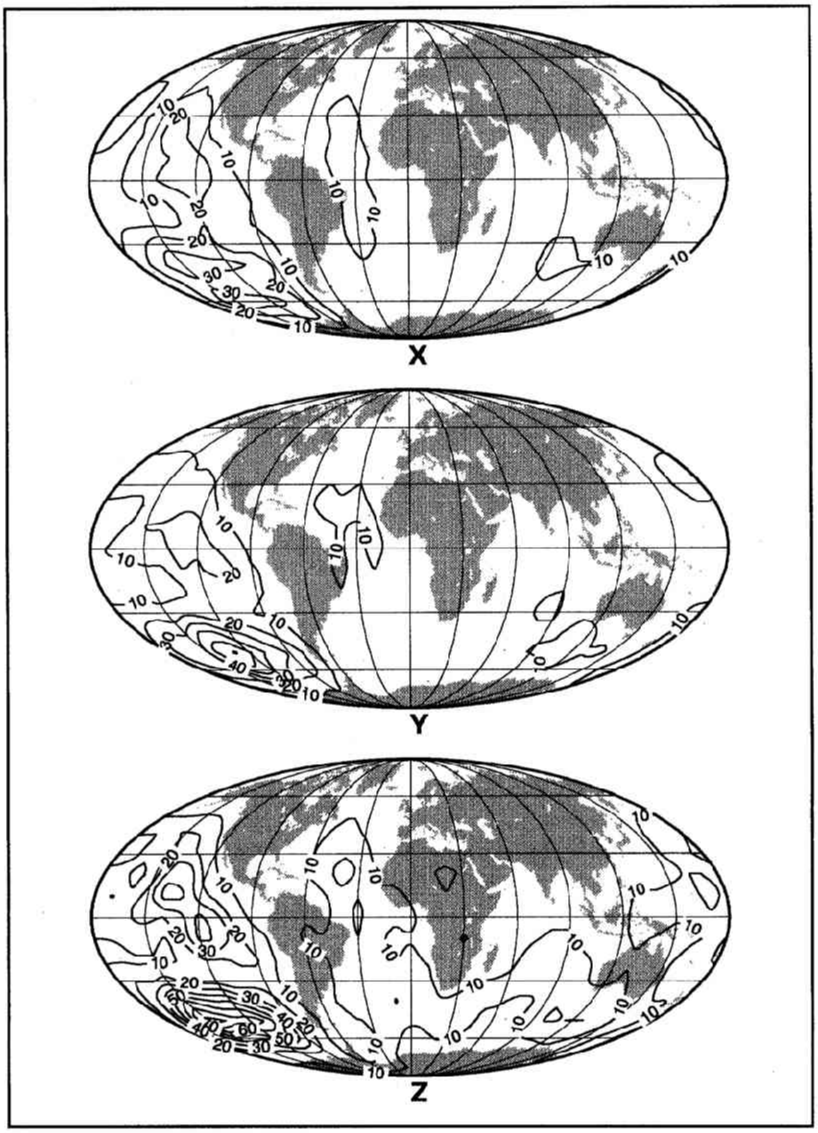


Fig. 11. Error plot for proposed distribution of magnetic observatories, without sea-bottom sites. Units are nT.

of all kinds, for adequate additional observatories for computation of magnetic indices, and, in the further future, for a denser "bridge" network. Only with all such measurements will the shortcomings of the present bridge and the full requirements of geomagnetic studies be addressed.

Implementation of the bridge we have proposed would be a major step toward meeting the data needs of the entire geomagnetic community. However, the resources for such implementation are not readily at hand. To expect individual users, or even a group of users, to fund such an effort is unrealistic. No single user requires the data badly enough to fund such a large effort. Further, a substantial part of the value of a magnetic observatory lies in obtaining continuous measurements at a fixed location over long periods of time, i.e., decades, which are far longer than the lifetime of a research grant or even a career. The obvious requirement is for implementation

