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MAGNETIC ANOMALY MAPS OF THE NORDIC COUNTRIES AND THE GREENLAND AND NORWEGIAN SEAS

G. V. Haines, W. Hannaford and P. H. Serson

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ABSTRACT: A three-component aeromagnetic survey of the Nordic countries and the Greenland and Norwegian seas was carried out in the fall of 1965. The survey data was processed to yield averages over one half minute of time, or roughly 3.5 km of flight track. A regional field, in the form of a third degree polynomial, was removed from the data, and the resulting '½-minute residuals' were plotted by computer. These residuals are represented in three ways: as residual profiles, for each magnetic component; as two-dimensional vector residuals, in two orthogonal planes; and as segments of contour lines. Attention is drawn to several large anomaly systems, although no interpretation is attempted.

RÉSUMÉ: On a effectué à l'automne de 1965 des levés aéromagnétiques à trois composantes dans les pays nordiques et au-dessus de la mer du Groenland et de la mer de Norvège. Les données ont été traitées de façon à fournir des moyennes de plus d'une demi-minute de temps, ou environ 3.5 kilomètres de vol. On a retiré des données un champ régional sous forme d'un polynôme du troisième degré, et les résultantes ≪résiduelles d'une demi-minute≫ ont été tracées par ordinateur. Ces résiduelles sont représentées de trois façons: profils résiduels pour chaque composante magnétique; résiduelles de vecteur à deux dimensions, en deux plans orthogonaux, et segments de courbes de niveau. L'auteur mentionne plusieurs importants systèmes d'anomalies sans toutefois tenter de les interpréter.

Introduction

In the fall of 1965, between September 13 and November 16, the Dominion Observatory conducted a three-component aeromagnetic survey of Greenland, the Greenland and Norwegian seas, Iceland, Norway, Sweden, Finland and Denmark (Figures 1-3). A DC6 aircraft was chartered from Pacific Western Airlines, together with a six-member crew. The magnetometer and direction-reference system were designed and built at the Dominion Observatory, and have been described by Serson, *et al.* (1957) and Hannaford, *et al.* (1967). The magnetometer system was operated by five scientists of the Dominion Observatory. The cost of the aircraft charter was shared by the governments of Canada, Norway, Sweden, Finland and Denmark.

For convenience, the survey has been divided into three areas: (i) the Greenland Survey, consisting of Greenland above 65°N, the Greenland Sea, the Norwegian Sea and Spitsbergen (Figure 1); (ii) the Iceland Survey, consisting of Iceland and the Reykjanes Ridge above latitude 62°N (Figure 2); and (iii) the Scandinavian Survey, consisting of Norway, Sweden, Finland, Denmark and the Gulf of Bothnia (Figure 3).

Various statistics concerning these three surveys are given in Table 1. The total number of kilometres flown (including calibration flights) was 126,000, and the total area covered was approximately 7 million square km.

The Data

The magnetic elements measured were the declination D, the horizontal intensity H, the vertical intensity Z, and the total force F. The measurements of F were more accurate than those of H and Z, and so the vertical force Z was derived from F and H whenever these were available. The methods used in correcting these data for aircraft fields and reducing them to a common altitude (viz., sea level) have been described by Hannaford and Haines (1969). The data have not been corrected for daily variation, for secular variation, or for magnetic disturbances. (However, this is at present being done for the Scandinavian Survey by the respective countries involved; see, for example, Sucksdorff, *et al.* (1968).)

Positions, approximately 20 minutes apart, are provided by the navigator at the end of the survey, and usually have an accuracy of 1 to 5 km. To obtain a position at any time between these given positions the assumptions are made that the ground velocity of the aircraft is constant during the 20-minute interval, and that the flight track during this time interval forms an arc of a great circle. The desired position is then given by a linear interpolation along this arc, and has a probable accuracy of ±5 km.

The magnetic data from the 1965 survey exist in the following forms:

(i) Continuous strip-chart records of D,H,Z and F, obtained during flight, not corrected for aircraft fields or altitude.

(ii) Five-minute averages of D, H and Z, on punched cards, corrected for aircraft fields but not corrected for altitude; referred to as 'source data'.

(iii) Five-minute averages of D,H,Z,X,Y,I and F, on punched cards, corrected for aircraft fields and for altitude; referred to as 'altitude-corrected data'.

(iv) Half-minute averages of D,H,Z,X,Y and F on digital magnetic tape, corrected for aircraft fields and altitude.

The 5-minute averages of D,H and Z were derived in flight by sampling the elements every 3 seconds with a digital voltmeter, and totalling 100 samples in three digital counters. The resulting averages were later corrected by computer to yield (ii) and (iii). The individual samples were also recorded on digital magnetic tape at 3-second intervals, but gaps and errors on the tape made it difficult to read. Consequently, the ½-minute averages (iv) were derived by

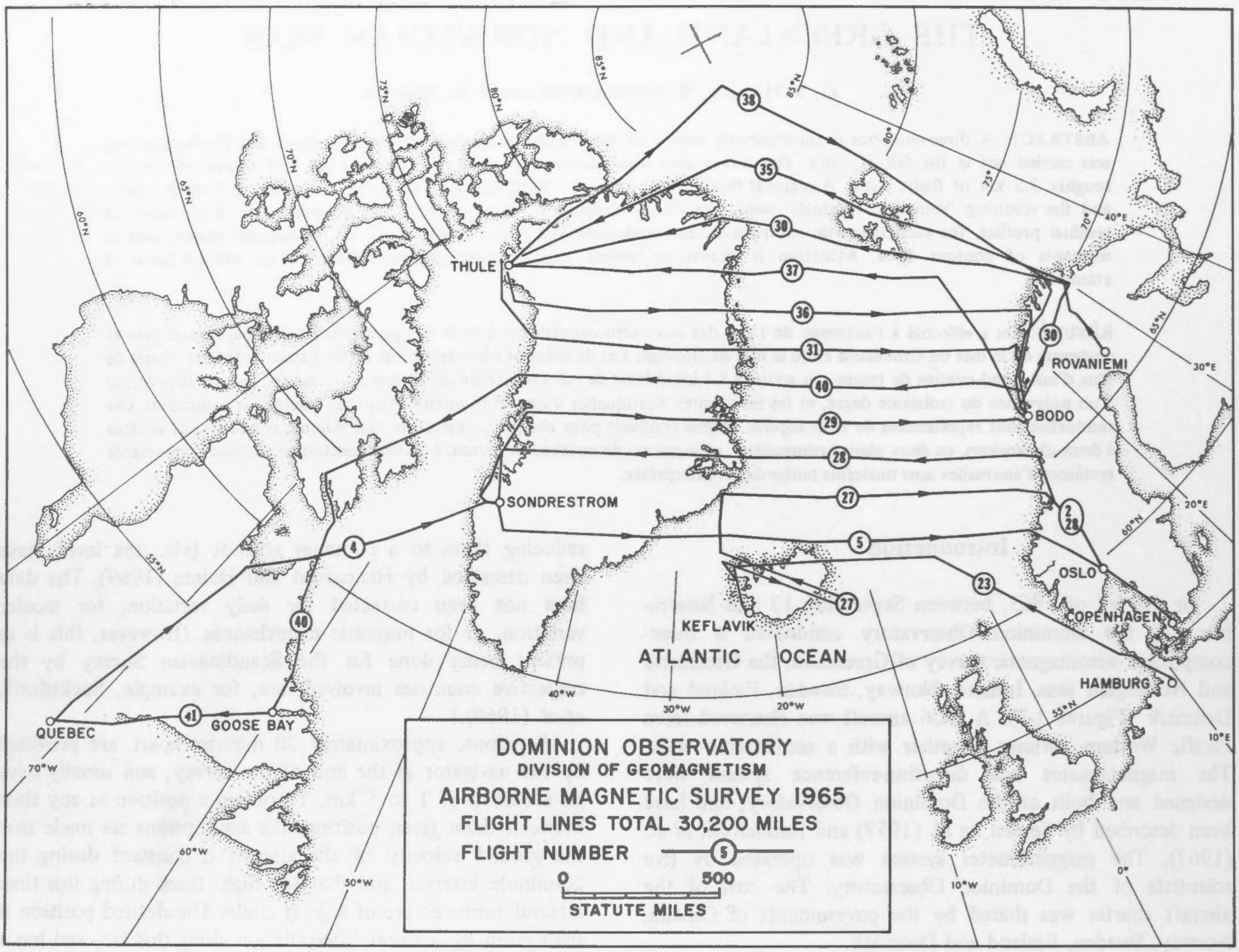

FIGURE 1. The Greenland Survey, 1965. Flight numbers and directions are shown.

