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MAGNETIC CHARTS OF CANADA FOR EPOCH 1965.0

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Magnetic Charts of Canada for Epoch 1965.0

E. DAWSON AND L.C. DALGETTY

ABSTRACT—Magnetic charts of Canada in components D, I, H, Z, F, X, Y, G, U, V and their annual changes were drawn for epoch 1965.0. Charts were compiled from some 18,000 observations in D, H, Z, acquired since 1947. Seventy-five per cent of these were airborne data. The observatory and repeat station network, necessary for reduction of data to epoch, is described. Machine processing techniques are used. Charts are drawn using average values computed over an equal area grid, a unit grid being equivalent to a 2-degree grid at the equator. The updating method yields probable errors of ±4 minutes in D and ±20 γ in H and Z over an 18-year reduction period. An estimate was made of the chart residuals by making a random comparison of some 1,200 updated observations in D, H, Z with corresponding chart values. The following r.m.s. differences were obtained: ±0.6 degree in D; ±125 γ in H, Z.

RÉSUMÉ—Les cartes magnétiques du Canada dans les composantes D, I, H, Z, F, X, Y, G, U et V ont été dressées, avec les modifications nécessaires, pour l'année 1965.0. Quelque 18,000 observations en D, H, Z, effectuées depuis 1947 à l'aide d'avions dans 75 p. 100 des cas, ont servi à établissement des cartes. Les deux auteurs décrivent le réseau d'observatoires et de stations de répétition qui a servi à réduire les données à l'année 1965, au moyen d'ordinateurs. On a dressé les cartes à partir de valeurs moyennes sur un quadrillage équivalent, chaque carreau étant équivalent à 2 degrés pris à l'équateur. La méthode de mise à jour donne des erreurs probables de ±4 minutes en D et de ±20 γ en H et en Z sur une période de réduction de 18 ans. Les auteurs ont fait une estimation des résiduelles de la carte en comparant au hasard quelque 1,200 observations mises à jour en D, H, Z avec les valeurs correspondantes de la carte. Ils ont obtenu les écarts-types suivants: ±0.6 de degré en D et ±125 γ en H et en Z.

Introduction

The first systematic magnetic survey in Canada was carried out by Sir John H. Lefroy between 1842 and 1844. Observations (D, I, F) were made at over 300 stations, and magnetic charts for epoch 1844.0, in these elements, were published in 1883.

In connection with the proposed building of a transcontinental railway and the expected influx of immigrants to the Canadian West, comprehensive land surveys were made by the Topographical Surveys Branch of the Department of the Interior from 1880 to 1888. Numerous magnetic observations in D, I, H were made at this time. This system continued until recent times, and observations made by the Topographical Surveys Branch formed the basis of all magnetic charts of Canada up to the early 1940's.

In 1907 the Dominion Observatory initiated its program of regular annual magnetic surveys. These have been continued with few interruptions to the present day. The Meteorological Service of Canada made several important surveys in the period 1908-12, including a survey of the Mackenzie River in 1910 and of Hudson Bay and Strait in 1912. It also maintained the only magnetic observatory in Canada, at Agincourt. Another was established at Meanook under its aegis in 1916. The administration of both observatories was transferred to the Dominion Observatory, Ottawa, at the end of 1936.

In 1905-13, the Carnegie Institution of Washington made some observations in Canada, but this practice was shortly abandoned, as it was considered that Canadian surveys covered this area adequately. Other contributing agencies whose results were freely used in compiling magnetic charts of Canada were the Hydrographic Service of Canada, The Geological Survey of Canada and the United States Coast and Geodetic Survey. The Dominion Observatory took over the compiling of magnetic charts in 1948. Table VII (Appendix II) lists magnetic charts produced in Canada since 1883.

Number, Type and Distribution of Observations

Owing to the efficient coverage achieved using airborne techniques for obtaining magnetic data, it was decided that the 1965 edition of magnetic charts would be compiled only from data observed since 1947. Although this meant losing thousands of declination values in western Canada alone, plus untold numbers of old I, H values, it was felt that this gap would be amply filled using the more recent aeromagnetic data. Also the error involved in reducing this recent data to epoch should be quite small. The distribution of the observations used in the compilation is shown on Figure 1. There is almost uniform coverage over the entire country. In particular, there is a striking increase in the density of Arctic data due to airborne measurements. Up to 1947 there were less than 500 magnetic observations made in theCanadian Arctic and the majority of these readings were D values only. Since 1953 the number of observations in all components has increased by an order of magnitude.

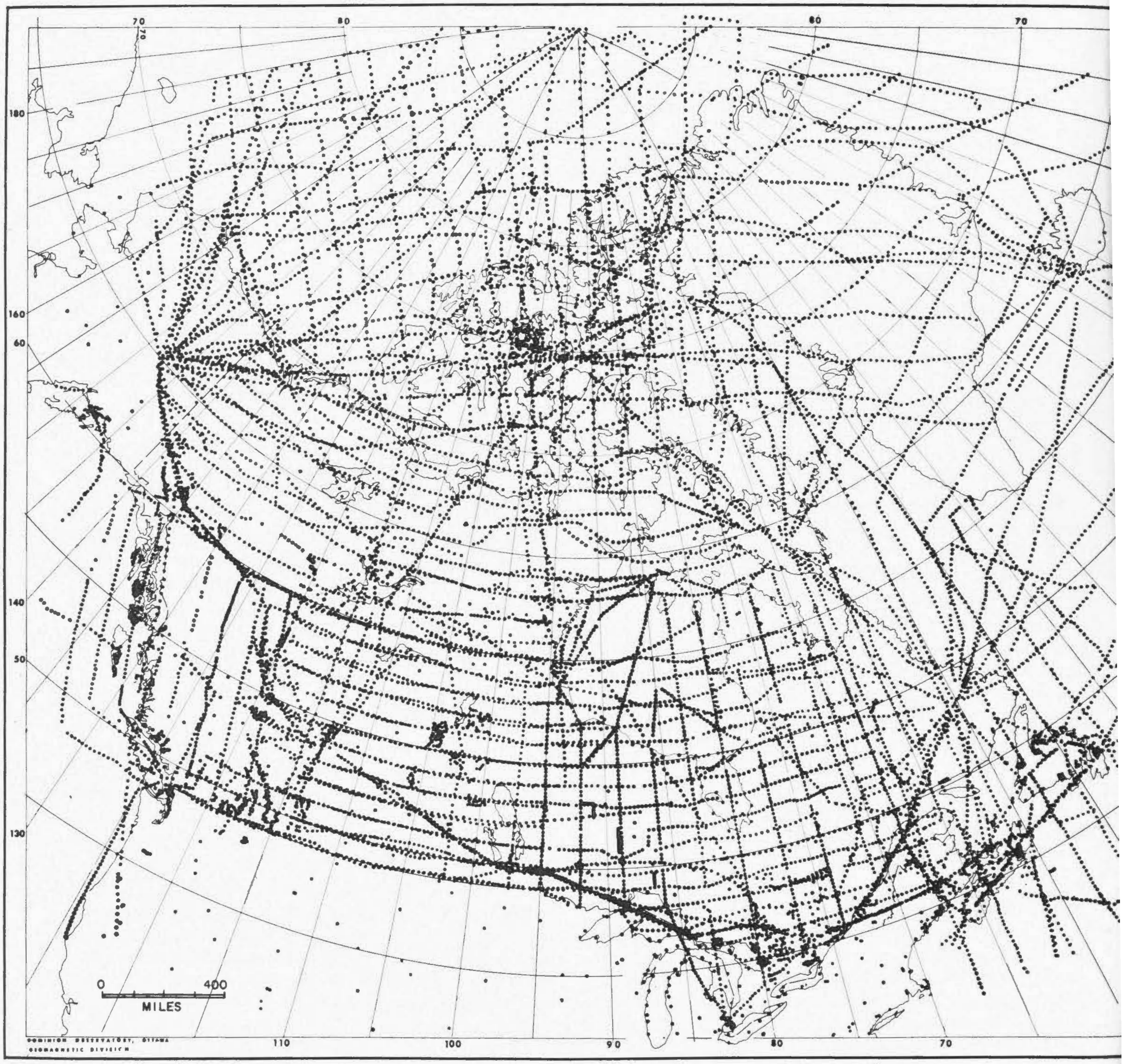


FIGURE 1. Distribution of magnetic survey observations 1945-1963.

Table I gives the total number of observations, both surface and airborne, in each component used in the compilation of the 1965 charts.

TABLE I

Latitude Range	Area	Number of Observations			Number of Observations per (100Km^2)		
	Km^2 x 10^6	D	H	Z	D	H	Z
40° — 60°N	14.6	11,400	9,000	9,200	7.8	6.2	6.6
60° — 90°N	16.8	6,000	6,000	7,100	3.6	3.6	4.2
Total	31.4	17,400	15,000	16,300	5.5	4.8	5.2

The area specified is the total mapping area including Alaska, Greenland, Iceland and the surrounding waters, representing 12 per cent of the northern hemisphere. Observation numbers are quoted to the nearest 100.

Table II gives a summary of the type of data, either surface or airborne. The numbers, quoted to the nearest 100, refer to geographic positions at which an observation has been made, without reference to the observed magnetic element or elements.

TABLE II

Type	40° — 60°N	60° — 90°N	Total
Airborne	7,100	6,500	13,600
Surface	3,900	500	4,400
Total	11,000	7,000	18,000

Project Magnet of the U.S. Naval Oceanographic Office contributed 23 per cent of the airborne observations, and the U.S. Coast and Geodetic Survey 19 per cent of the surface observations. The average altitude of the airborne data is between 2 and 3 km. These data were reduced to sea-level using a simple dipole correction.

From 1907 to 1964 approximately 2,000 ground stations were occupied by Dominion Observatory survey parties. From 1953 to 1963 the Dominion Observatory airborne magnetometer has been flown 300,000 miles, completing more than 150 flight lines with 12,000 observations in D, H, Z. One fifth of these flights were flown outside our mapping area.

Observed Elements

Prior to 1947, Canadian surface observations were made using deflection magnetometers, earth inductors, dip circles and theodolites with compass attachments to measure the elements D, I and H. Although these instruments are extremely accurate, it takes an hour, under ideal conditions to make a complete set of observations. In 1947, observing techniques were greatly improved with the introduction of portable electronic magnetometers of the saturable core type, for the determination of the vector geomagnetic field (Serson and Hannaford, 1956). With these instruments a complete set of observations in D, I, F, can be made in 15 minutes with an accuracy comparable to that obtained using the older type field instruments. In 1962, nuclear proton precession magnetometers were used to supplement these field instruments, with quick, dependable measurements of F.

The Dominion Observatories three-component airborne magnetometer records D, H, Z as continuous profiles (Serson et al, 1957). In addition, the instrument supplies automatically computed averages of D, H, Z, the averages being computed over 5-minute intervals. It is these averaged values that are referred to as "airborne observations" in this report.

The airborne observations contributed by the U.S. Navy Oceanographic Office consist of D, I values averaged over an interval of 100 seconds and an instantaneous F value for the centre of the interval (Schonstedt and Irons, 1955). A continuous record of F is also obtained.

The surface observations contributed by the U.S. Coast and Geodetic Survey were made using a variety of instruments, such as earth inductors and deflection magnetometers for the measurement of D, I, H. (Hazard, 1957).

Observatory and Repeat Station Coverage

Covering Canada adequately with a network of repeat stations, from logistic considerations alone, is a formidable task. The earlier work was done under great practical difficulties readily understood, since the greater part of the country lies to the north of the railway belt. The bequest from this early work, although valuable, was a poorly distributed network of repeat stations.

Since 1907, 270 repeat stations have been occupied by Observatory field parties. Of these, 82 per cent were established before 1935. At present, only 100 of these repeat stations can be classified as active and have been reoccupied within the past 10 years.

