COMPILATION OF MAGNETIC MAPS OF ANTARCTIC REGION FOR 1975

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Abstract: "Magnetic Maps 1975 of the Antarctic" have been compiled by the Geographical Survey Institute of Japan (GSI).

At the request of the Scientific Committee on Antarctic Research (SCAR), the data of observation and survey by the member countries of SCAR were sent to GSI for the purpose of spherical harmonic analysis.

Distribution and annual change of the earth's magnetic field are represented by isomagnetic and isoporic lines respectively in seven maps corresponding to seven components. Residual total intensity at observation points is shown on the eighth map, where general distribution of magnetic anomaly is illustrated by colored circles of 7 classes.

Location of the south magnetic pole was ascertained. The pole has been moving on the Continent toward north or northwest, and is now located at a point off the coast of Adélie Land. It appears that the dipole moment of the earth's magnetic field is still decreasing at an approximately constant rate.

1. Introduction

By the official request of the Scientific Committee on Antarctic Research (SCAR) and the SCAR Working Group on Solid Earth Geophysics in April 1976, the South Polar Magnetic Maps for the epoch 1975 illustrating the distribution of the earth's magnetic field and its annual change have been constructed by the Geographical Survey Institute of Japan. Residuals at the observation points, obtained by subtracting an adjusted value from an observed value, are plotted on a magnetic anomaly map.

As requested by SCAR, the following countries furnished data:

Australia, France, Japan, New Zealand, South Africa, United Kingdom, United States of America and Union of Soviet Socialist Republics.

These data included the annual and monthly mean values at the observatories and the results of airborne, seaborne and land traverse surveys. Supplementary data from WDC/C2 (Kyoto) and compilations of annual mean values by IZMIRAN and the Royal Greenwich Observatory were also employed.

The data were available from 27 observatories in the southern hemisphere whose latitudes are higher than 30°S.

For the purpose of illustrating the distribution of the field over the South Polar region in the latitudes higher than 55°S, the survey data obtained after 1957 in the south of 40°S were put into use in the following analysis. They consisted of measurements at 9583 points of observation including observatories located in the south of 40°S. Of these points 849 provided vector magnetic data. Total intensity was observed at 8022 points, and the vertical intensity was measured at the remaining 712 points.

Extremely anomalous values showing differences of more than 2000 nT compared with the values computed by the IGRF 1975 were excluded.

The data from shipborne surveys included not only individual observed values along routes, but also mean values or representative values given at grids every 1° in longitude and latitude.

2. Computation of Secular Variation and Epoch Reduction

All observed values were reduced to the common epoch 1975.0, considering the secular change from the time of observation to the epoch.

As no continuous records from the observatories in the region were available no corrections were made for transient variations. Although these variations are remarkable in a polar region, it is hard to eliminate them from individual observed values, owing to the uneven distribution of observatories over the region, even if the records were available. As stated already, observed values which show discrepancies of more than 2000 nT compared with values computed by IGRF 1975 were excluded. Thus, most of the data obtained during a severe magnetic storm and blunders that occurred under various unfavorable conditions were eliminated.

Correction for elevation was not taken into account.

Method of reduction for the secular change is explained below. Magnetic annual change distributions have been determined for every year from 1957 on, by means of spherical harmonic analysis using the data from the magnetic observatories. Although the data were collected from 27 observatories in the latitudes higher than 30°S, the results of only 21 observatories where the observation continued for more than three years have been used for the analysis of secular variation. For the purpose of obtaining the spherical harmonic coefficients of magnetic secular change, the data of not only the above-mentioned 21 observatories but also those of 11 observatories located in the north of 30°S parallel have been used for the adjustment computation of $\dot{g}_n^m$ and $\dot{h}_n^m$ by means of the least squares method, because the adjustment by the data of only the southern part of the earth would produce a considerably distorted result. These 32 observatories are listed in Table 1. Next, annual or monthly mean values of X, Y and Z components from an observatory are fitted respectively by cubic formulas of time by the least square method as follows;

Table 1. List of magnetic observatories.