Table 1

SOME STATISTICS OF THE DOMINION OBSERVATORY AEROMAGNETIC SURVEY, 1965

	Greenland	Iceland	Scandinavia
Flight-line spacing (km)	180	35	35
Line-kilometers flown	48,500	13,200	64,400
Area covered ($km^2 \times 10^6$)	5	0.4	1.5
Flight altitudes (km)	4.5 – 5.3	3.0 – 4.1	3.0 – 4.5
Average flight altitude (km)	5	3	3
Date survey conducted	Sept. 13-Sept. 20 Oct. 16-Nov. 15	Oct. 17-Oct. 25	Sept. 22-Oct. 16

manual scaling of the analog records (i), and applying corrections by computer.

The 5-minute averages represent the mean field over segments of the flight track about 35 km long, roughly equal to the distance between adjacent flight lines in the Scandinavian and Iceland surveys. The interval over which the ½-minute averages are taken is about 3.5 km, roughly equal to the altitude of observation, and of the same order as the uncertainty in geographical position.

The corrections applied to reduce the data from the altitude of observation to sea level are based on the assumption that the vertical gradient in any geomagnetic component P is given by the equation

$$\partial P / \partial r = -(3/a)\,P$$

where r is the distance from the centre of the earth and a is the radius of the earth. The resulting correction is

$$\Delta P = 4.6 \times 10^{-4}\,P\,h$$

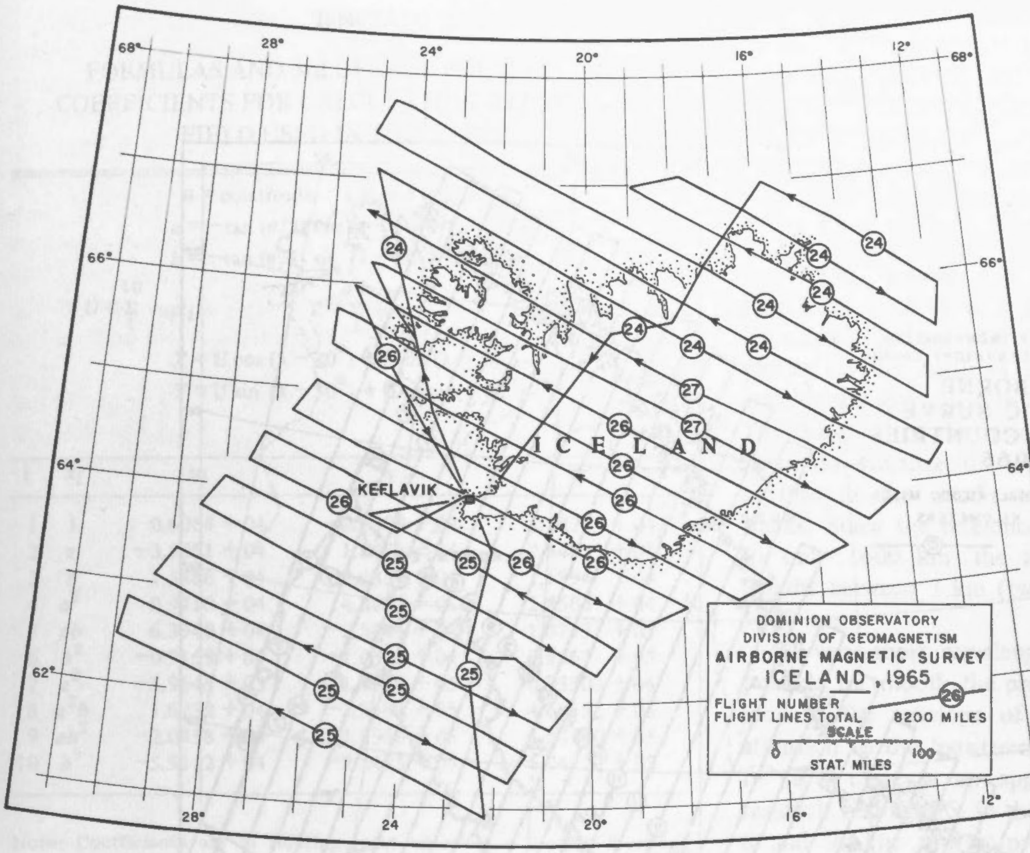

FIGURE 2. The Iceland Survey, 1965.

where *h* is the altitude of observation above sea level, in km. Haines (1968) has estimated the actual vertical gradients in the various components over Scandinavia from the horizontal gradients of the field, and has shown that the average error in using the above approximation is less than 10 γ. The approximate correction was therefore used for simplicity.

The Main and Anomaly Fields

A geomagnetic measurement can be considered as having three components of information.

(i) Information of long wavelength, arising from electric currents in the core.
(ii) Information of short wavelength, arising from the magnetization of rocks above the Curie point isotherm.
(iii) Noise, which is a result of instrumental errors, navigational errors, errors in corrections applied to the raw data, and variability in the magnetic field caused by diurnal and disturbance fields.

Information of intermediate wavelength appears to be of very small amplitude (Alldredge and Van Voorhis, 1961), implying that the mantle is a forbidden region for magnetic sources.

Alldredge, *et al.* (1963) have shown that in describing the main part of the earth's field, wavelengths smaller than 4000 km are probably not required. Bullard (1967) has suggested that wavelengths over 5000 km are probably adequate in representing the fields produced in the core, and that wavelengths less than 2000 km probably should be retained in the residual, or anomaly, field.

Polynomial Analysis and Representation of the Anomaly Field

A 3rd degree polynomial was fitted, by the method of least squares, to all the 1965 survey five-minute averages (corrected for aircraft fields and altitude), in each of three orthogonal magnetic components. Two components were referred to the Greenwich Grid system, and the third one to the vertical. These three polynomials represent the main, or long wavelength, part of the earth's magnetic field, and probably do not contain wavelengths less than 1600 km. The complement of this polynomial-derived field, the 'residual field', will then represent the anomaly, or short-wavelength, part of the earth's field.

The coefficients of these reference polynomials and the formulas required to calculate magnetic components from them are given in Table 2A. In Table 2B are listed the RMS errors of the 3rd degree polynomial estimates, together with the corresponding errors for 1st and 2nd degree polynomials. There is a very significant reduction in carrying the degree of the polynomial from 2 to 3, as would be expected for an area of 7 million square kilometres.

It should be emphasized that the polynomial reference field used in this paper differs from that used in the papers by Haines (1968) and Hannaford and Haines (1969). In the