In 1962 a revised network of repeat stations, built up almost entirely from the existing stations, was initiated to provide the uniform coverage necessary for accurately defining secular change across the country (Fig. 2). The network of 103 stations consists of 31 primary stations

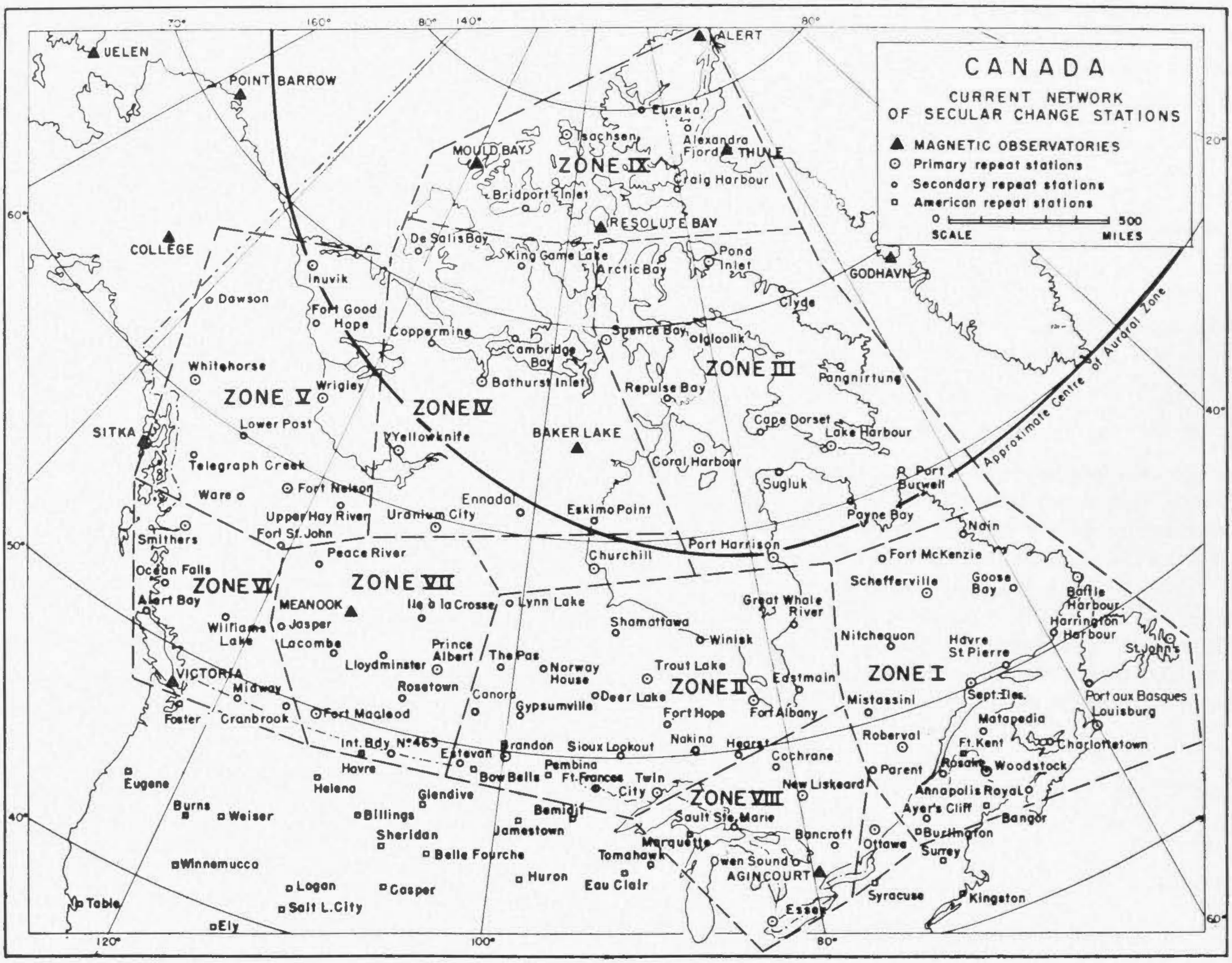


FIGURE 2.

and 72 secondary ones. At the present time, all stations will be occupied at least once every 5 years. If required, adequate secular change coverage over the entire country could be achieved using only those stations designated as primary, and secondary stations could be reoccupied at 10-year intervals. The country is divided into nine zones. Dividing the work between staff of the outlying observatories and headquarters staff, all stations can be occupied in a 5-year period. At least 80 per cent of these stations have had two or more reoccupations within the past 15 years. To ensure continuity of isolines in those areas of continental U.S.A. and Alaska, contiguous to Canada, there is an excellent system for interchange of secular change data with the U.S. Coast and Geodetic Survey. Data from 56 American repeat stations were also used in compiling secular change.

Canadian observatories are listed in Table III. The elements reoorded at each are also shown.

TABLE III

Observatory	Geographic Lat.°(N)	Geographic Long.°(W)	Year Established	Elements Recorded
Agincourt	43.8	79.3	1898	D H Z
Meanook	54.6	113.3	1916	D H Z
Baker Lake	64.3	96.0	1951	D H Z
			1957	X Y Z
Resolute Bay	74.7	94.9	1953	X Y Z
Victoria	48.5	123.4	1957	D H Z
Alert	82.5	62.5	1961	X Y Z
Mould Bay	76.2	119.4	1961	X Y Z

In addition to these, data from the following observatories were also used in compiling secular change.

American—Fredericksburg, Tucson, Sitka, College, Barrow.

Russian—Uelen, Cape Chelyuskin, Dikson, Srednikan, Tiksi, Tikhaya Bay, Druzhnaya and Yakutsk.

Others—Thule, Godhavn, Leirvogur, Tromso, Dombas, Sodankyla, Lovo, Rude Skov and Lerwick.

Accuracy of Observations

The sources of error in the data used to compile the 1965 magnetic charts of Canada fall into three natural divisions: instrumental errors, errors due to transient variations, and errors in reducing the data to epoch.

For airborne observations, there are additional errors such as errors in geographical position, errors due to aircraft magnetism and errors in the direction reference system. These errors have been examined in great detail by Serson et al. (1957) and Schonstedt and Irons (1955). We are concerned here only with the overall operational accuracy of the airborne instruments.

Instrumental Errors

The probable errors for a single complete observation of the geomagnetic vector field at a particular time and place, under good survey conditions, are listed in Table IV.

TABLE IV

	Surface		Airborne	
	Dominion Observatory	U.S.C.G.S.(1)	Dominion Observatory	U.S.N.O.O.(2)
D	±0.3′	±0.5′	±0.3°(3)	±0.1° to ±0.2°
I	±0.2′	±0.1′		±0.1°
H		±10γ(4)	±60γ	
Z			±30γ	
F	±10γ to ±50γ(5)			±15γ

(1)United States Coast and Geodetic Survey.
(2)United States Naval Oceanographic Office.
(3)The Dominion Observatory airborne magnetometer records D to the nearest degree in much of the Arctic area.
(4)For a field of H = 20,000 γ, and varies directly with H.
(5)Dependent on frequency of standardization.

More detail concerning these errors can be found in the following sources, from which the table was derived: Serson and Hannaford (1956) and Svendsen (1962), for the surface observations; and Serson et al. (1957), Schonstedt and Irons (1955) and Byrnes (1960) for the airborne observations.

In his review of airborne magnetic surveys for world charts, Serson (1960) concluded that the operational accuracy of the two airborne instruments listed in Table IV was about the same and ranged from 50 to 100 γ.

Errors Due to Transient Variations

These errors are more difficult to deal with. None of the airborne observations are corrected for these variations since any attempt to correlate such variations over great distances would probably introduce additional errors. Whitham and Niblett (1961) have shown that r.m.s. differences in transient variations are proportional to the r.m.s. level of activity and to the separation of stations or in the airborne case, the proximity of the nearest observatory to a flight line. Their quantitative results, only valid for the Meanook-Edmonton area, were obtained using instantaneous values of F, at intervals of 2½ minutes, over a period of 3 days. Whitham et al. (1960), using hourly mean ranges in the principal horizontal field component for 16 Canadian I.G.Y. magnetic observatories and variation stations, showed that a high level of irregular activity is more or less continuously present over most of Canada. Serson et al. (1957) estimate that the probable error, due to disturbances and diurnal variation combined, is ±30 γ in any component. This estimate was based on an airborne survey made over western Canada near the auroral zone in 1955.

At the present time, surface observations are corrected to a mean value for the day only, unless the observations are taken in the vicinity of an observatory. Previous to 1964, Canadian observers used the following procedure in the field. Repeated observations were made for a period of 24 hours or more in three elements and the effect of diurnal variation was eliminated by averaging or by drawing a smooth curve through the series. Irregularities in the readings were attributed to the influence of magnetic disturbance and these readings were rejected. The curves of secular variation for repeat stations suggest that in general, this procedure appears to be quite satisfactory. In 1964, a temporary portable observatory was set up at 15 repeat stations in the Baffin Island, Melville Peninsula area. The average recording time was 30 hours. Four baseline readings were taken at each station and normal observatory procedure used to derive a mean value for the day. An attempt was made to further correct these readings to a monthly mean value by means of another temporary observatory operating at Frobisher Bay for the duration of the survey. The average distance from a station to the nearest observatory (Resolute Bay and Baker Lake records were also used) was 300 miles. No correlation between records was found. Whitham and Loomer (1960) investigated post-perturbation and the effect on daily means using observatory values of the Dm field for Resolute Bay and Baker Lake over 17 months in 1953-55. They found a marked seasonal variation to this effect. For the equinox-summer period, that is the normal field season period, errors contributed by ignoring these effects are of the order of 2′ in D, I and 35 γ in Z.

Since 1958, the U.S.C.G.S., in order to diminish errors due to transient variations, set up the following system. Portable observatories are established such that the distance to a repeat station is generally not more than 200 miles. Svendsen (1962) estimates that such errors in C.G.S. surface measurements are of the order of $\pm 1'$ in D, I and $\pm 10\ \gamma$ in H.

Errors in Reducing Data to Epoch

For all observatories and most repeat stations, updated values of D, H and Z were compared with graphs of observed values, extrapolated to 1965.0. More than 300 values were examined. The probable errors in reduction over an 18-year period are as follows:

$$\pm 4' \text{ in D}; \ \pm 16\ \gamma \text{ in H}; \ \pm 20\ \gamma \text{ in Z}.$$

Machine Processing of Magnetic Data

A modified version of the method outlined by Hurwitz et al. (1954) was used. Due to the complexity of the D-isogones in the Canadian Arctic the country is divided into two areas (Fig. 3), and each area is dealt with separately. The magnetic components updated in Area I are D, H, Z and in Area II, U, V, Z where U, V, the grid components of H, are defined as follows:

U (grid-north component) = H cos G

V (grid-east component) = H sin G

The grid variation G (grivation) is defined in the following terms:

$$G = D - \lambda \text{ where } \lambda \text{ is east longitude,}$$

and D is positive for east declination.

The reasons for using U, V have been previously outlined by Dawson and Loomer (1963). Prior to the updating process, all declination values are converted to minutes of east declination. This step simplifies the updating and averaging of values in those areas adjacent to the agonic lines. Also, at this time, all airborne data are corrected for altitude using the simple dipole correction.

$$X = X^1 (1 + 1.4 \times 10^{-7} h)$$

where X^1 is the observed component at altitude h feet, and X is the value at sea-level.

Reduction of Data to Epoch 1965.0

The period 1947-1965 is divided into four time-intervals or epochs centered on 1950, 1955, 1960 and 1965. Isoporic charts in $\dot{D}$, $\dot{H}$, $\dot{Z}$, $\dot{U}$, $\dot{V}$ are prepared for each time-interval. Values are scaled off for the corners of each zone (Fig. 3), in each component, for the four time-intervals. These values are assumed to be constant over a 5-year period. Master cards listing these data are prepared for each zone, with each master card controlling the updating of all observations within the zone.