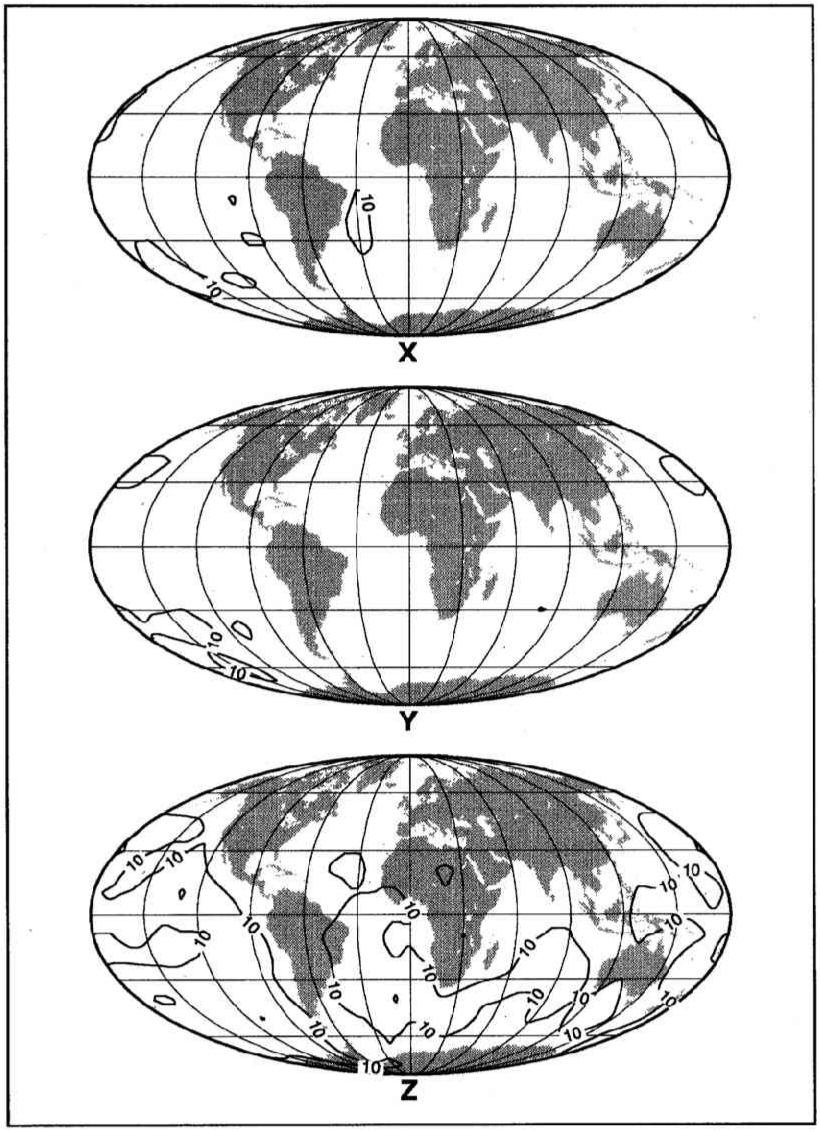


Fig. 12. Error plot for all sites in proposed distribution. Units are nT.

by the national, or state, agencies concerned with geomagnetic measurements, perhaps through the INTERMAGNET organization. Within the U.S., the national agencies include the USGS, NASA, DOD, DOE, and NOAA. The USGS is charged with operating magnetic observatories, but this does not preclude other agencies from establishing and operating independent facilities or from contributing resources to enable the USGS to broaden the scope of its operation. But no single country can, or should, shoulder the full burden of implementation. The danger is that each agency will conclude either that they have/want no responsibility, or that they have not enough resources to contribute significantly. In that case, little or nothing will be done.

Fortunately, some recent developments provide encouragement. The formation of INTERMAGNET and the opening, or planned opening, of observatories at such locations as Ascension

Island, Djibouti, and Port Stanley is not only closing some gaps in the distribution but is doing so with modern digital equipment and the latest communication technology for rapid recovery of the data. Similarly, aid furnished to observatories at risk by established observatories has, and will, forestall closure of some key stations. INTERMAGNET is cooperating with Dr. Steve Constable of Scripps Oceanographic Institution and the IRIS and IDA organizations to seek funding for installation of digital magnetic observatories and to establish absolute measurement programs at existing and proposed IRIS/IDA sites.

In our view, what is now needed in the U.S. is formation of a university-interagency working group specifically to move, however slowly, toward rallying resources and coordinating effort toward implementation of the network expansion. Similar efforts should be initiated in other countries, as appropriate. At the same time IAGA, perhaps working through INTERMAGNET, should solicit and coordinate participation by other national agencies.

We expect that the response of the agencies will depend heavily upon the attitude of the geomagnetic community. If we, as a community, make it clearly known that upgrading the geomagnetic network is important and necessary, then the agencies may move in that direction. If we are silent they will sense our apathy and do nothing.

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