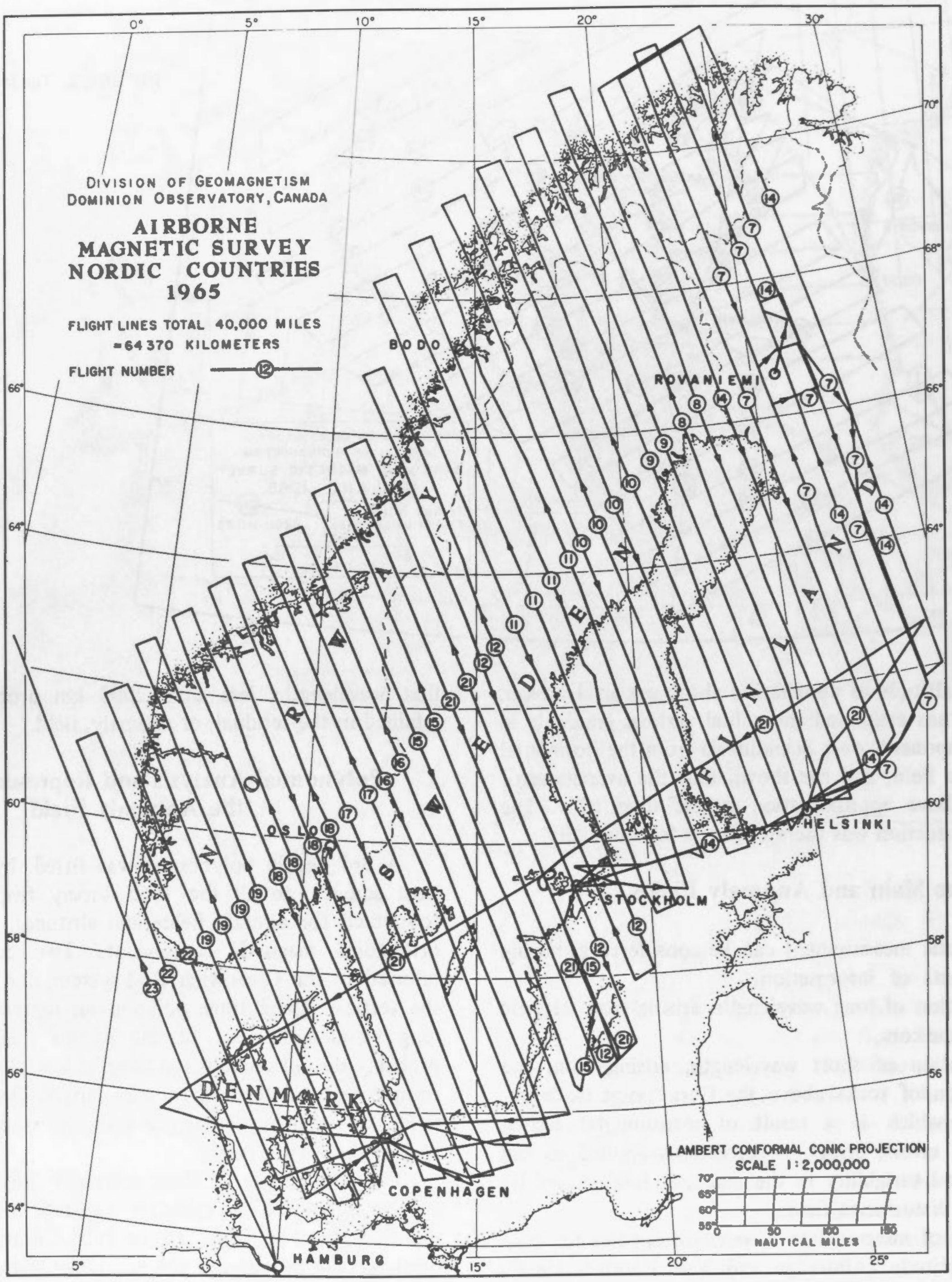

FIGURE 3. The Scandinavian Survey, 1965.

Table 2A

FORMULAS AND 3rd DEGREE POLYNOMIAL COEFFICIENTS FOR CALCULATING REFERENCE FIELD USED IN THIS PAPER

θ = colatitude λ = east longitude

$$a = -\tan(\theta/2)\cos(\lambda - 30^\circ) + .11319$$
$$b = \tan(\theta/2)\sin(\lambda - 30^\circ) - .03460$$
$$U = \sum_1^{10} u_i x_i \qquad V = \sum_1^{10} v_i x_i \qquad Z = \sum_1^{10} z_i x_i$$
$$X = U\cos(\lambda - 30^\circ) - V\sin(\lambda - 30^\circ)$$
$$Y = U\sin(\lambda - 30^\circ) + V\cos(\lambda - 30^\circ)$$

i	x_i	u_i	v_i	z_i
1	1	0.6054 +04	−0.5609 +04	5.2829 +04
2	a	−3.5051 +04	1.5956 +04	2.3483 +04
3	b	1.5486 +04	−2.2350 +04	−2.1994 +04
4	a^2	0.9710 +04	4.8632 +04	2.8503 +04
5	ab	6.3340 +04	−2.5441 +04	1.0713 +05
6	b^2	−0.9169 +04	−1.0533 +04	0.5367 +05
7	a^3	−1.9645 +05	1.4788 +05	0.33303 +06
8	a^2b	1.6732 +04	−2.3667 +05	4.69555 +05
9	ab^2	−2.0458 +05	−1.5968 +05	1.37200 +05
10	b^3	−5.9162 +04	−2.2485 +05	−0.74777 +05

Note: Coefficients are in floating-point notation, a decimal fraction followed by a power of ten.

Table 2B

THE RMS ERRORS IN THE 3RD DEGREE POLYNOMIALS OF TABLE 2A, AND THE IMPROVEMENT OBTAINED OVER 1ST AND 2ND DEGREE POLYNOMIALS

	U	*V*	*Z*	*D*	*H*	*X*	*Y*
Observations	2292	2292	2342	2292	2336	2292	2292
1st degree	296 γ	273 γ	432 γ	2.1°	265 γ	309 γ	257 γ
2nd degree	166	233	188	1.3	148	174	226
3rd degree	130	118	155	0.7	116	117	130

latter papers separate polynomials were obtained for each of the three survey areas: The Greenland area, the Scandinavian area and the Iceland area. By dividing the total area into these three parts a much better representation could be made for each data area, an important consideration when initially checking the data for aircraft-heading effects and other errors. In this paper, on the other hand, a more important consideration seemed to be that the residual charts match up at the edges, so that one can move visually from one area to another without encountering any discontinuity in the residual profile. The price to be paid for this convenience, of course, is the presence of higher-wavelength anomalies in the residual charts.

The anomaly field obtained by subtracting the polynomial reference field from the ½-minute averages has been represented in three ways:

(i) Residual profile maps, in which this anomaly field is plotted perpendicular to the flight track at the point where the ½-minute average was made.

(ii) Vector residual maps, in which the anomaly field is plotted as a two-dimensinal vector.

(iii) Maps of zero gradient of the magnetic component lying along the flight track.

Residual profile maps of D,H,X,Y,Z and F are given in Figures 4-9, 13-18 and 22-27 for the three survey areas, Greenland, Iceland and Scandinavia. Positive residuals are plotted to the north of the flight track on the Greenland and Iceland maps, and to the east on the Scandinavian maps. The 'baseline' of the residual profiles is thus the flight track itself: to visualize the anomaly surface, merely rotate the profiles in the mind's eye through 90° about the flight tracks. Since the reference field removed wavelengths down to only 1600 km, the anomaly field may contain wavelengths between 7 km (twice the measurement interval) and 1600 km.

If very short wavelengths are of interest, it is naturally possible to smooth the profiles by eye; hence it is correct to look at the envelope of the profiles and not give undue attention to the 'positiveness' or 'negativeness' of the curves. In fact, there is an apparent dc error in the Z and F residuals of Flight 5, in the lower left hand corner of Figures 8 and 9. The proton precession F-magnetometer was not operating during this flight, and thus there were no checks on the fluxgate Z-measurements as there were on other flights.

When survey lines are widely spaced, a graphical presentation by residual profiles has the following advantages over contour charts. contouring requires some assumption concerning the behaviour of the field in the region between data points. A minimum requirement for unbiassed contouring is that it should not attempt to depict anomalies with wavelengths less than the separation of the survey lines. With profiles, on the other hand, all of the observed variations, including the shortest wavelengths, can be shown. A further advantage of the profiles is that one can discount a systematic error in the level along a particular survey line, such as was discussed in the preceding paragraph. Errors of this type would produce a serious and misleading distortion in a contour chart.

Vector residual maps for the three survey areas are given in Figures 10-11, 19-20 and 28-29. Suppose a Cartesian co-ordinate system with axes, u,v, and z is chosen so that the average flight line is parallel to the v-axis, and z is vertically downward. Denote the magnetic components in this coordinate system by U,V, and Z, and their residuals by ΔU, ΔV, and ΔZ. Then the vector residual in the horizontal plane is the vector sum of ΔU and ΔV; the vector residual in a vertical plane is the vector sum of ΔV and ΔZ. Naturally, other vertical planes could be chosen; this one was chosen for the relative ease with which one can visually rotate the vectors about the flight track.

In plotting any quantity, there is always the problem of sign convention. Usually positive quantities are plotted pointing toward either the top, or the right-hand side, of the page. Hence the residual ΔZ is plotted upward, when positive, on the residual profile maps of Figures 8 and 17 even though Z is defined as positive when vertically downward. Similarly the vertical-plane vector residuals of Figures 11 and 20 have been plotted following the same convention. A positive anomaly in any component, is plotted either upward or to the right; a negative anomaly either downward or to the left.

In the case of an isolated anomaly due to a point pole, the intersection of the residual vectors indicates the location of the source relative to the path of the aircraft, and their direction the polarity of the source. Hence, the residual vectors could aid in drawing contour lines, and in determining the depth of sources. However, the anomaly vector at a point is generally the vector sum of contributions from many different sources, and no simple interpretation is possible. (Hence it is much more difficult to discount the effect of long-wavelength anomalies, or errors in level, on the residual vectors than on the residual profiles.)