Name of observatory	Country	Location		Period
		Latitude	Longitude	
Amberley	New Zealand	−43°09′	172°43′E	1947–74
Argentine Island	United Kingdom	−65 15	64 16 W	1957–67, 75, 76
Byrd	USA	−79 59	120 00 W	1957–61
		−80 01	119 31 W	62–65, 67, 68
Dumont d'Urville	France	−66 40	140 00 E	1957–58
		−66 40	140 01 E	60, 62–74
Gnangara	Australia	−31 47	115 57 E	1958–75
Halley Bay	United Kingdom	−75 31	26 37 W	1957–66, 75
Macquarie Island	Australia	−54 30	158 57 E	1951–75
Mawson	Australia	−67 36	62 53 E	1955–75
Mirny	USSR	−66 33	93 01 E	1957–74
Molodezhnaya	USSR	−67 40	45 51 E	1965–73
Novolazarevskaya	USSR	−70 46	11 49 E	1961–73
Port-aux-Français	France	−49 21	70 12 E	1957–69, 72–74
Sanae	South Africa	−70 18	2 22 W	1962–70
		−70 19	2 20 W	72–75
Scott Base	New Zealand	−77 51	166 47 E	1957–59, 64–75
South Pole	USA	−89 59	13 19 W	1959–71
Syowa Station	Japan	−69 00	39 35 E	1958–62, 66–76
Toolangi	Australia	−37 32	145 28 E	1941–75
Trelew	Argentina	−43 15	65 19 W	1957–70
Vostok	USSR	−78 27	106 52 E	1959–61, 63–73
Watheroo	Australia	−30 19	115 53 E	1919–58
Wilkes	Australia	−66 15	110 35 E	1957–66
Alibag	India	18 38	72 52 E	1957–73
Apia	New Zealand	−13 49	171 47 W	1958–74
Fredericksburg	USA	38 12	77 22 W	1957–75
Honolulu	USA	21 19	158 00 W	1957–75
Huancayo	Peru	−12 03	75 20 W	1957–74
Kakioka	Japan	36 14	140 11 E	1957–75
Logrono	Spain	42 27	2 30 W	1957–73
Sitka	USA	57 04	135 20 W	1957–75
Sodankylä	Finland	67 22	26 39 E	1957–75
Sverdlovsk	USSR	56 44	61 04 E	1957–75
Yakutsk	USSR	62 01	129 43 E	1957–73

$$X = X_1t^3 + X_2t^2 + X_3t + X_4K_1 + X_5K_2$$
$$Y = Y_1t^3 + Y_2t^2 + Y_3t + Y_4K_1 + Y_5K_2 \qquad (1)$$
$$Z = Z_1t^3 + Z_2t^2 + Z_3t + Z_4K_1 + Z_5K_2$$

where K_1 and K_2 are both constant having usually $K_1=1$, $K_2=0$, but when the observatory has changed its site for some reason the value becomes $K_1=0$, $K_2=1$. Table 2 shows numerical coefficients of Z component thus obtained. Other components are also computed at the beginning of each year from the above formulas. Annual change of each element is given by taking the difference in the values for successive years.

Table 2. Coefficients of the experimental cubic formula expressing the secular change of Z (epoch 1900.0).

Name of observatory	Z_1	Z_2	Z_3	Z_4	Z_5
Amberley	−.03	1.35	10.4	−55,189.1	—
Argentine Island	.01	− 1.81	151.0	−38,057.0	—
Byrd	−.46	19.31	−148.0	−58,542.1	−58,388.9
Dumont d'Urville	−.91	45.35	−662.6	−68,310.0	−68,119.0
Gnangara	−.09	4.87	− 81.5	−53,069.5	—
Halley Bay	.84	−41.89	715.8	−47,259.6	—
Macquarie Island	−.05	2.33	− 1.9	−64,572.5	—
Mawson	−.12	7.72	− 53.9	−48,945.3	—
Mirny	−.09	5.61	− 35.1	−60,487.8	—
Molodezhnaya	−.52	40.80	−896.6	−37,132.5	—
Novolazarevskaya	.45	−25.46	584.3	−43,893.7	—
Port Français	−.10	10.27	−251.9	−42,568.7	—
Sanae	−.25	14.49	−147.9	−38,411.3	−38,476.4
Scott Base	.04	− 2.48	133.3	−70,389.5	—
South Pole	−.57	26.75	−287.3	−56,331.9	—
Syowa Station	−.11	7.07	− 5.7	−43,725.8	—
Toolangi	.01	.18	− 11.0	−56,321.8	—
Trelew	−.17	6.96	− 50.6	−18,783.4	—
Vostok	.06	− 5.37	232.2	−63,269.3	—
Watheroo	.02	.58	− 40.6	−51,977.7	—
Wilkes	.82	−26.66	322.1	−66,350.4	—