The basic data cards are automatically sorted according to the epoch in which the observation occurred, and within the epoch, into the zones defined by the master

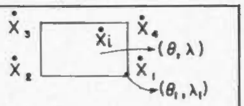
Interpolation Formula to Operate on the S.E. corner (θ, λ_1) of each Zone.

$$\dot{X}_i = \dot{X}_1 + C(\lambda - \lambda_1)(\dot{X}_2 - \dot{X}_1) + 0.2(\theta - \theta_1)\left\{(\dot{X}_4 - \dot{X}_1) + C(\lambda - \lambda_1)(\dot{X}_1 + \dot{X}_3 - \dot{X}_2 - \dot{X}_4)\right\}$$

where $\dot{X} = \dot{D}, \dot{H}, \dot{Z}, \dot{U}$ and $\dot{V}$

and $C = 0{\cdot}2$ for area I

$C = 0{\cdot}07$ for area II



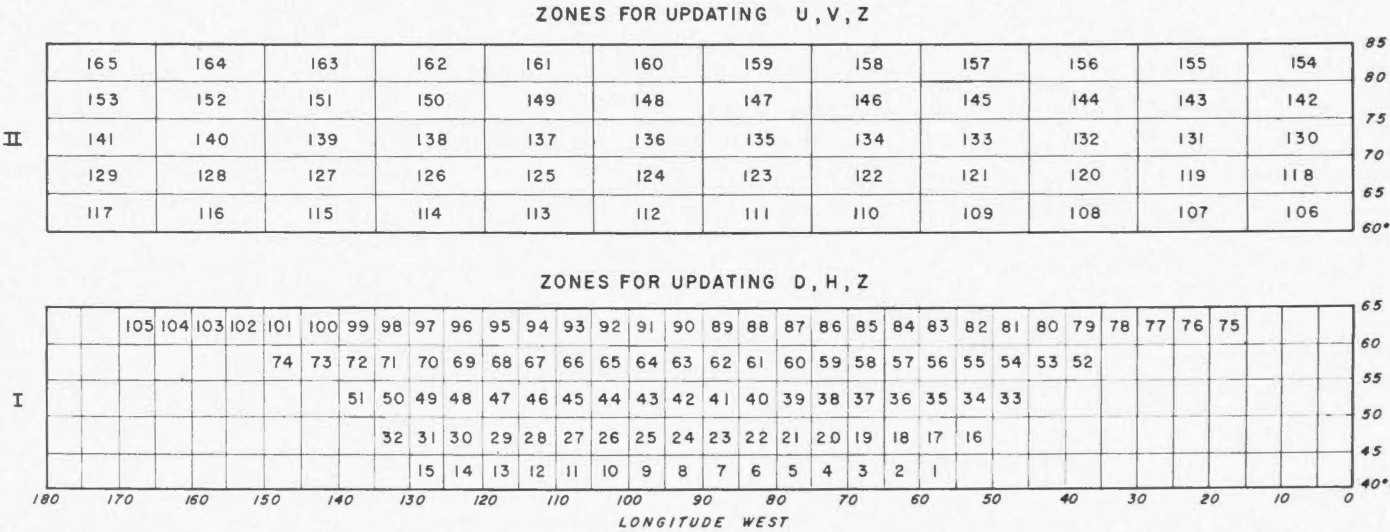


FIGURE 3.

cards. Cards outside the mapping area are extracted at this time. The time, t, between the date of the observation and the middle of the epoch in which it took place, is punched on the basic data card. Two passes are required to complete the reduction to epoch. In the first pass, the secular change for the interval t is computed for each observation from t $\dot{X}_i$; $\dot{X}_i$ is interpolated linearly from the $\dot{X}$ values on the master cards, where $\dot{X} = \dot{D}$, $\dot{H}$, $\dot{Z}$, $\dot{U}$ or $\dot{V}$. The interpolation formula is shown on Figure 3. This value is added algebraically to the observed value $\dot{X}$. Thus each observation is updated, or backdated as the case may be, to the nearest intermediate epoch.

The second pass through the computer, for reducing observations from the intermediate level to the required epoch 1965.0, is quite similar to the procedure used for the first pass. The annual secular-change values $\dot{X}$ are replaced by net secular-change values ΔX. These net values are computed in the following way. If we refer to the annual change in epoch 1950, in any component, as $\dot{X}_{50}$, in epoch 1955 as $\dot{X}_{55}$ and so on, then the net secular-change ΔX required to reduce an observation from 1950.0 to 1965.0 is

$$\Delta X = 2.5\,\dot{X}_{50} + 5.0\,\dot{X}_{55} + 5.0\,\dot{X}_{60} + 2.5\,\dot{X}_{65}$$

At the end of the second pass, all observations are reduced to the required epoch.

Averaging Operations

After the data cards are updated, the problem of constructing the chart begins. The approach to this problem depends on the purpose of the chart and the type of chart required to fulfill this purpose. In his review of airborne magnetic surveys for world charts, Serson (1960) states that most magnetic charts are used as a prediction of values which would be obtained if observations were to be made at any point. This certainly expresses the purpose of the Canadian charts. In attempting to fulfill this requirement, some of the earlier D-charts issued in Canada tried to satisfy every observation. The resulting contour lines had so many sinuosities and loops as to render the chart almost useless to most users. In the type of chart produced more recently the short wave-length anomalies due to crustal effects are smoothed out. The remaining field depicts the long wave-length anomalies, due to causes within the core, superimposed on the 'normal' field. To achieve this aim subjectively, smoothing formulae were applied laboriously to individual contour lines until the cartographer was satisfied with the degree of smoothness obtained.

For the current series of charts, the prospect of plotting some 80,000 points, contouring and smoothing, was overwhelming, particularly in view of the limited staff to do the job. It was realized that either an analytical approach or some averaging procedure would have to be used. It was decided to proceed with an averaging technique. Analytical approaches will be discussed at the end of the paper.

Ballenzweig (1959) discusses the deficiencies of various methods used for mapping the geographical variation of geophysical quantities. He advocates the use of an equal-area grid, particularly if the area studied has considerable latitudinal extent. A modified equal-area grid was devised such that each quadrangle had an area equivalent to a 2-degree quadrangle at the equator. Complete equality was not attained because the box widths were made variable in 0.5-degree steps only, to simplify the computing. The areal standard deviation from the mean is 4 per cent. There are 607 boxes, so that on the average, the mean values are 220 kilometers apart. It is obvious that charts drawn from this distribution of mean values will obscure the short wave-length anomalies. From the linear interpolation curves of Serson and Hannaford (1957), the expected r.m.s. errors in such charts are $\sigma_H = 170\gamma$, $\sigma_Z = 200\gamma$, and $\sigma_D = 170\ \gamma/H$. To effect a marked increase in the accuracy of the charts, quadrangles smaller than 0.5 degree would have to be used, equivalent to approximately 10,000 mean values.

During the averaging procedure, Chauvenet's criterion of rejection is used to reject doubtful observations. Rejectability is determined as a function of the deviation, dispersion and the number of measurements used in determining the mean. Less than 1 per cent of the observations were rejected. The distributions of observations over the equal-area grid are shown in Figure 4 for Areas I and II. On the average there are 31 and 21 observations per quadrangle, respectively, for these areas.

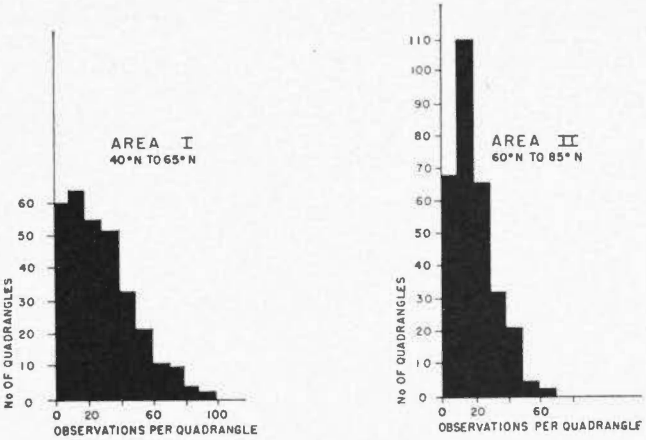


FIGURE 4. Distribution of observations over equal-area grid.

Standard deviations are computed during the averaging procedure as a test of observational scatter after the rejection criterion has been applied. The distribution of

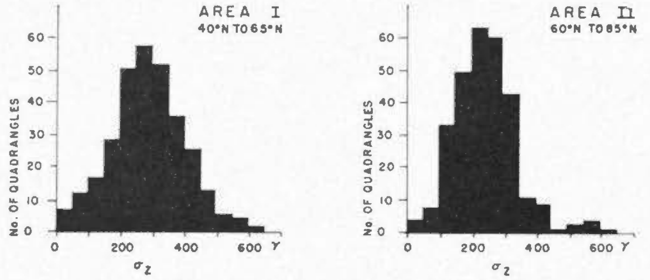


FIGURE 5. Distribution of mean standard deviations in Z.

these deviations is shown in Figure 5 for Z, the only element common to both areas. The distributions are approximately the same for the other elements. The average deviation from the mean is shown in Table V.

TABLE V

Area I			Area II		
Element	σ	% within 1 σ	Element	σ	% within 1 σ
D	0.84°	78	U	141 γ	71
H	160 γ	74	V	98 γ	69
Z	119 γ	69	Z	92 γ	65

For Area II the mean values ($\bar{U}$, $\bar{V}$, $\bar{Z}$) are plotted and contoured. U,V-isolines are adjusted for mutual consistency using an adaptation of the Chapman curl test by Hutchison (1949) for horizontal grivation components. The geographical positions of the points of intersection of the adjusted U,V-isolines are scaled off. Values of $\dot{Z}$, $\dot{U}$, $\dot{V}$ are also scaled for these positions. New cards are punched listing these data. The simple block diagram of Figure 6 depicts the program flow for computing the remaining elements. These values are plotted with the best predicted values (obtained graphically) for all observatories and reliable repeat stations and the final magnetic charts for Area II are drawn. This procedure, of using graphically obtained values to supplement those values obtained automatically, is used for all elements and their time derivatives in both areas. It seems a reasonable requirement that, if these charts are to serve the purpose of prediction as outlined earlier, then the predicted values at undisturbed magnetic observatories and repeat stations should be satisfied.

For Area I the mean values ($\bar{D}$, $\bar{H}$, $\bar{Z}$) are plotted and the final charts drawn. Originally it was thought that F, I, X, Y and their time derivatives could be computed in a single run from $\bar{D}$, $\bar{H}$, $\bar{Z}$ and their time derivatives. As it turned out, since there were many more D values than H or Z, the derived mean positions did not correspond and this plan had to be dropped. Two new sets of computing cards are prepared. From one set, listing $\bar{H}$, $\bar{Z}$, and the corresponding $\dot{H}$, $\dot{Z}$ scaled from the isoporic charts, F, I, $\dot{F}$, $\dot{I}$, are computed. From the other set, listing D, H, $\dot{D}$, $\dot{H}$, scaled off the completed charts at intervals of 5° longitude and 2.5° latitude, X, Y, $\dot{X}$, $\dot{Y}$ are computed. The simple block diagrams (Fig. 6) depict the procedure used.

The isolines in the overlapping zone between Areas I and II are averaged so that a harmonious union is obtained between these areas. Linear interpolation

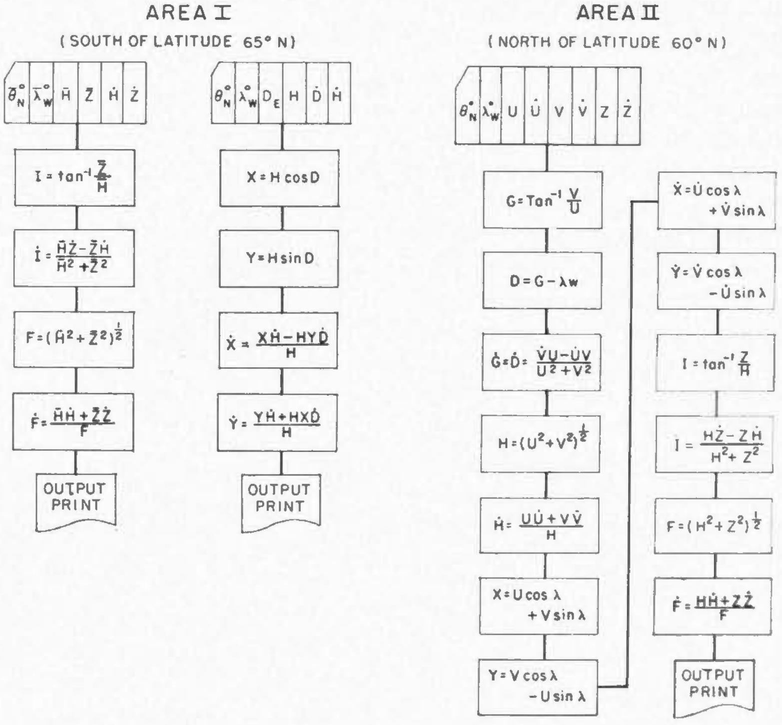


FIGURE 6. Program flow for processing of magnetic elements.

between values is used to obtain the isolines. Also, it should be stated that while the isolines, obtained by the method outlined above, were much smoother than those obtained previously for Canadian magnetic charts, a certain amount of smoothing by eye still had to be done—much more so than was expected.