It is apparent from the theory of potential that when the components of the geomagnetic field are measured continuously along a line, gradients in other directions can be computed. Consider the coordinate system u,v,z as before, with the v-axis parallel to the flight path. The gradients $\partial(\Delta U)/\partial v$ and $\partial(\Delta V)/\partial v$ are both known. If the field is derivable from a potential, $\partial(\Delta V)/\partial u = \partial(\Delta U)/\partial v$. The direction of the contour lines of ΔV as they intersect the flight lines is given immediately by $\partial(\Delta V)/\partial u$ and $\partial(\Delta V)/\partial v$.

To estimate the above gradients, differences were taken between consecutive ½-minute residuals. The resulting vector was plotted midway between the two positions. The length of the vector was drawn proportional to the magnitude of the gradient, to emphasize the more significant directions obtained in regions of larger gradient.

Figures 12, 21 and 30 show the directions of the contour lines of the horizontal component along the flight track. This technique has proved very useful in tracing linear features of the anomaly pattern, especially over Iceland and the mid-Atlantic Ridge.

Some Large Anomaly Systems

The Z-residuals of Figures 8, 17 and 26 are of particular interest in that the Z anomalies bear a more direct relationship to geological sources.

In Figure 8 the anomalies associated with the mid-Atlantic Ridge system can be followed northward from Iceland for about 500 km, then northeastward over Mohn's Ridge for another 800 km. There is no obvious correlation with the ridge system north of 74° N.

A feature at least 800 km long, with anomalies from 300 to 600 γ, exist over Greenland between 72°N and 79°N. It runs parallel to Greenland's western coast, the distance between it and the coast being about 300 km. The feature curves somewhat, and, when extrapolated toward the Arctic Ocean, seems to join up with the axis of the Lomonosov Ridge. Several large amplitude anomalies also occur over the central east Greenland geosyncline and the northeast Greenland geosyncline. The large anomaly at 84°30'N 26°W is probably associated with the Innuitian orogenic belt along the north coast of Greenland.

In Figure 17, the anomalies over the Reykjanes ridge can be seen to diminish in amplitude when approaching the Reykjanes Peninsula. A discussion and explanation of the major anomalous features over Iceland itself will be found in Serson, *et al.* (1968).

In Figure 26, a very large anomaly feature is centred at 62°N 14°E. It covers an area 400 km long and 200 km wide, and anomaly amplitudes are around 700 γ. It has been discussed by Serson (1968) who calculated the minimum intensity of magnetization necessary to cause such an anomaly to be .004 emu/cc. Anomalies of 600 to 800 γ occur over the Oslo graben, and the anomalous zone over northern Sweden and Finaland (at about 67°N) is especially prominent. The rest of the Baltic Shield, Denmark and the Gulf of Bothnia are very flat magnetically.

Acknowledgments

The authors wish to thank D.G. Smith, a student assistant, who spent the summer of 1967 scaling ½-minute averages of D, H and F for the 240-hour survey. Two other assistants, J.A. Dunn and M.E. Nidd, helped in preparing data for computer analysis.

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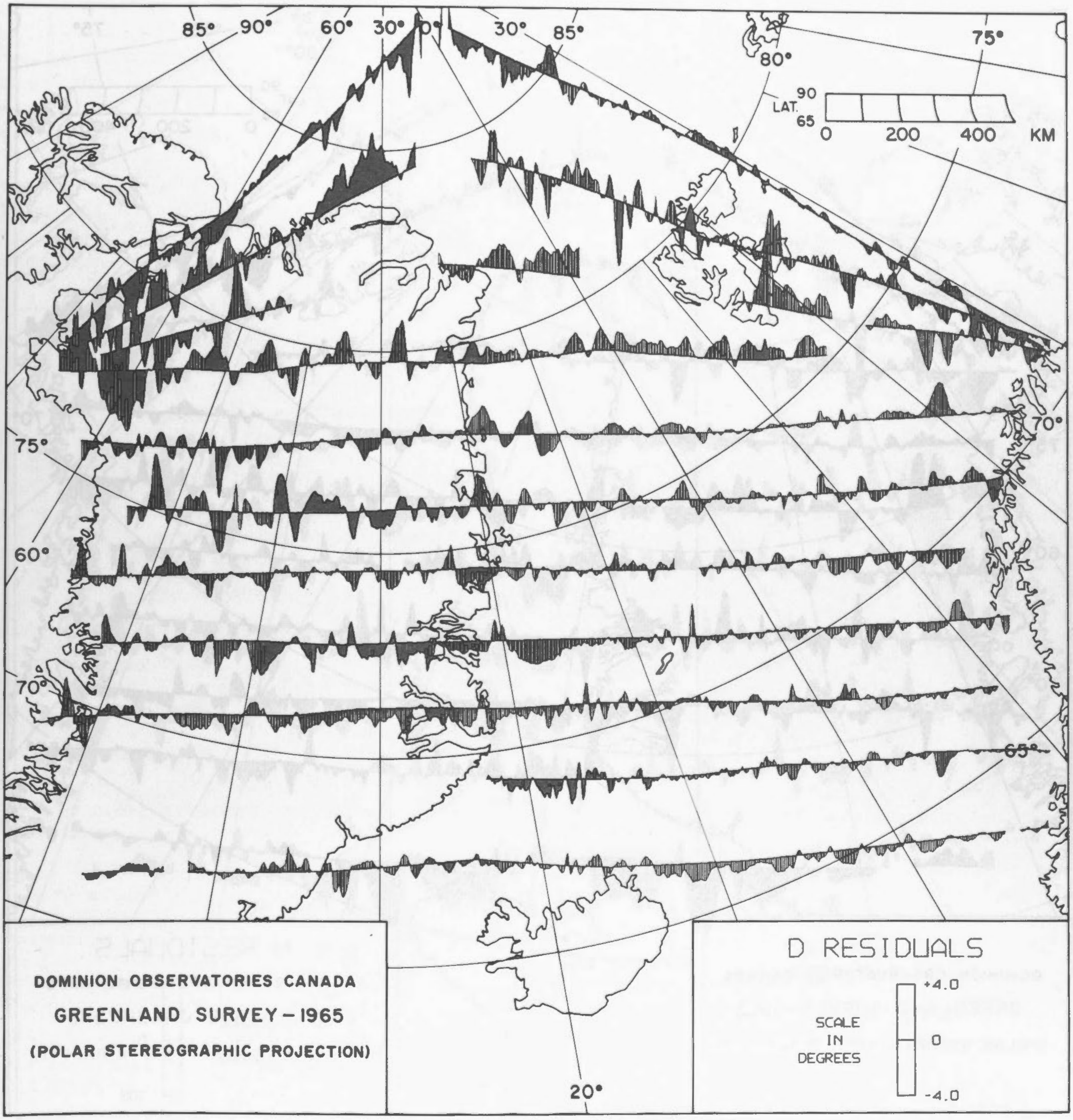

FIGURE 4. Residual profiles of declination, Greenland Survey.