Annual change at an arbitrary point on the earth's surface can be obtained, if the potential of variation field $\dot{W}$ is represented by a series of spherical harmonics as follows;

$$\dot{W} = a_0 \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{a_0}{r}\right)^{n+1} \{\dot{g}_n^m \cos m\lambda + \dot{h}_n^m \sin m\lambda\} P_n^m(\theta) \qquad (2)$$

where a_0, r, θ and λ are the earth's radius, distance from the earth's center, colatitude and longitude respectively, $\dot{g}_n^m$ and $\dot{h}_n^m$ being Gauss coefficients of secular variation. $P_n^m(\theta)$ is the Schmidt spherical function defined by

$$\left.\begin{aligned} P_n^m(\theta)&=P_{n,m}(\theta) & m&=0 \\ P_n^m(\theta)&=\sqrt{2\frac{(n-m)!}{(n+m)!}}P_{n,m}(\theta) & m&>0 \end{aligned}\right\} \tag{3}$$

where $P_{n,m}(\theta)$ being Legendre's spherical function.

By the data described above, harmonic coefficients of variation field $\dot{g}_n^m$, $\dot{h}_n^m$ are determined up to degree and order 4 at the beginning of each year from 1957 to 1975. The coefficients for 1975 are tabulated in Table 3. By the coefficients from 1957 to 1975, annual changes of X, Y and Z can be calculated at any point for the respective years. Combining them with X, Y and Z at the same year computed by Gauss coefficients of the main field, annual change in total intensity can also be obtained by using the following formula,

$$\dot{F}=(1/F)(X\dot{X}+Y\dot{Y}+Z\dot{Z}). \tag{4}$$

The IGRF 1975 was used for computing X, Y, Z and F in eq. (4) because our own coefficients of the field are not yet determined at this stage. Annual changes of X, Y, Z and F are computed at grids every 2 degrees in latitude and 4 degrees in longitude over the South Polar region. Annual changes of these components at the observation points are obtained by linear interpolation between these grid values.

Using the above-mentioned results, the correction for the reduction of survey

Table 3. Obtained Gauss coefficients and their annual variation.

n	m	g_n^m(nT)	h_n^m(nT)	$\dot{g}_n^m$(nT/y)	$\dot{h}_n^m$(nT/y)
1	0	−30,164		24.4	
	1	− 2,026	5,690	14.5	−16.8
2	0	− 1,920		−23.2	
	1	3,003	−2,076	2.3	− 3.9
	2	1,580	− 43	9.4	−22.9
3	0	1,306		− 4.2	
	1	− 2,158	− 397	−13.7	6.9
	2	1,269	254	− 9.1	4.7
	3	800	− 248	.6	− 8.0
4	0	960		− 2.7	
	1	818	169	2.6	0.0
	2	476	− 264	− 5.5	− 0.5
	3	− 391	28	− 5.9	3.7
	4	240	− 306	3.2	− 1.1

Table 3. Continued.

n	m	g_n^m(nT)	h_n^m(nT)	n	m	g_n^m(nT)	h_n^m(nT)
5	0	−221			8	−3	−1
	1	364	33		9	0	0
	2	274	133	10	0	−1	
	3	− 16	−136		1	−3	−3
	4	−169	−101		2	2	2
	5	− 38	76		3	0	−2
6	0	59			4	2	1
	1	55	− 23		5	−4	−1
	2	8	117		6	4	−2
	3	−218	78		7	−2	−5
	4	8	− 40		8	4	1
	5	− 10	− 13		9	1	1
	6	−115	− 5		10	0	0
7	0	75		11	0	3	
	1	− 53	− 84		1	1	−5
	2	5	− 27		2	−1	1
	3	7	− 2		3	−1	0
	4	− 19	3		4	1	−3
	5	− 8	30		5	−3	2
	6	17	− 17		6	2	−2
	7	− 11	− 11		7	−1	1
8	0	− 13			8	0	1
	1	11	34		9	−4	−4
	2	− 9	− 30		10	2	−1
	3	− 1	9		11	−1	0
	4	− 22	− 7	12	0	2	
	5	11	3		1	1	2
	6	− 14	20		2	0	−4
	7	17	− 14		3	−1	4
	8	0	− 20		4	−5	1
9	0	− 2			5	9	2
	1	2	2		6	−7	1
	2	2	6		7	6	6
	3	− 3	− 2		8	−7	−5
	4	2	2		9	8	7
	5	4	− 3		10	−6	1
	6	− 3	5		11	4	1
	7	0	4		12	0	−1

data from the date of observation to the common epoch 1975.0 can be made by summing up the annual change at the observation point.