Accuracy of Charts

Charts of elements D, H, Z, F, I, X, Y, G, U, V and their annual changes for 1965.0 are shown in Figures 7-16. An estimate was made of the chart residuals by making a random comparison of updated values with chart values over the entire chart. Table VI lists the number of values tested and the results of these tests.

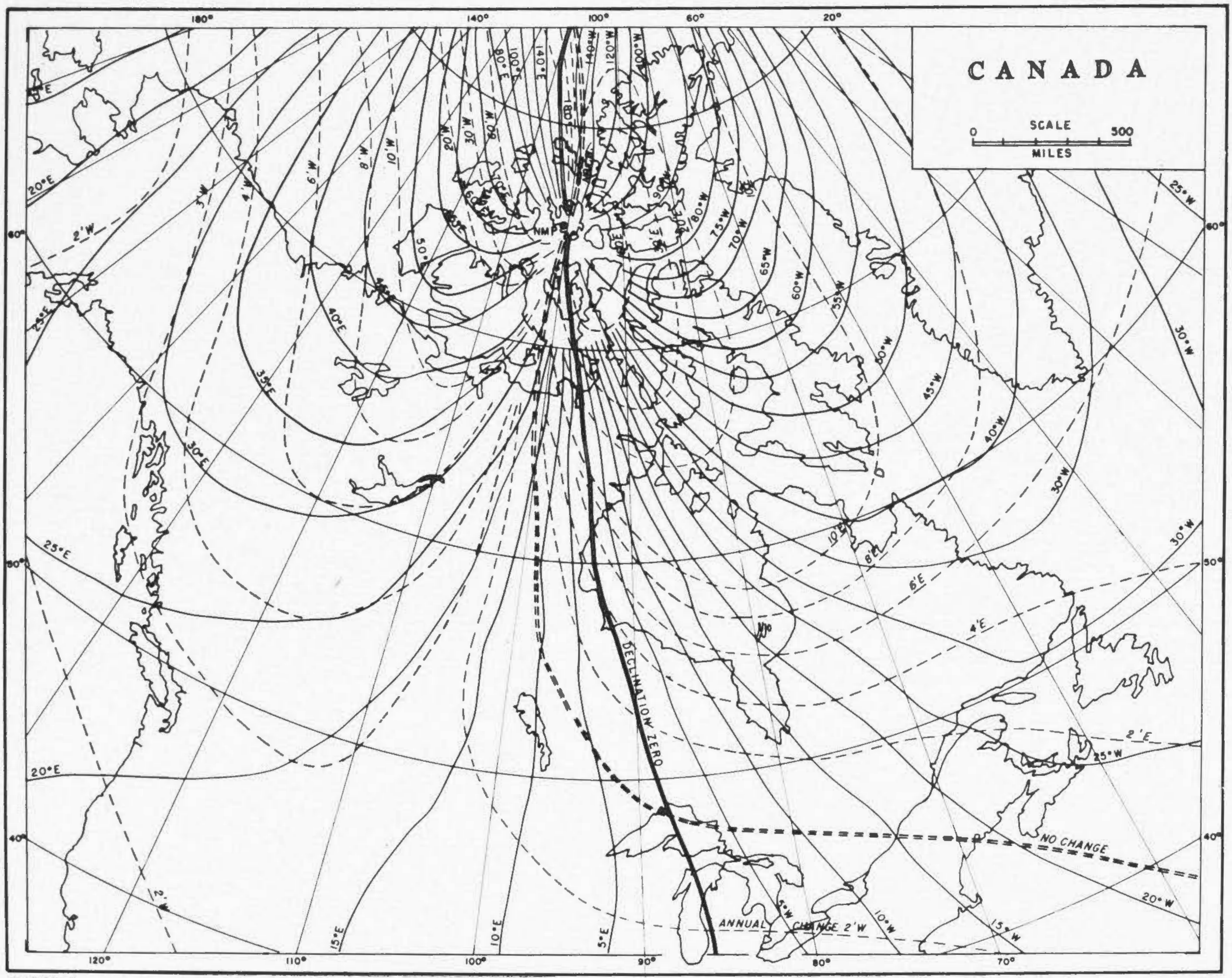
Table VI

Element	Number Tested	R.M.S. Difference
D	918	0.6°
H	1401	128 γ
Z	1242	122 γ
F	250	147 γ

A more realistic test of the accuracy of these charts will have to wait until the results of future surveys can be tested against the chart values.

Tests of the F-chart were made using the sea magnetometer results of Hood (1964) and Keen (1963). Their observations, made over Hudson Bay, the Labrador Sea

MAGNETIC DECLINATION (D) CANADA, 1965·0



D 1965·0

D 1965·0

FIGURE 7.

and Davis Strait, were not used in the compilation of these charts. These values were updated and a comparison made with the corresponding chart values showed that the r.m.s. differences were 20 per cent higher than those found for Z. This is probably due in part to the increasing presence of the shorter wave-length anomalies in the sea magnetometer results.

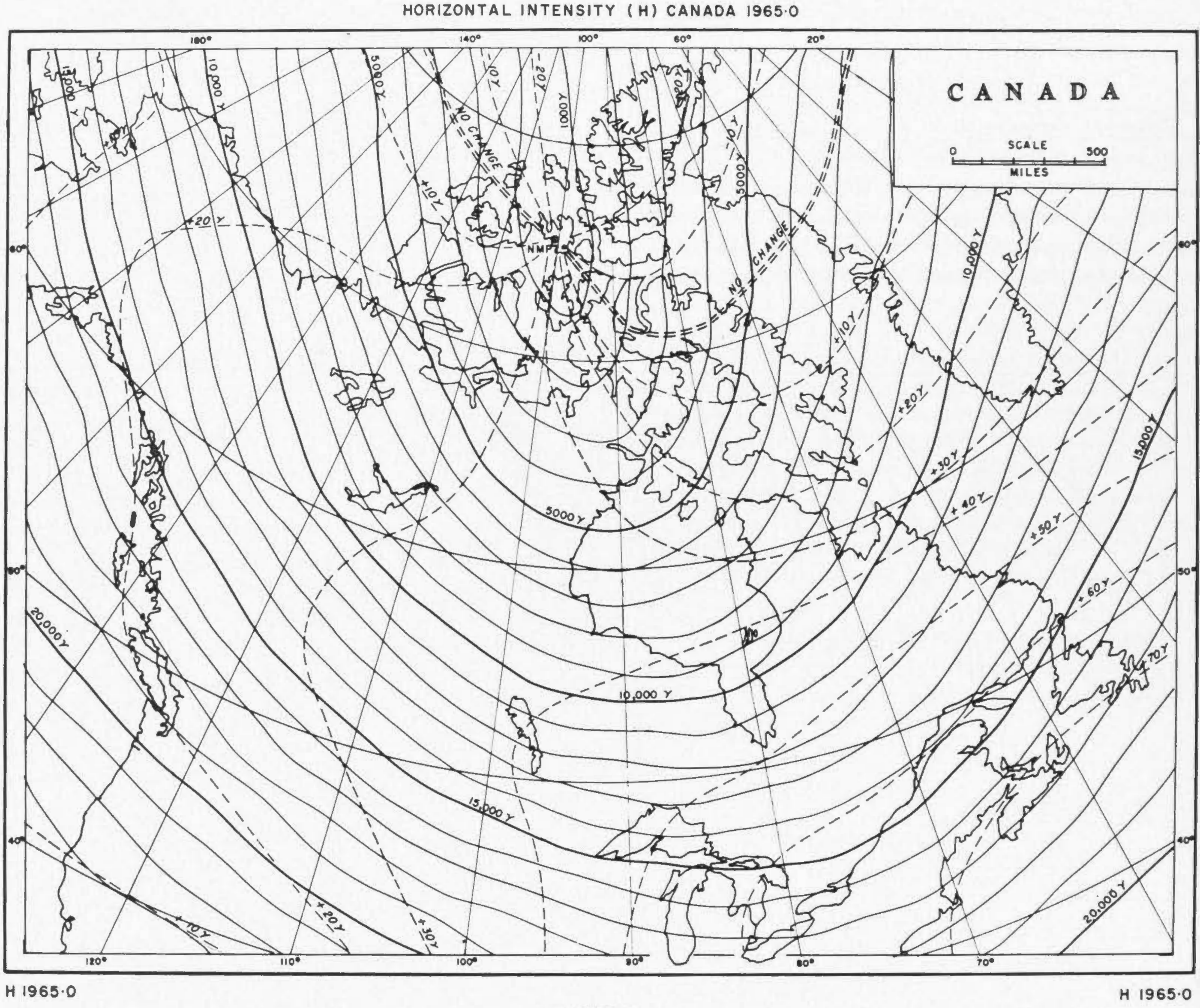
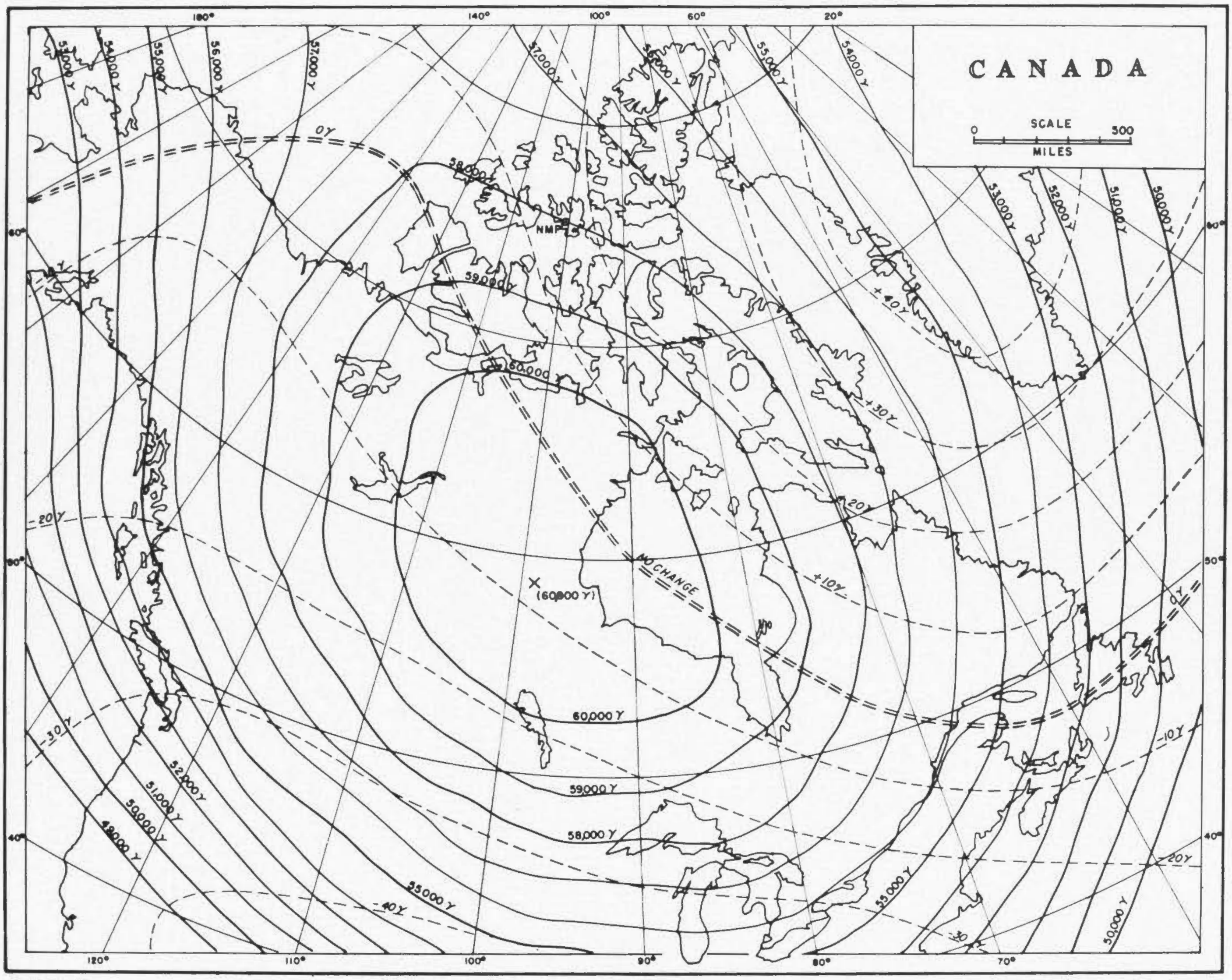


FIGURE 8.