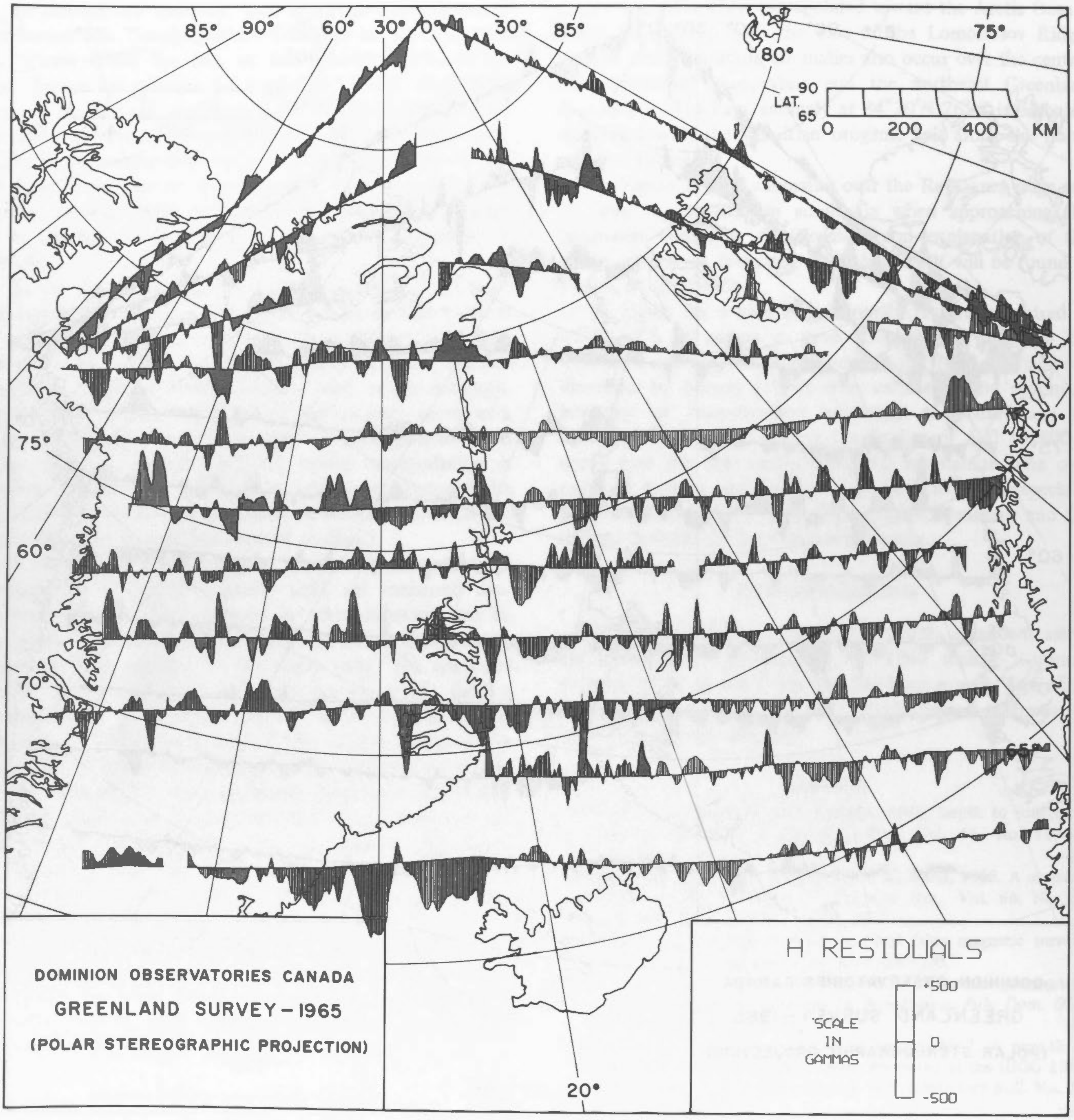

FIGURE 5. Residual profiles of horizontal intensity.

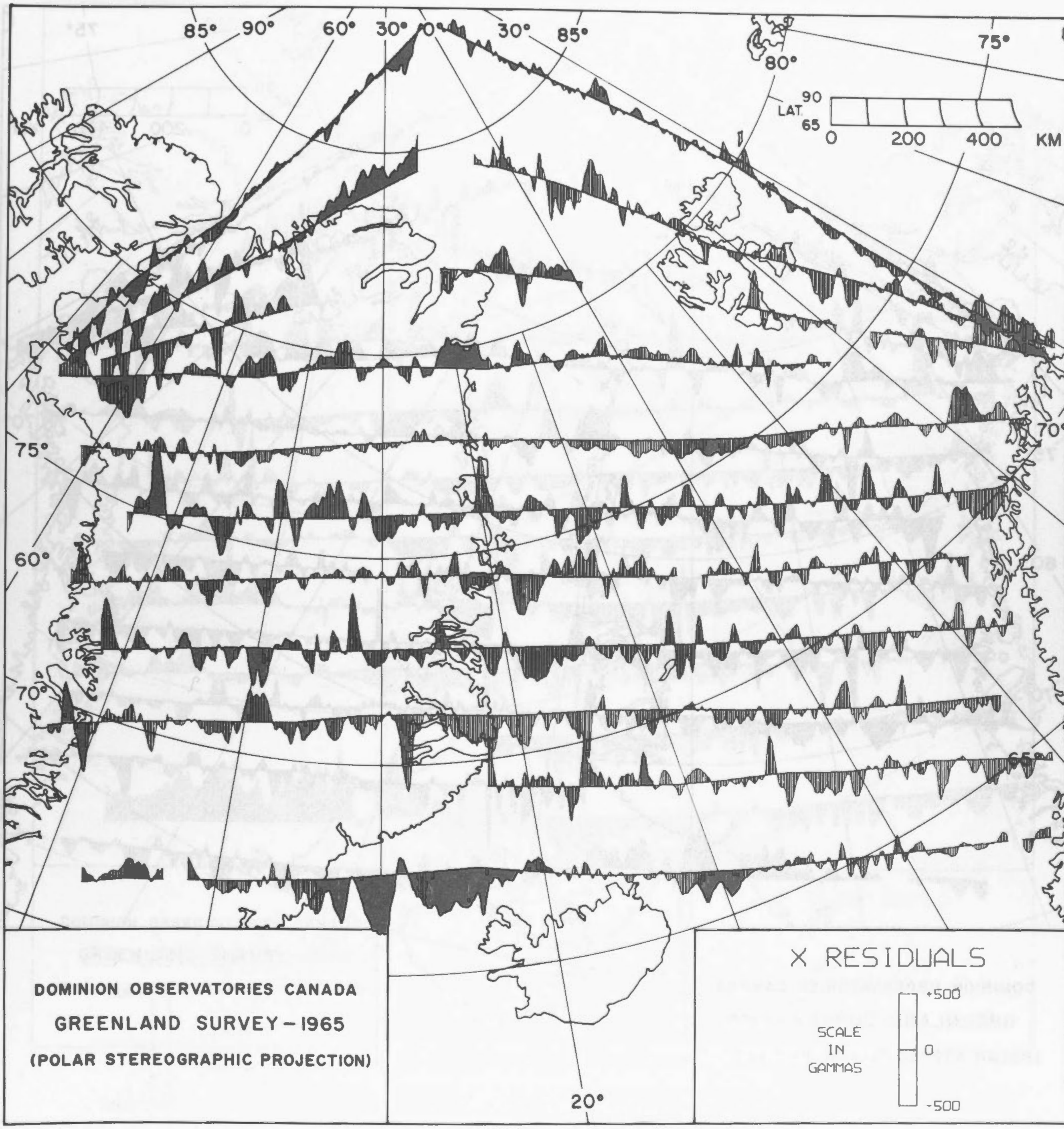

FIGURE 6. Residual profiles of geographic north component.