3. Potential of the Main Field

Although magnetic charts for all components are required in this program, almost all data are those of total intensity and the distribution of observation points is not uniform. Under these circumstances, it may be reasonable to obtain the potential of the field in terms of spherical harmonics and to illustrate the distribution of the field derived from it. Harmonic coefficients of the potential must be determined by the least square adjustment so that the field derived from the potential secures the best fit to the reduced values at the observation points distributed over the area south of 40°S. However, as is already stated in the case of the annual change distribution, it is inadequate to deal with the problem using the data of only the southern part of the earth. Therefore, the Antarctic data are supplemented by the values of X, Y and Z components computed by IGRF 1975 at each 10° grid in latitude and longitude in the region between 60°N and 60°S. Along the parallels of latitudes 70° and 80° in the northern and southern hemispheres, they are computed at points every 20° in longitude. Thus, an appropriate amount of information is given for the part of the earth north of 40°S where the survey has not yet been carried out, so that a reasonable solution for the potential can be obtained which represents particularly well the magnetic field over the south polar region based on the observation at about 10000 points and also may be free from distortion due to uneven distribution of observation points.

The potential of the main field W may be expressed by

$$W=a_0 \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{a_0}{r}\right)^{n+1} \{g_n^m \cos m\lambda + h_n^m \sin m\lambda\} P_n^m(\theta). \tag{5}$$

Then, three components X, Y and Z can be computed by

$$X=\frac{1}{r}\frac{\partial W}{\partial \theta}, \quad Y=-\frac{1}{r\sin\theta}\frac{\partial W}{\partial \lambda}, \quad Z=\frac{\partial W}{\partial r}. \tag{6}$$

From eqs. (5) and (6), observation equations of X, Y and Z can be expressed by linear combinations of Gauss coefficients g_n^m and h_n^m to be determined, whereas in the case of the total force F, the observation equation is intrinsically non-linear. To make the problem tractable, the equation of F is linearized as follows;

$$\Delta F=\frac{X_0}{F_0}\Delta X+\frac{Y_0}{F_0}\Delta Y+\frac{Z_0}{F_0}\Delta Z \tag{7}$$

where X_0, Y_0, Z_0 and F_0 are first order approximations at an observed point respectively computed by the potential of IGRF 1975, ΔX, ΔY, ΔZ and ΔF being differences between observed and calculated values. Thus, 12901 observation equations are

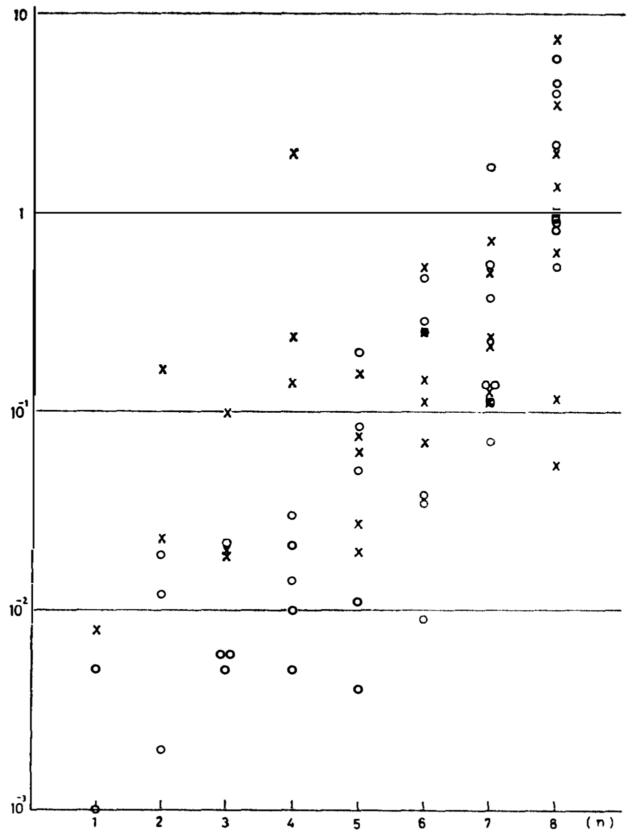

Fig. 1. Discrepancy between Gauss coefficients obtained and those of IGRF 1975.