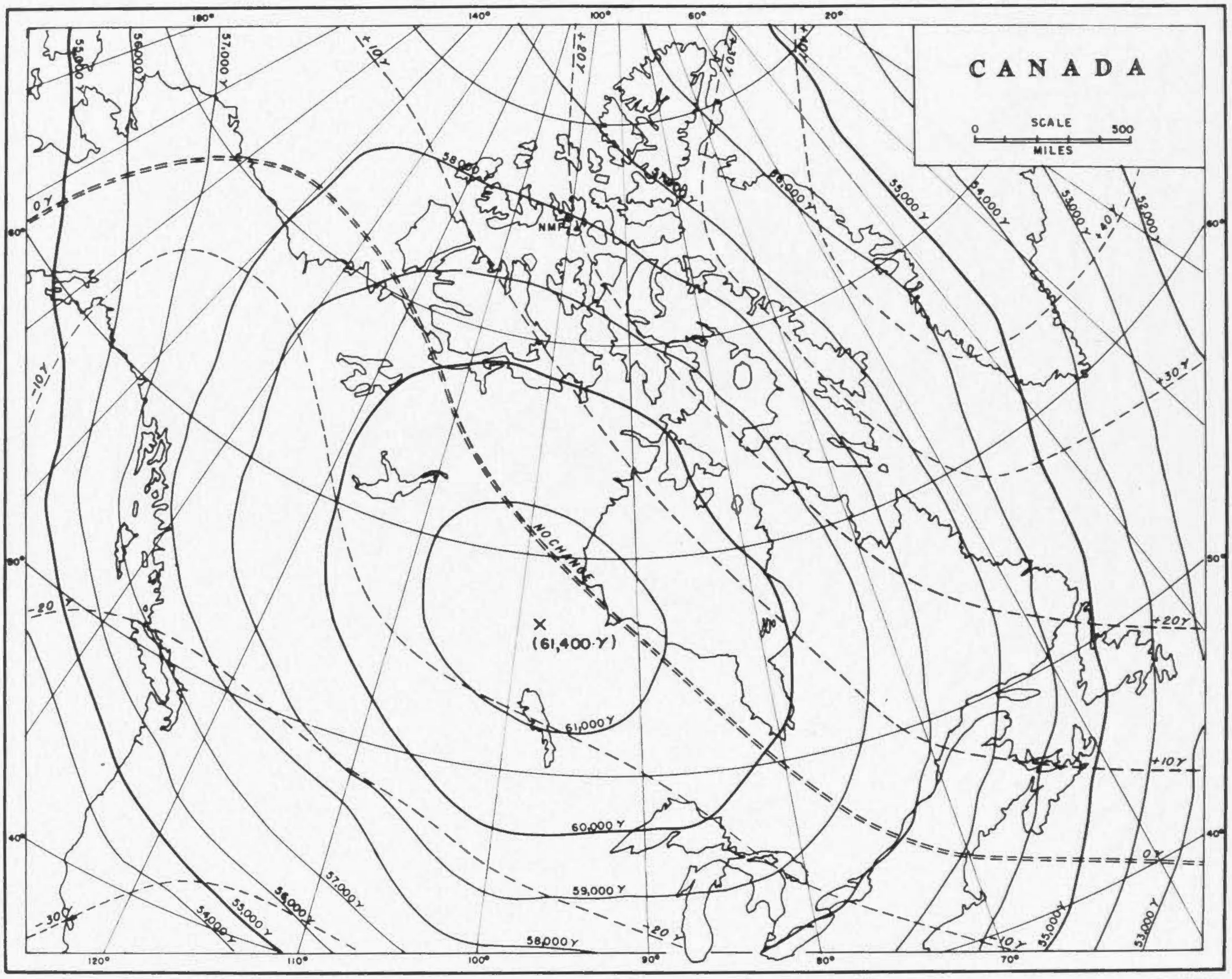
VERTICAL INTENSITY (Z) CANADA 1965·0



Z 1965·0 Z 1965·0

FIGURE 9.

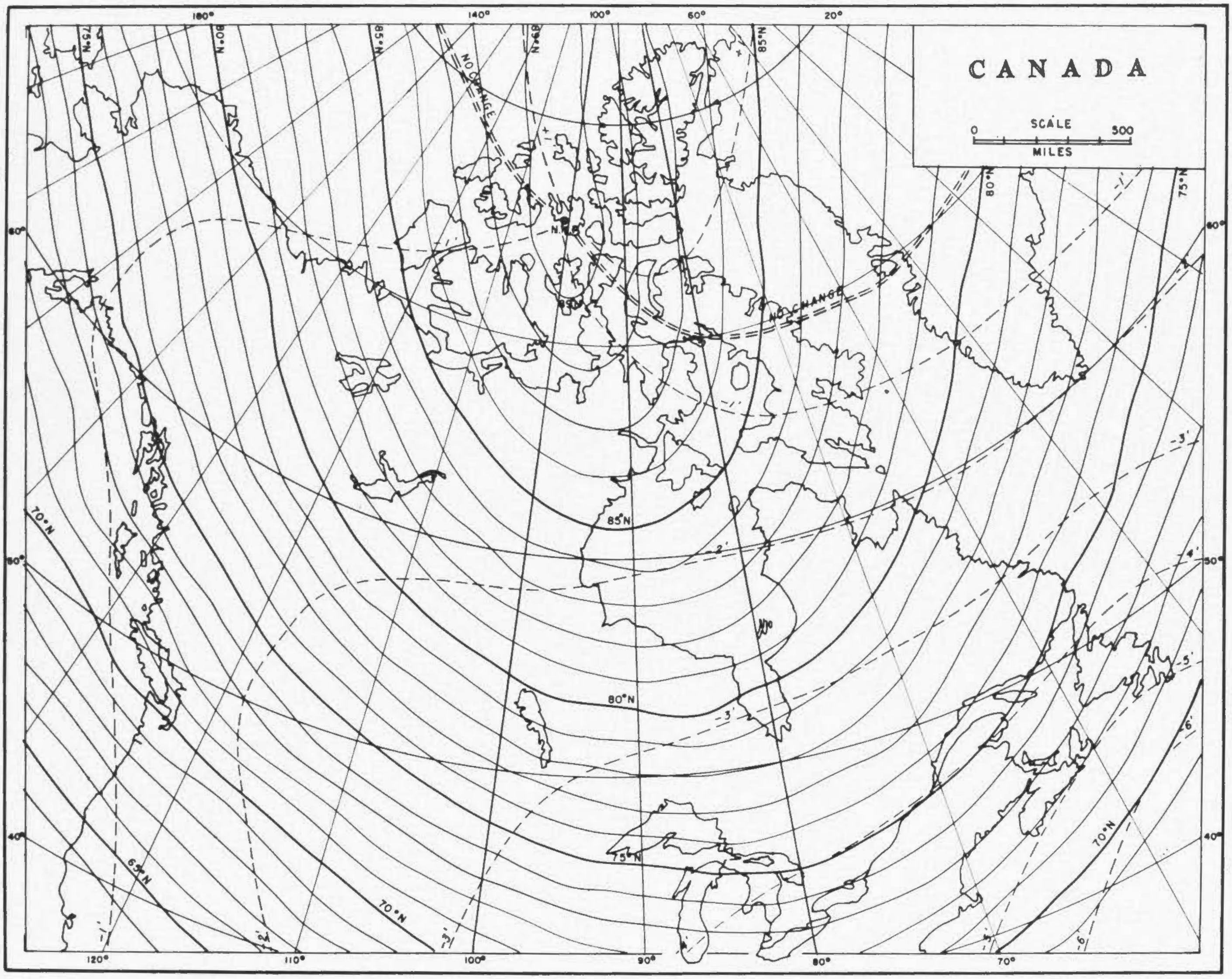
TOTAL INTENSITY (F) CANADA 1965·0



F 1965·0 F 1965·0

FIGURE 10.

MAGNETIC INCLINATION (I) CANADA 1965·0



I 1965·0

I 1965·0

FIGURE 11.