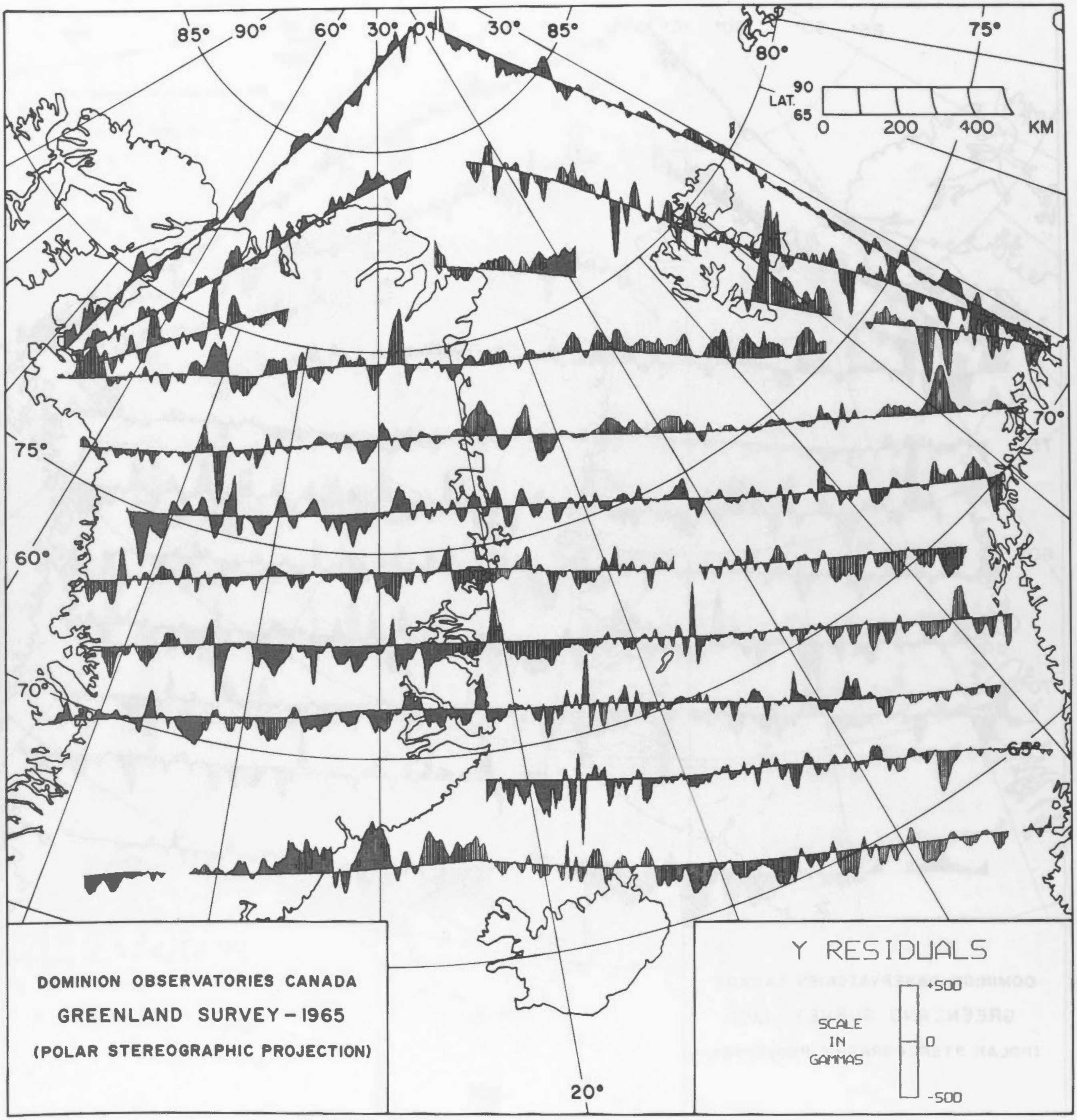

FIGURE 7. Residual profiles of geographic east component.

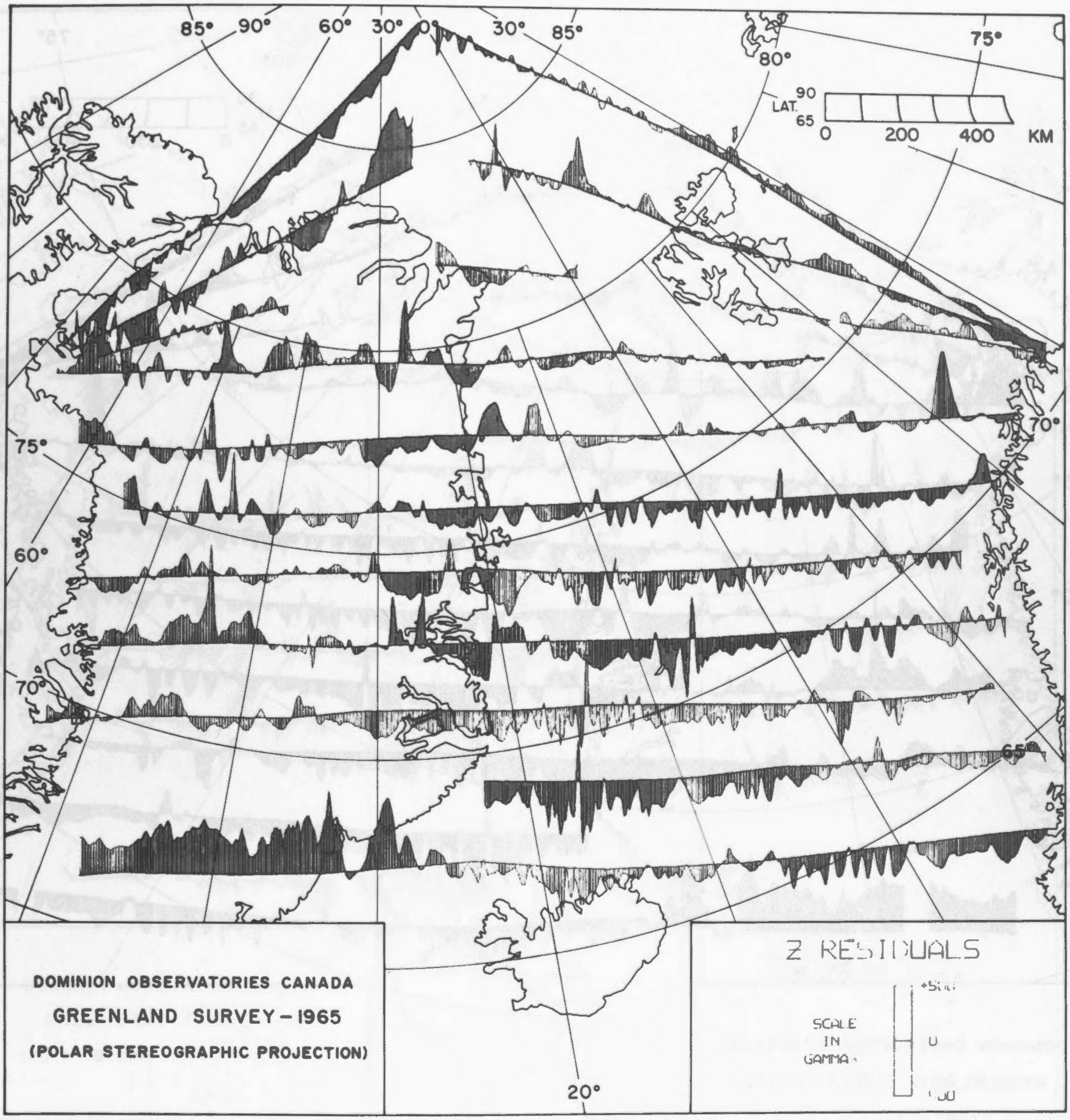

FIGURE 8. Residual profiles of vertical downward component.