$$\circ: \left|\frac{g_{GSI}-g_{IGRF}}{g_{IGRF}}\right|, \quad \times: \left|\frac{h_{GSI}-h_{IGRF}}{h_{IGRF}}\right|$$

set up where all data for ΔX, ΔY, ΔZ and ΔF may be expressed as linear equations in terms of small unknown quantities Δg_n^m and Δh_n^m up to degree and order 12, which are defined as differences between Gauss coefficients to be determined and those of IGRF 1975. The resulting model of the geomagnetic field, containing 168 Gauss coefficients, fits the observatory and survey data with a standard deviation of ± 220 nT. The coefficients are tabulated in Table 3. Comparison of the values of new Gauss coefficients with respect to those of IGRF 1975 may be illustrated in Fig. 1, where differences of the coefficients between the models are taken, and the ratios of the differences to the magnitudes of the original coefficients of IGRF 1975 are plotted against the degree of the spherical harmonics. It may be stated from the figure that although the values of coefficients lower than $n=3$ are in good agreement between the two models, as a matter of course, the discrepancy becomes remarkable with the increase in the degree of spherical harmonics.

4. Construction of Isomagnetic and Isoporic Maps

With the present Gauss coefficients of the earth's magnetic field and its annual change for the epoch of 1975.0, isomagnetic and isoporic lines are drawn on 7 maps for Declination, Inclination, Horizontal Intensity, Total Force, North Component, East Component and Vertical Component, using the stereographic projection on a scale of 1 : 15,000,000. Furthermore, a magnetic anomaly map was made for illustrating the distribution of residuals of the total force given by a difference between the values calculated and observed. In the map, colored small circles denote observation points so that the map serves also as a location chart. The residuals are divided by values into 7 classes. Each class covers a range of 400 nT, except the uppermost and lowermost classes which extend to infinity. Each class is specified by colors as indicated in the lower left corner of the map. However, detailed results from the airborne survey are not shown on the residual map, because they cannot be suitably represented on a map of this scale.

5. Concluding Remarks

Some remarks may be pointed out from the results obtained. The dipole moment of the earth's magnetic field is given as

$$M = a_0^3\sqrt{(g_1^0)^2+(g_1^1)^2+(h_1^1)^2} = 7.96\times 10^{25} \text{ cgsemu}$$

which agrees with that of IGRF 1975.

The location of the south magnetic pole is determined by searching for a position where the horizontal component of the field vanishes. The result is

Latitude=65.8°S

Longitude=139.3°E

which is in good agreement with the position indicated on the U. S. World Magnetic Charts 1975. It can be recognized that the pole has migrated more than 1000 km over the land towards the north or northwest since the first determination of its position by J. C. ROSS in 1841 and now it is located at a point off the coast of Adélie Land.

Significant features of the geographical distribution of magnetic anomaly are as follows; the South Pacific Ocean from 150° to 210° in longitude has rather small disturbance while remarkable positive and negative anomalies are found in the area near the tip of the Antarctic Peninsula, and also a coastal area of about 100° in longitude has large negative anomalies.

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References

BEHRENDT, J. C. and BENTLEY, C. R. (1968): Magnetic and Gravity Maps of the Antarctic. New York, Am. Geogr. Soc., 9 plates (Antarct. Map Folio Ser., Folio 9).

CHAPMAN, S. and BARTELS, J. (1951): Geomagnetism, Vol. 2. London, Oxford University Press, 611–612.

GLAVNOYE UPRAVLENIYE GEODEZII I KARTOGRAFII MG SSSR (1966): Atlas Antarktiki I. Moscow, 34–38.

IAGA COMMISSION 2 WORKING GROUP 4 (1969): International geomagnetic reference field 1965.0. J. Geophys. Res., **74**, 4407–4408.

IAGA DIVISION I STUDY GROUP GEOMAGNETIC REFERENCE FIELDS (1976): International geomagnetic reference field 1975. Geophys. J. R. Astron. Soc., **44**, 733–734.

PEDDIE, N. W. and FABRIANO, E. B. (1976): A model of the geomagnetic field for 1975. J. Geophys. Res., **81**, 2539–2542.

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