NORTH COMPONENT (X) OF THE HORIZONTAL INTENSITY .965·0

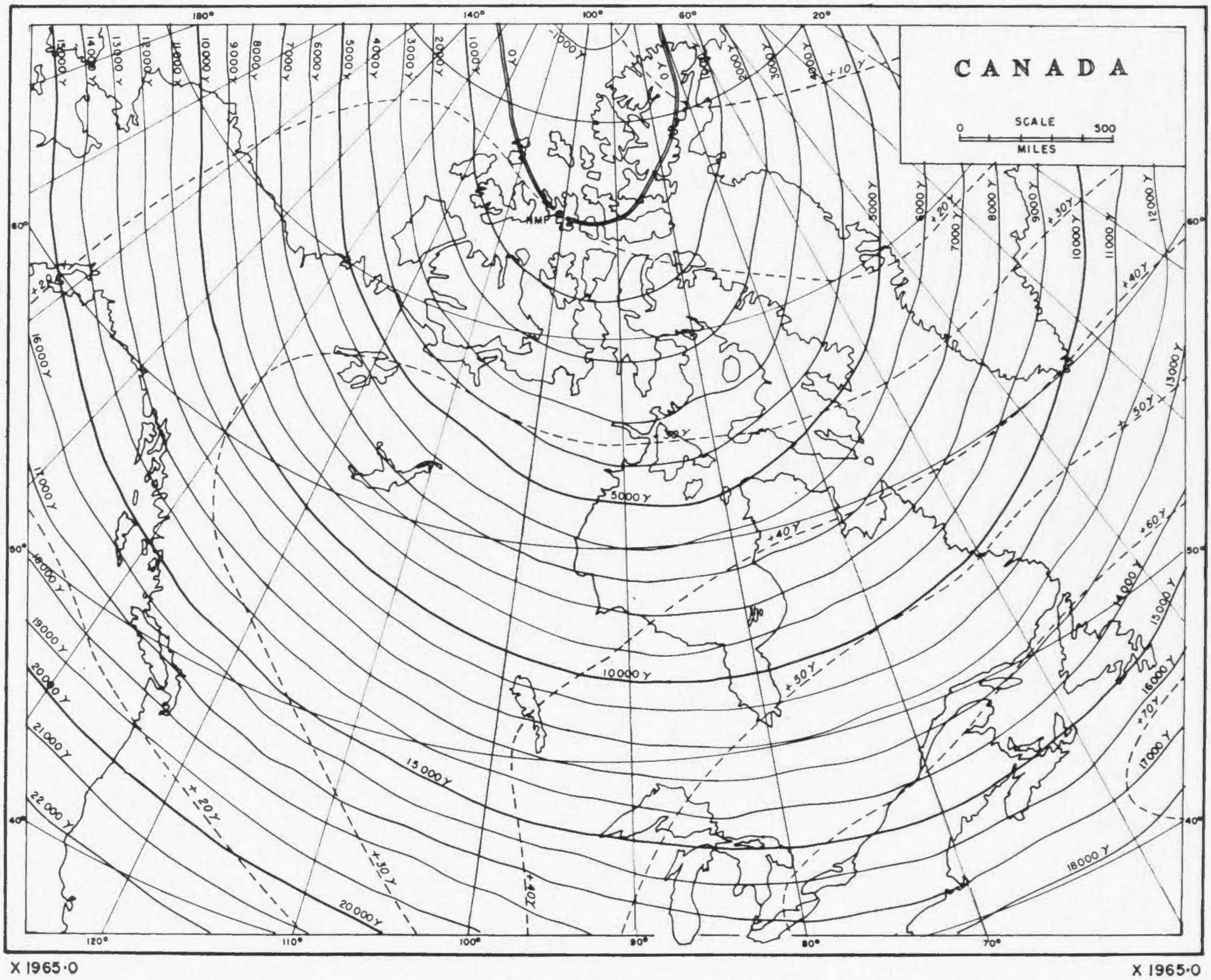
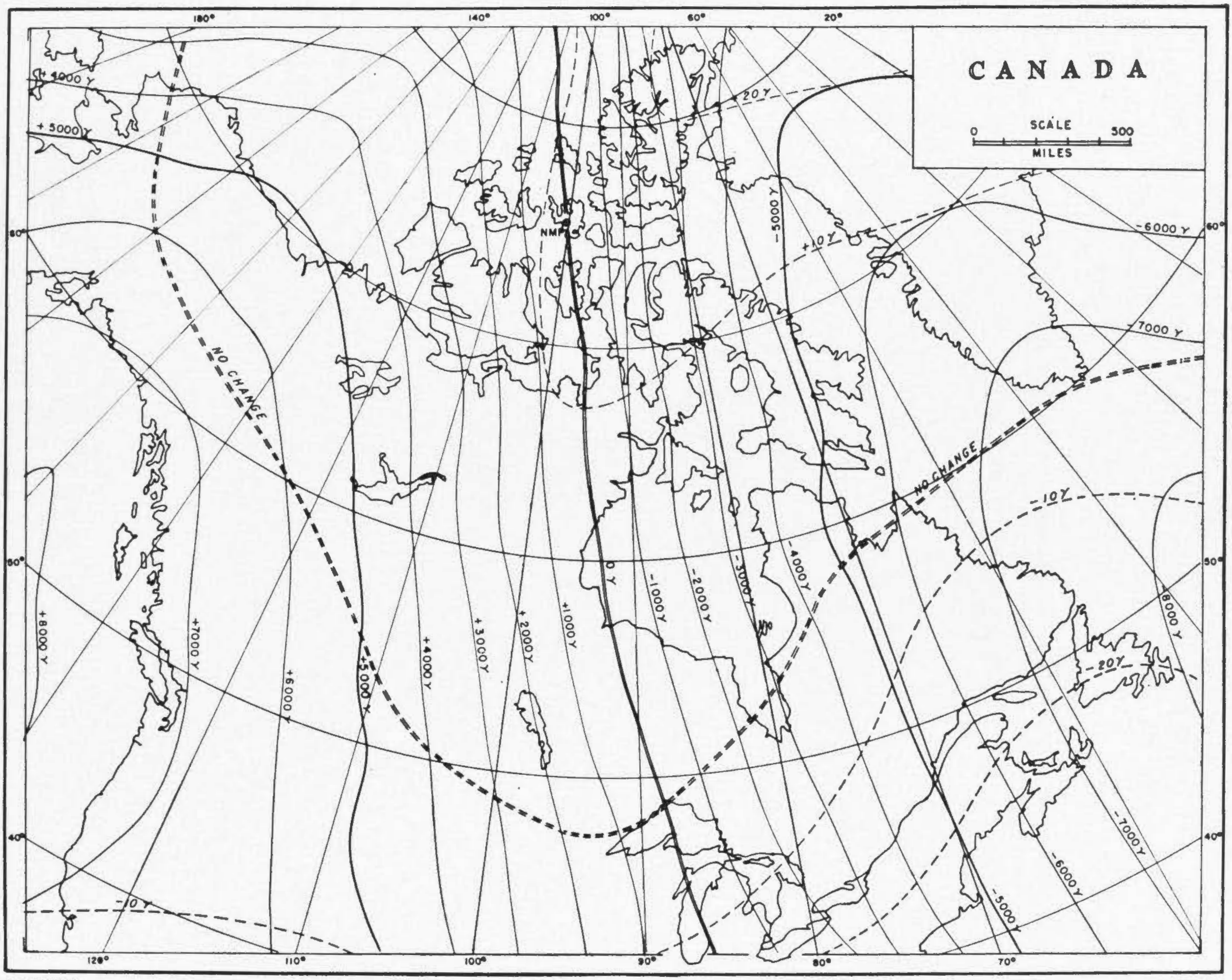


FIGURE 12.

EAST COMPONENT (Y) OF THE HORIZONTAL INTENSITY 1965·0



Y 1965·0 Y 1965·0

FIGURE 13.

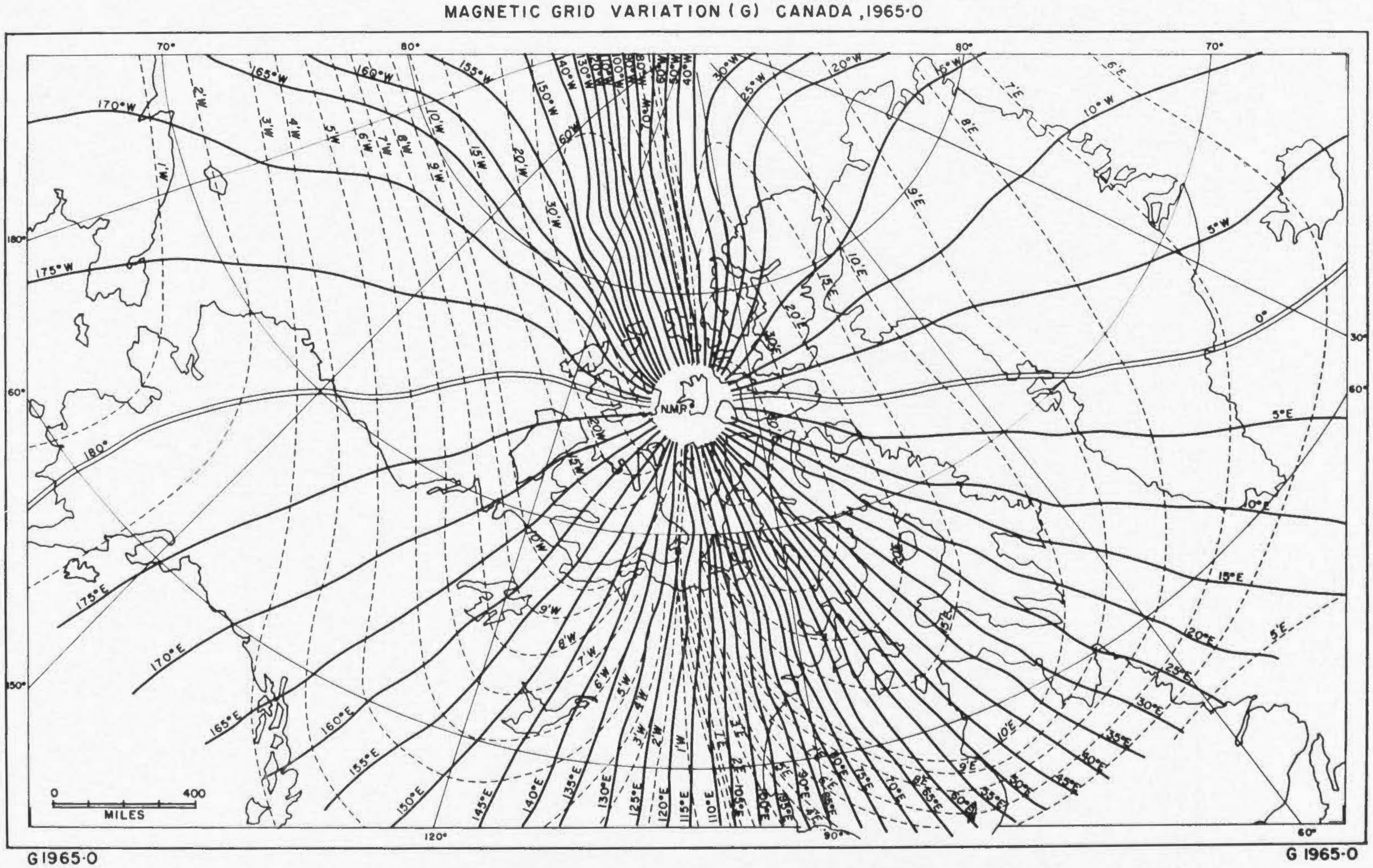

MAGNETIC GRID VARIATION (G) CANADA, 1965·0
N.M.P.
170°W
175°W
180°
175°E
170°E
165°E
160°E
155°E
150°E
145°E
140°E
135°E
130°E
125°E
120°E
115°E
110°E
165°W
160°W
155°W
150°W
140°W
130°W
60°W
30°W
25°W
20°W
10°W
5°W
0°
5°E
10°E
15°E
20°E
25°E
30°E
35°E
40°E
45°E
50°E
55°E
60°E
65°E
70°E
75°E
80°E
90°E
1°W
2°W
3°W
4°W
5°W
6°W
7°W
8°W
9°W
10°W
15°W
20°W
30°W
1°E
2°E
3°E
5°E
6°E
7°E
8°E
9°E
10°E
15°E
20°E
30°E
0
400
MILES
70°
80°
80°
70°
180°
60°
150°
120°
90°
60°
30°
60°
G1965·0
G 1965·0

FIGURE 14.