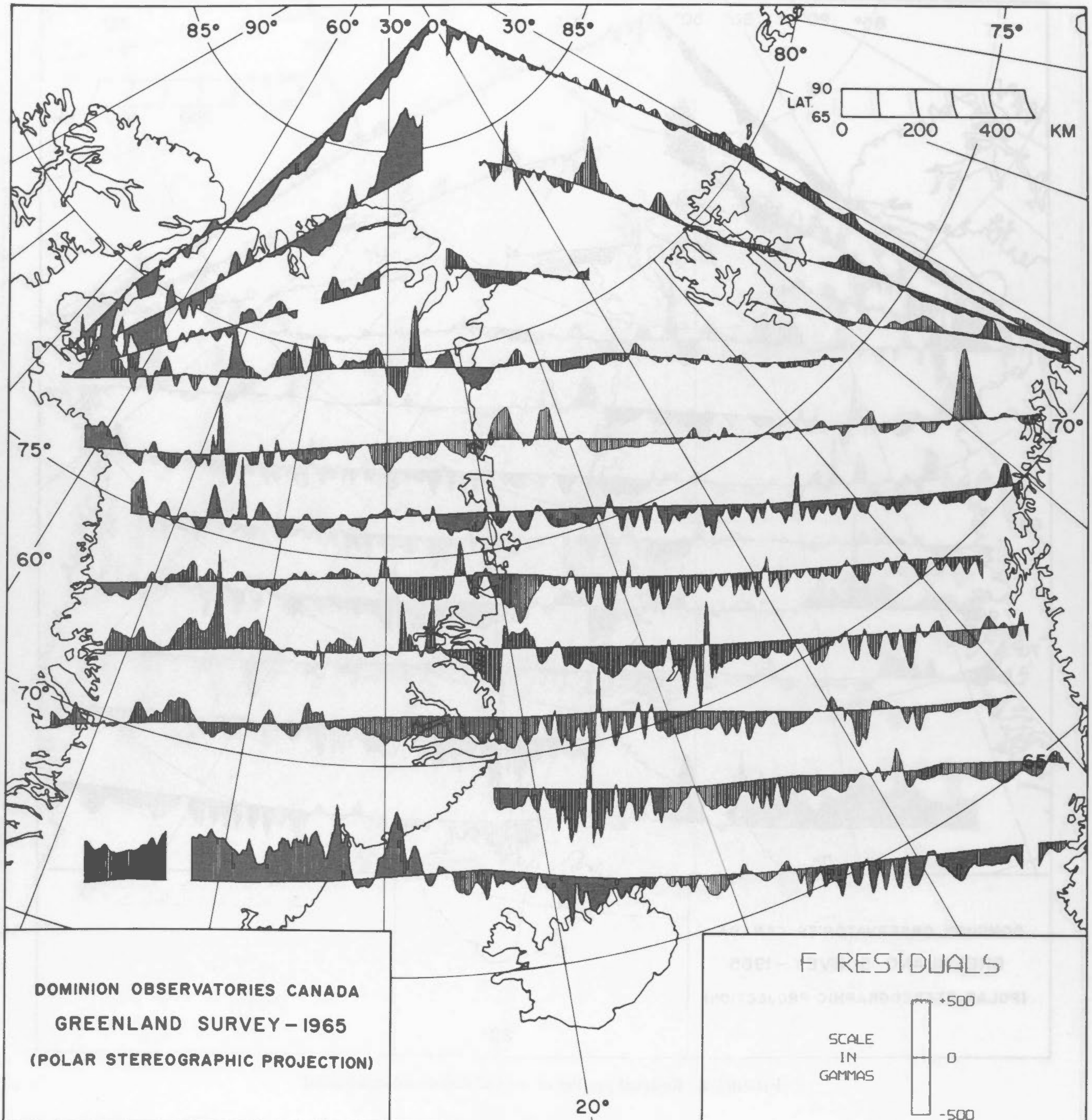

FIGURE 9. Residual profiles of total magnetic field intensity.

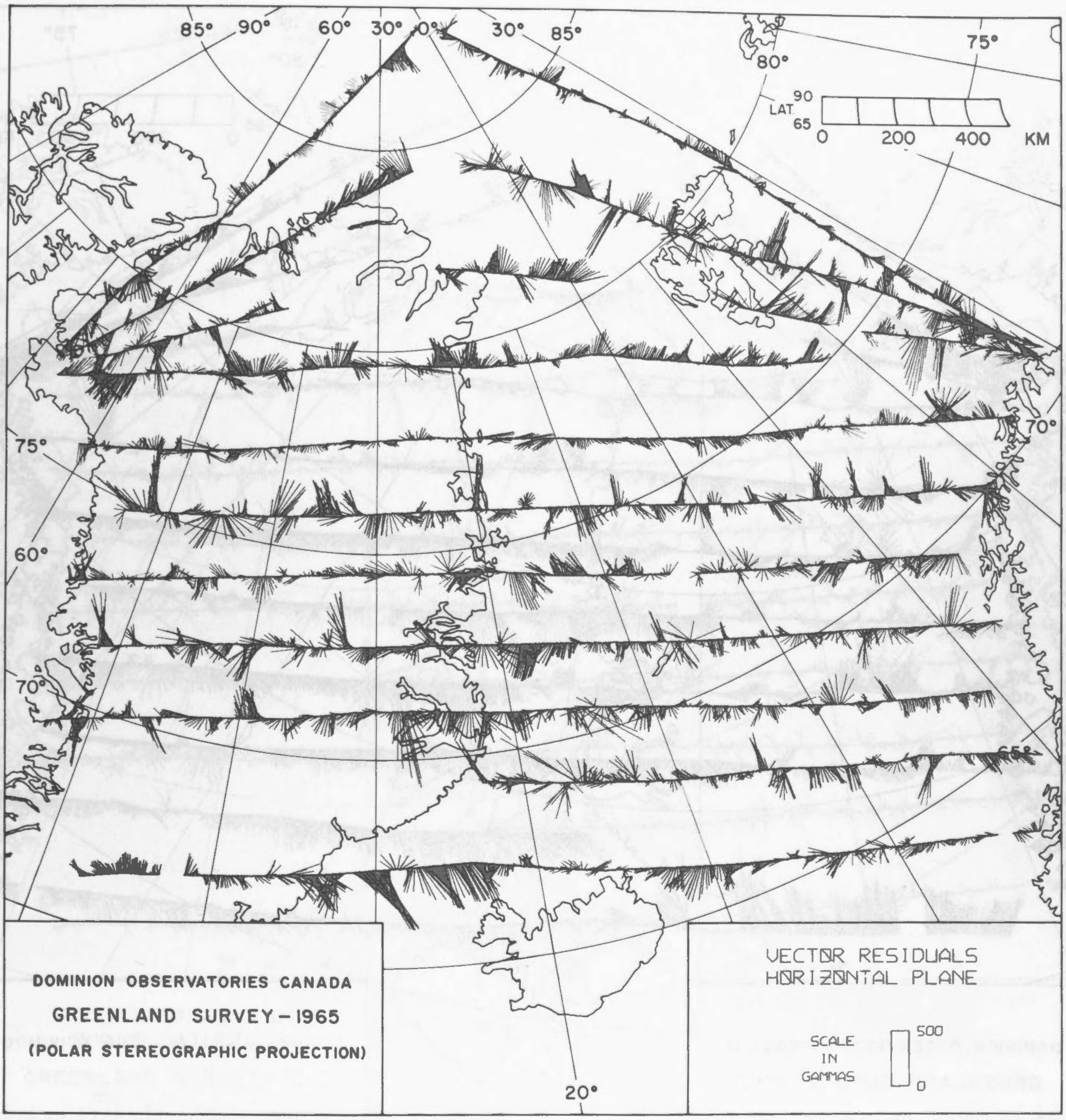

FIGURE 10. Projection of total residual vector onto horizontal plane.

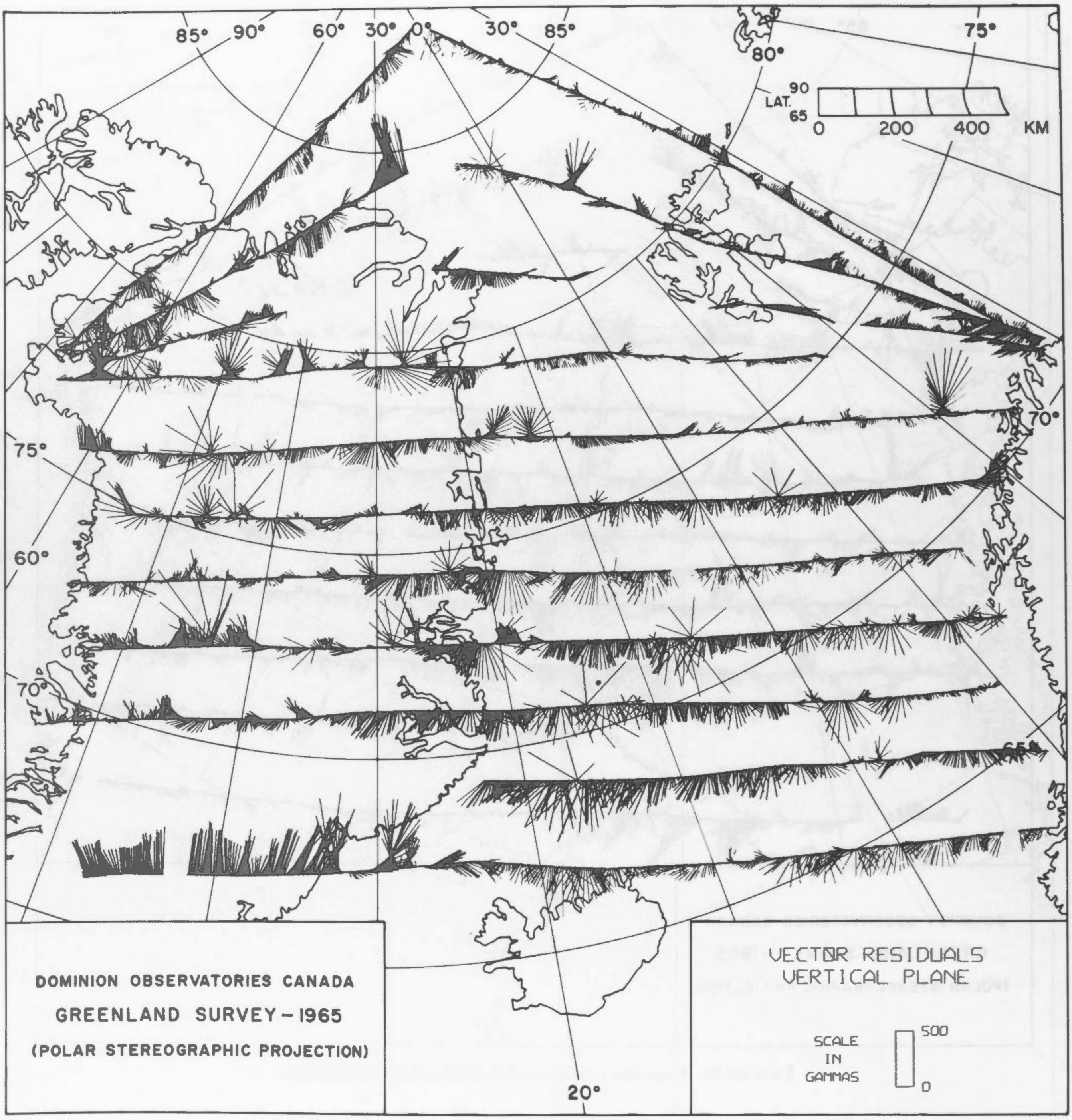

FIGURE 11. Projection of total residual vector onto vertical plane passing through the flight track.