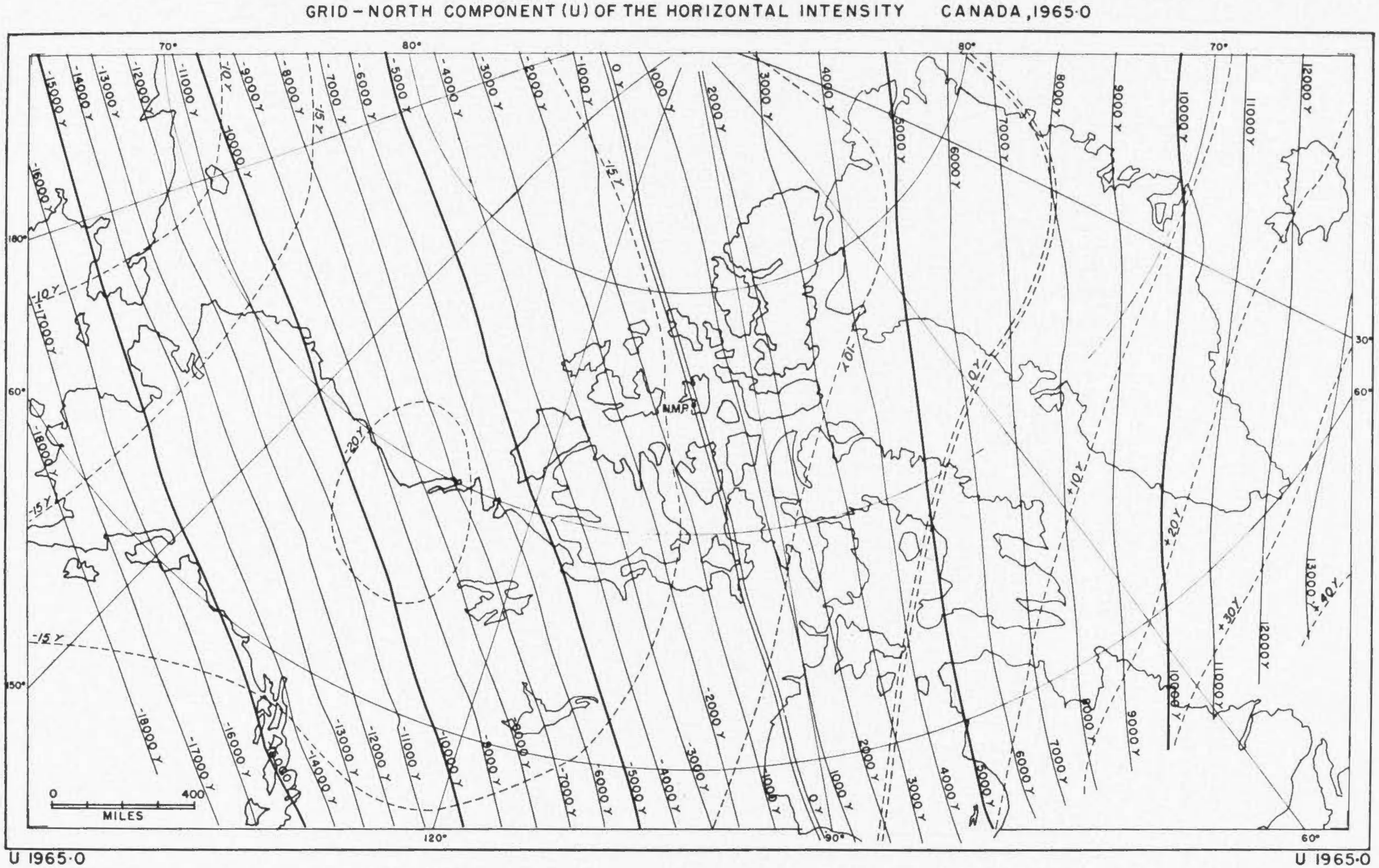
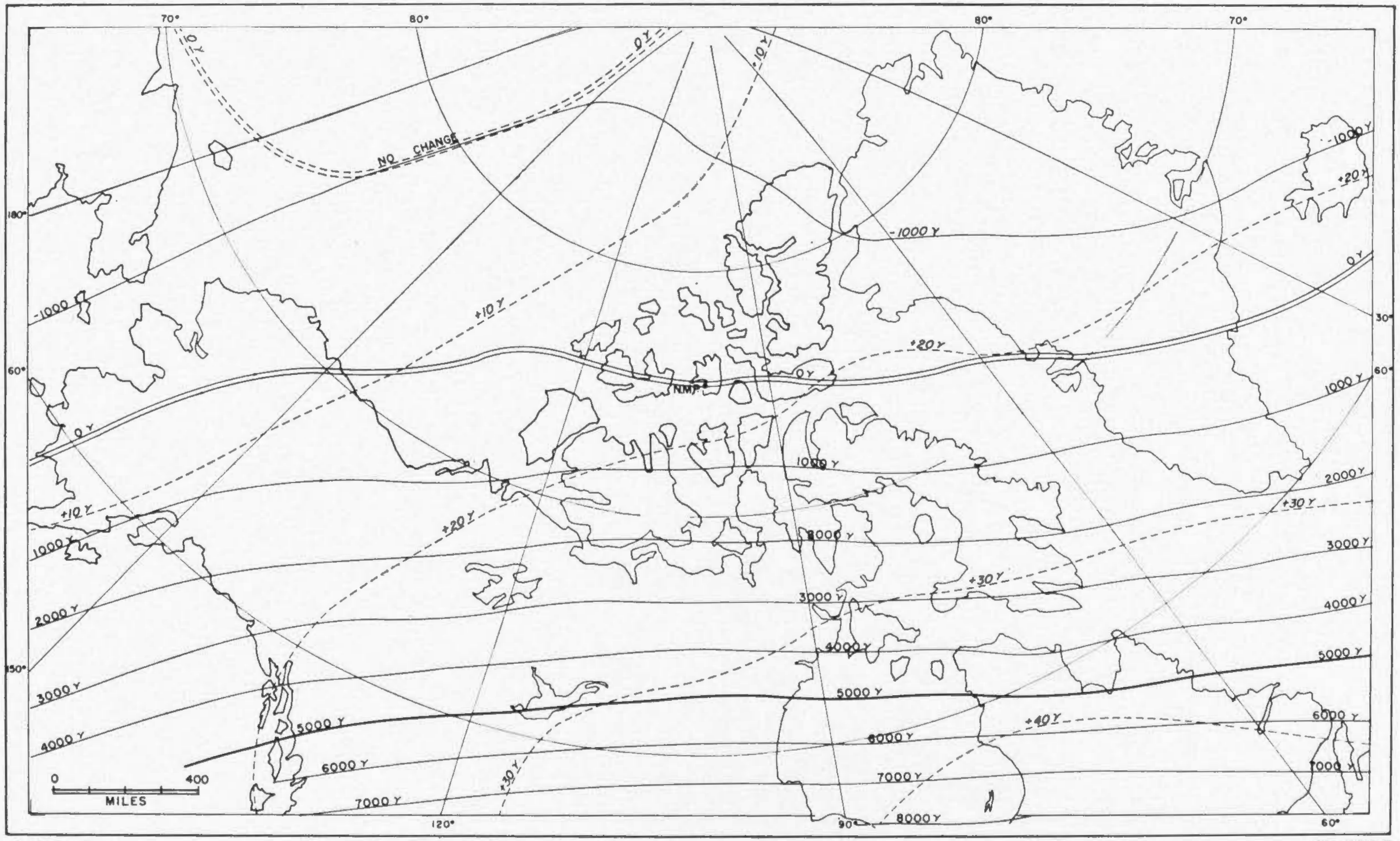

GRID – NORTH COMPONENT (U) OF THE HORIZONTAL INTENSITY CANADA, 1965·0
70°
80°
80°
70°
180°
60°
150°
120°
90°
60°
30°
60°
NMP
0
400
MILES
-15000 γ
-14000 γ
-13000 γ
-12000 γ
-11000 γ
-10 γ
-10000 γ
-9000 γ
-8000 γ
-15 γ
-7000 γ
-6000 γ
-5000 γ
-4000 γ
-3000 γ
-2000 γ
-1000 γ
0 γ
1000 γ
2000 γ
3000 γ
4000 γ
5000 γ
6000 γ
7000 γ
8000 γ
9000 γ
10000 γ
11000 γ
12000 γ
13000 γ
-16000 γ
-17000 γ
-18000 γ
-20 γ
+10 γ
+20 γ
+30 γ
+40 γ
U 1965·0
U 1965·0

FIGURE 15.

GRID_EAST COMPONENT (V) OF THE HORIZONTAL INTENSITY CANADA, 1965·0



V 1965·0

V 1965·0

FIGURE 16.

Conclusions

The present system of producing Canadian charts has many advantages. The programming steps are relatively simple. The system is adaptable to smaller computer systems such as the I.B.M. 1620. Large amounts of data are easily handled due to the various natural divisions in the program logic. Regarding the charts, the average residuals were lower than expected and represent a 20 per cent improvement over the 1955 set of charts for Canada.

However, there are still many disadvantages to this system. By using equal-area grid intervals, poorly mapped areas receive the same weight as those that are well mapped. While the use of the rejection criteria with mean values spaced 220 kilometres apart contributes a certain amount of smoothing, in the final analysis the method used is basically a graphic one and is subject to all the well-known objections to the graphic method. Programming continuity has to be interrupted while intermediate charts are constructed. More sophisticated methods will be tried in the future to see what improvements can be made.

In recent years, a great deal of work has been done by Cain and his associates (1964) in evaluating spherical harmonic descriptions of the main geomagnetic field.

In 1962, Cain (private correspondence) seeking a test for his fitting programs using vector data over a small area, experimented with updated 1960 Canadian data, approximately 12,000 values in D, H, Z. He determined a set of spherical harmonics that minimized the sums of $\Delta H^2 + (H \Delta D)^2 + \Delta Z^2$ for all the data. Here ΔD, ΔH, ΔZ are the differences between the observed and computed values. The following average residuals were obtained. The residuals decreased significantly going from n = 3 to 4 and there was very little improvement above n = m = 7 (63 coefficients). This led Cain to believe that the most useful fit to the data over this area is with n = 4. Charts in H,Z were plotted using the U.S. Weather Bureau automatic techniques. Although these smooth charts agreed quite favourably with preliminary charts of H,Z produced for Canada in 1960, except for a few small irregularities, the magnitude of the residuals is twice that obtainable with our present method. It appears that little improvement in the fit can be obtained without carrying the spherical harmonic analysis out to much higher orders, involving hundreds of coefficients.

	n=3	n=4	n=5	n=6	n=7
H ΔD	359.3æ	304.8æ	304.1æ	303.9æ	303.5æ
ΔH	347.4	294.8	293.4	297.5	290.6
ΔZ	295.1	243.9	238.7	236.1	236.1

From Heppner's review (1963) on field sources and the number of coefficients required to describe the earth's main field, it now appears that coefficients up to order 6 are necessary, and orders > 6 are attributed to crustal sources. An improvement in fit could probably be made by performing a separate analysis on the anomaly field by a method similar to that developed by Knapp (1942)

There are other analytical methods in current use. One of the oldest and still popular is the fitting of polynomial expressions to the observed data with coefficients to be determined by least-square approximations. To apply this method to Canadian data, a series of overlapping areas would have to be used. A system using a minimum of twenty equal areas is visualized with a unit area being equivalent to a 10 × 20° quadrangle at the equator. The area around the north magnetic pole would require a special treatment.

Figures 7-16 show that the families of isolines are quite uniform and suggest that simple geometric expressions might provide a realistic fit; for example, the fitting of a family of ellipses to the H and I isolines.

Fougere and McClay (1957) devised a method whereby the measured values of X, Y, Z and F are fitted to polynomials in latitude and longitude in such a way that the radial component of the curl F vanishes identically and $F^2 = X^2 + Y^2 + Z^2$ is satisfied identically. Fougere (1964) presented an improvement over part of this method, in which the horizontal vector is expanded in a set of orthogonal functions. These orthogonal functions can be tested for statistical significance by the variance ratio test in order to obtain the best representation of the data with vanishing curl. The final result is a pair of simple polynomials in X and Y. He applied the method to a sample of data consisting of observations of the field at 69 locations above Eglin Air Force Base in Florida. Over the small area chosen (200 sq. miles) the standard error is about 91 γ.

Pochtarev and Vints (1962) developed a method which they claim is more objective than the graphical method and less formal than the analytical method. The method determines the normal field containing only the long wave-length anomalies and eliminates the local anomaly effect. This is achieved by computing the field at an altitude where these local effects are completely attenuated. Their studies showed that to eliminate anomalies up to 200 kms in extent, an altitude of 50 kms was necessary. The field was computed by solution of the Dirichlet-Neumann problem in the form of a Poisson integral for the potential function

$$U_p = \frac{R^2 - R_o^2}{4\pi R_o} \int \frac{\bar{U}}{P^3} \, d\sigma$$

Mathematical descriptions of the earth's field are extremely useful, particularly in this present space-oriented age, for extrapolating the field to greater altitudes. There are other methods however that have more physical meaning, such as the use of a central dipole with radial dipoles placed at the core-mantle interface, approximating electrical loops. It is not the authors' intention to review these methods but we would like to mention briefly the very good fit in H,Z and magnetic meridians that Alldredge and Van Voorhis (1962) obtained using this method to explain the observed features of the great Arctic anomaly. They did not try to adjust the magnitudes and locations of the radial dipoles by a least-squares procedure to obtain a better fit with the observed field, since their main goal was to show that the magnetic patterns observed in the Arctic could be explained by very deep seated sources as opposed to crustal geological explanations.

Alldredge and Hurwitz (1964) used a least-squares method to adjust the amplitude and location of each dipole for a best fit to the observed field components. Using various models, they were able to produce a fit to the U.S. 1945 world charts almost as good as Vestine's mathematical representation using 48 spherical harmonic coefficients. Other models obtained excellent fits to the 1955 U.S. and British Admiralty world charts.

With the volume of observations now available, it is apparent that the problem of producing accurate Canadian magnetic charts is primarily a data-handling one. Since the ultimate aim is to produce accurate charts which best fit the observed data, many of the methods listed above will be tried with our present updated observations to determine which method is most suitable for future chart production.

The fundamental problem in magnetic cartography today is to obtain a mathematical description of secular change. Our present graphical system, as stated earlier, yields probable errors of ±4′ in D and approximately ±20 γ in H and Z over an 18-year reduction period. Any improvement on this, with the present data, will have to come from a different approach.

The laws of physics demand that the secular change field have smooth continuity in the space-time continuum. At any one time, the rate of change is a single-valued function of space with continuous derivatives, and at any one point in space, a typical component is a continuous single-valued function of time with continuous derivatives. The problem is to find a practical expression of this function.

With our present system the rate of change is considered constant over a 5-year period. Thus at a fixed point, where the field is a function of time alone, this function is represented by a series of straight-line segments, and the laws of continuity are subverted in order to find a simple but workable solution.

Hutchison et al. (1953) in an unpublished paper on the secular field in Canada treated the field at each point as a continuous function of time having the forms of a Fourier series. They analysed components of X, Y and Z for six observatories and some 200 repeat stations. The equations had the form

$$X(t) = X_o + A_o (t-t_o) + A_1 \cos\omega (t-a_1) + A_2 \cos 2\omega (t-a_2) + \ldots$$

$$Y(t) = Y_o + B_o (t-t_o) + B_1 \cos\omega (t-a_1) + B_2 \cos 2\omega (t-a_2) + \ldots$$

$$Z(t) = Z_o + C_o (t-t_o) + C_1 \cos\omega (t-t_1) + C_2 \cos 2\omega (t-a_2) + \ldots$$

where X_o, Y_o, and Z_o are the values of the element at the time of the observation. It was found that X(t), Y(t) both exhibited a fundamental period of 133 years and one harmonic period of 67 years, while the expression for Z(t) required only a single periodic term of 50 years. There was no real physical significance attached to these periods but they were introduced only as a mathematical convenience for reducing Canadian observations to epoch.

The residuals obtained on fitting the observed values to the mathematical expressions were unfortunately high; 90 per cent of the values in X, Y and 65 per cent in Z had residuals of 100 γ's or better. However this analysis was done under considerable handicaps. The secular change data was limited. Owing to the lack of computer facilities, many graphical approximations were used, thus limiting the accuracy of the results. The authors feel that with the availability of these facilities a more refined approach may lead to expressions describing the secular change field much more accurately, over a limited period.

There are, of course, other mathematical approaches for determining secular change, of which spherical harmonic analysis of time derivatives is the most common. Alldredge and Hurwitz (1964) determined secular change from two sets of dipole parameters for the United States charts for epochs 1945 and 1955. Although they were able to obtain a mathematical description of secular change based on changes in the parameters of a dipole set, the changes shown were not much larger than the scatter for the three different sets of 1955 parameters.

Even though, at the present, our repeat station observations consist of reliable means of the day values only, the future seems promising for better secular-change determinations in Canada. There are now eight well-distributed observatories throughout the country plus the possibility of one more establishment in the not too distant future. We also share the benefits of eight other observatories in adjacent areas. The difficulties of reducing repeat station observations to a satisfactory epochal value are being overcome. Whitham and Loomer (1957) have expressed fears that programs of repeat observations, at infrequent intervals over short durations are of doubtful use in the Arctic. Certainly the curves of secular variation for repeat stations in the lower latitudes suggest that the procedure is satisfactory, and only time will tell whether or not a regular program of observations will be of similar value in the Arctic.

Acknowledgments

The mapping programs were carried out by the Departmental Computing Centre under the able guidance of the officer-in-charge Mr. K. Shimizu. In particular, the authors would like to thank Miss Mabel Grieve, who was directly responsible for these programs.

The magnetic data shown on Figure 1 was plotted by the staff of the Canadian Army Survey Establishment, Ottawa, on their AERO-Digitork plotter.

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Appendix I

In 1960 the Canadian Hydrographic Service requested an outline of the behaviour of magnetic compasses in the Arctic, particularly in the vicinity of the north magnetic pole. Also required was a definition of the area in which magnetic compasses are valueless, the magnitude of the fluctuation in variation and the frequency and effect of magnetic disturbances. Since these notes would be of great value to a mariner they were to be included in *Pilot of Arctic Canada*, a compilation of sailing directions for the Canadian Arctic.

It was decided that a chart outlining this information would make the most effective presentation. Thus was born the "Magnetic Chart of the Canadian Arctic, 1960.0". The new chart for 1965.0 is shown as Figure 17. A note incorporated in the legend of the published chart (not shown on Fig. 17) states the following:

> Most days are magnetically disturbed in the Arctic; at Resolute Bay only 1 day in 5 is classified as reasonably quiet magnetically and only 1 day in 14 as very quiet.
>
> During moderate magnetic disturbances the daily track of the North Magnetic Pole approximates an ellipse with a major axis 30 miles long roughly north-south and a minor axis of about 18 miles roughly east-west. During a severe disturbance, its effective position can shift between 50 and 100 miles.
>
> The magnetic variation at any one place fluctuates and the amount of this fluctuation is shown on the chart as the Mean Daily Range of Magnetic Variation. These data are based on hourly mean values obtained from five northern magnetic observatories at Resolute Bay, Baker Lake, Alert, Mould Bay and Churchill, for the summer months of 1964, a period of sunspot minimum; during periods of magnetic disturbance, the values shown may be doubled for brief periods.

The chart for 1965 was compiled in the following way:

> Where $H < 6000\ \gamma$, the ordinary magnetic compass is erratic.
> Where $H < 3000\ \gamma$, the ordinary magnetic compass is useless.
> (International Hydrographic Conference, 1962).

The 1965 H-isolines were used to outline these areas.

Since ships operate in these areas in the summer months only, the D range in the mean hourly values for the summer of 1964 was examined for the five northern observatories mentioned in the note. The values obtained were used in conjunction with the 1965 H-isolines to derive the lines of equal mean daily range of magnetic variation, using the simple equation

$$r_D = \frac{R_D \cdot H_O}{H}$$

Where R_D is the D range for the observatory,
H_O is the chart value of H at the observatory,
and r_D, the D range at any point on the H-chart.

MAGNETIC CHART OF THE CANADIAN ARCTIC 1965·0

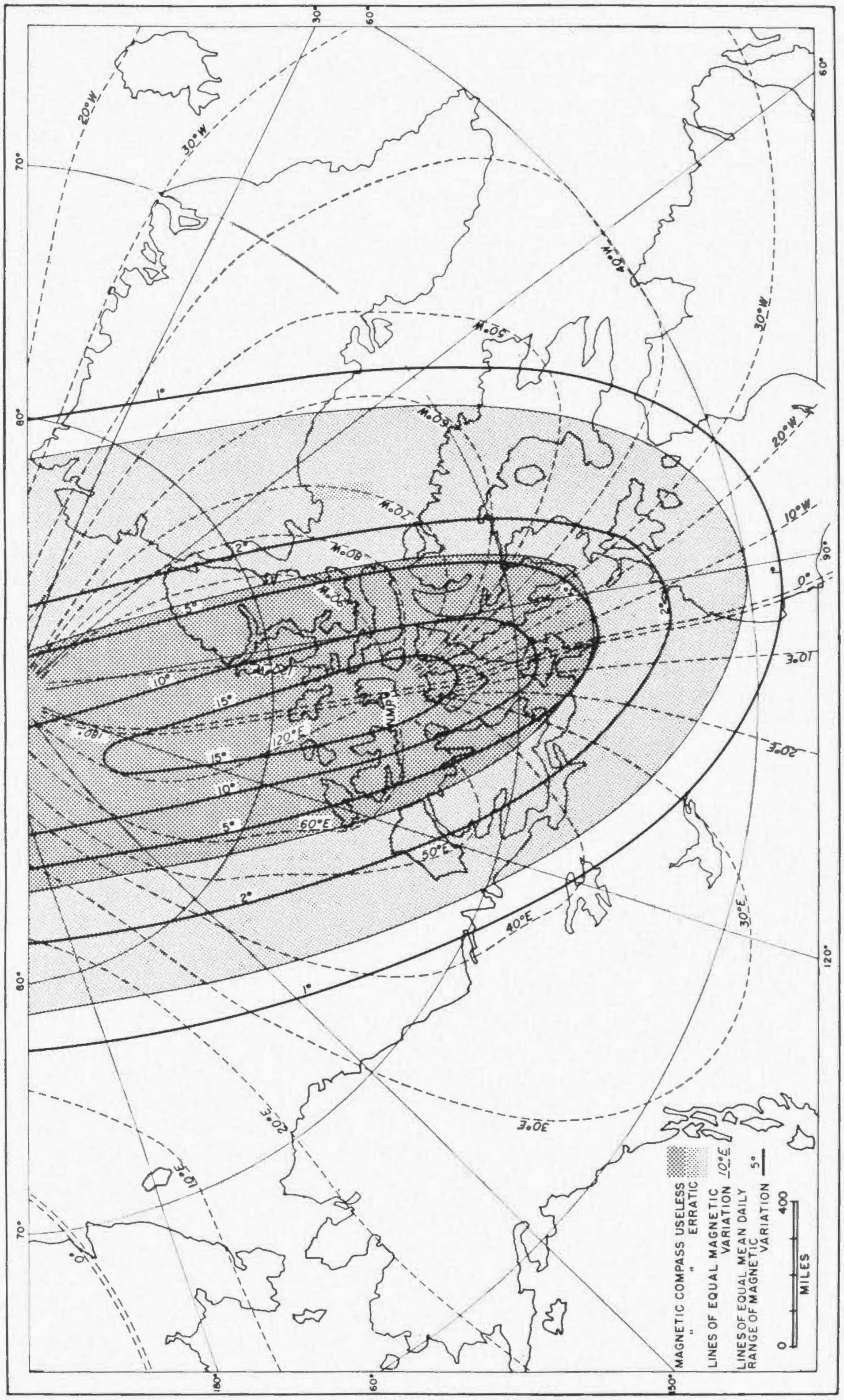

FIGURE 17.

Appendix II

TABLE VII

COMPENDIUM OF CANADIAN MAGNETIC CHARTS PRODUCED SINCE 1883

Chart	Area	Epoch	Scale Mi/in	No. of Stns.	Compiling Agency	Notes
D, I, F	Canada	1844	100	300	Lefroy	south of 60°N, produced in 4 sections
D	W. Canada	1904.0	——	——	T.S.	D.L.S. use only
D	W. Canada E. Canada	1911.0	100	4,500	T.S.	in two sections
D	W. Canada	1912.0	35	4,000	T.S.	
D	W. Canada	1914.0	300	6,800	T.S.	produced in 2 sections
D, $\dot{D}$	W. Canada	1917.0	100	9,400	T.S.	first graphical showing of secular change up to 60°N; all future charts to show isopors
I, $\dot{I}$	W. Canada	1917.0	100	900	T.S.	
H, $\dot{H}$	W. Canada	1917.0	100	900	T.S.	
D	W. Canada	1922.0	100	20,000	T.S.	first Canadian magnetic chart showing location of NMP on northern end of King William Island
I	W. Canada	1922.0	197.3	1,200	T.S.	
H	W. Canada	1922.0	197.3	1,200	T.S.	
D	Canada	1922.0	100	——	T.S.	
D	Canada	1927.0	100	24,000	T.S.	
I	Canada	1927.0	300	1,700	T.S.	
D	Canada	1932.0	100	30,000	T.S.	
H	Canada	1932.0	300	3,750	T.S.	
D, $\dot{D}$	Canada	1940.0	100	——	S.E.B.	Surveys and engineering Br.
D.I.H. Mag. Mer.	Polar	1942.5	100	——	Dom.Obs.	Gnomonic projection
D	N.W.T., Yukon	1948.5	80	——	Dom.Obs.	
D	Canada	1948.5	100	——	Dom.Obs.	
D	Canada	1955.0	100	20,000	Dom.Obs.	
I, H, Z, F	Canada	1955.0	100	2,000	Dom.Obs.	
D	Man.	1955.0	20	3,470	Dom.Obs.	compiled mainly from D observations made by T.S.
D	Sask.	1955.0	20	6,250	Dom.Obs.	
D	Alta.	1955.0	20	6,650	Dom.Obs.	
D	Canada	1960.0	100	24,000	Dom.Obs.	including 5,000 airborne observations
Special	Arctic Canada	1960	137.5		Dom.Obs.	
D, I, H, Z, F	Canada	1965.0	100	18,000	Dom.Obs.	Observations from 1947 on
Special	Arctic Canada	1965.0	120		Dom.Obs.	