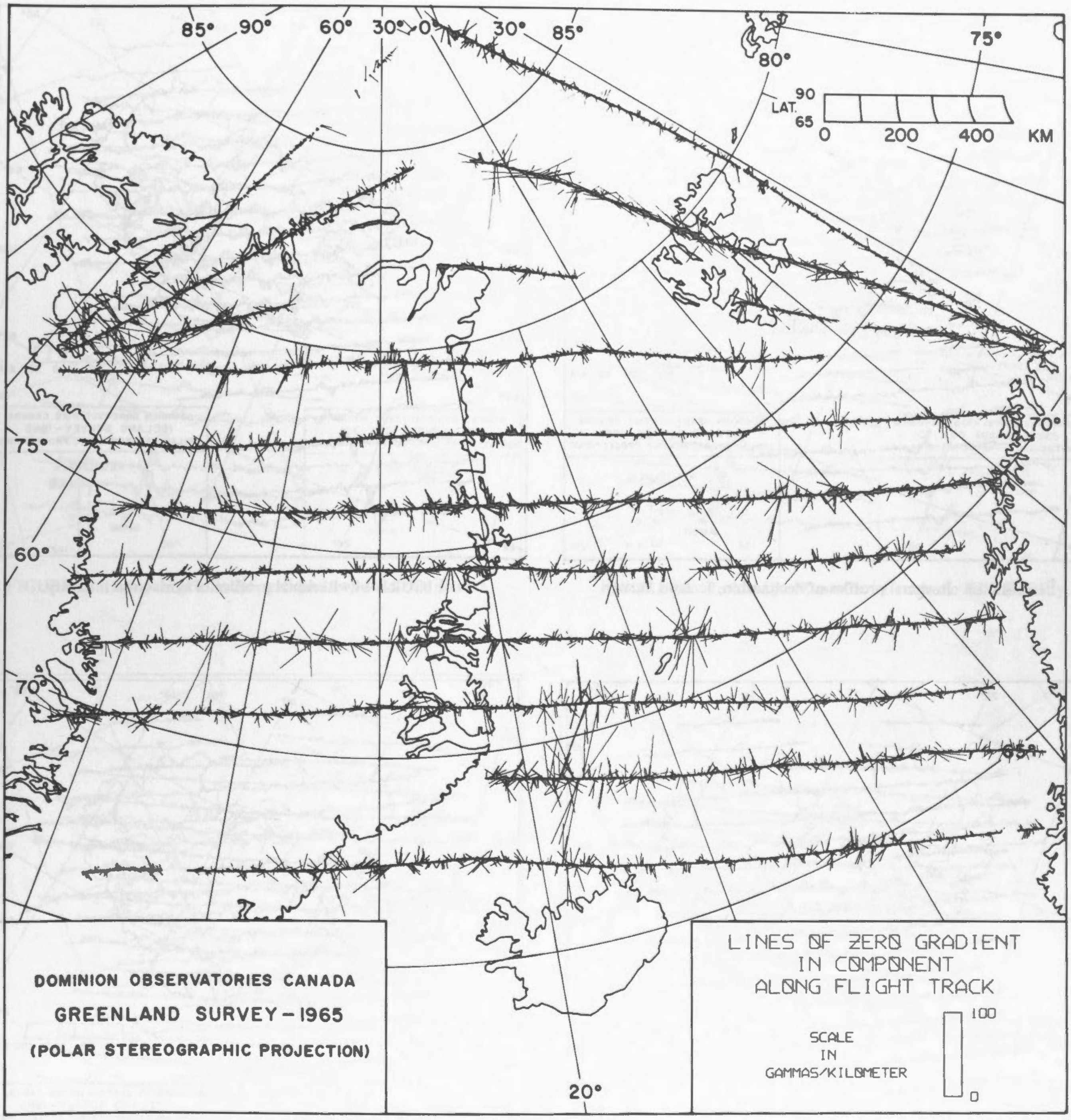

FIGURE 12. Contour line segments of the magnetic component along the flight track.

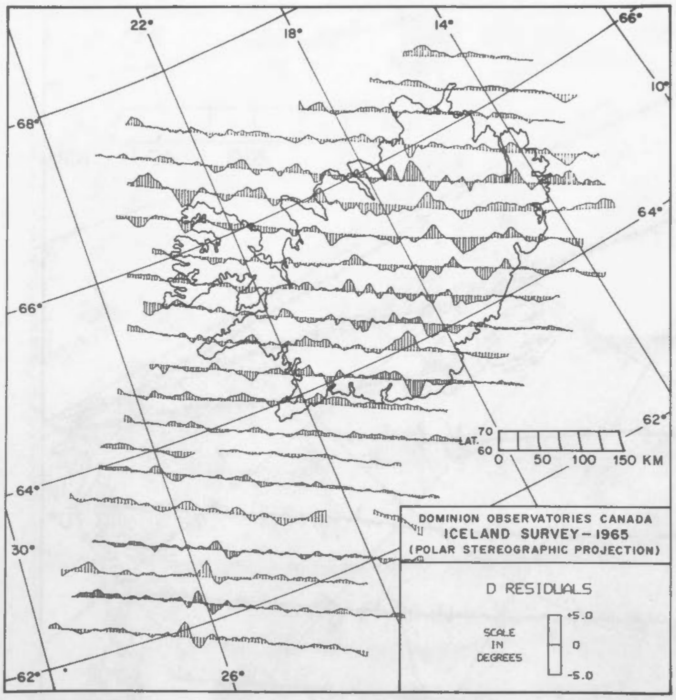

FIGURE 13. Residual profiles of declination, Iceland Survey.

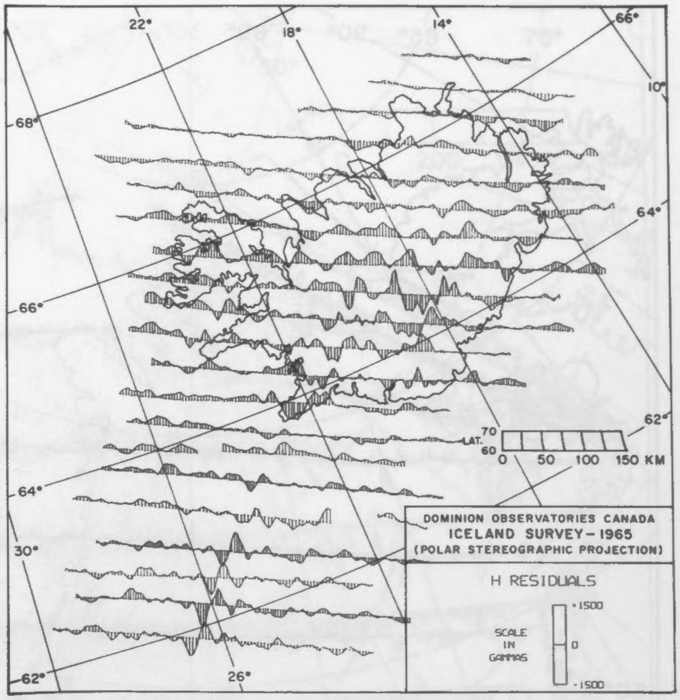

FIGURE 14. Residual profiles of horizontal intensity.

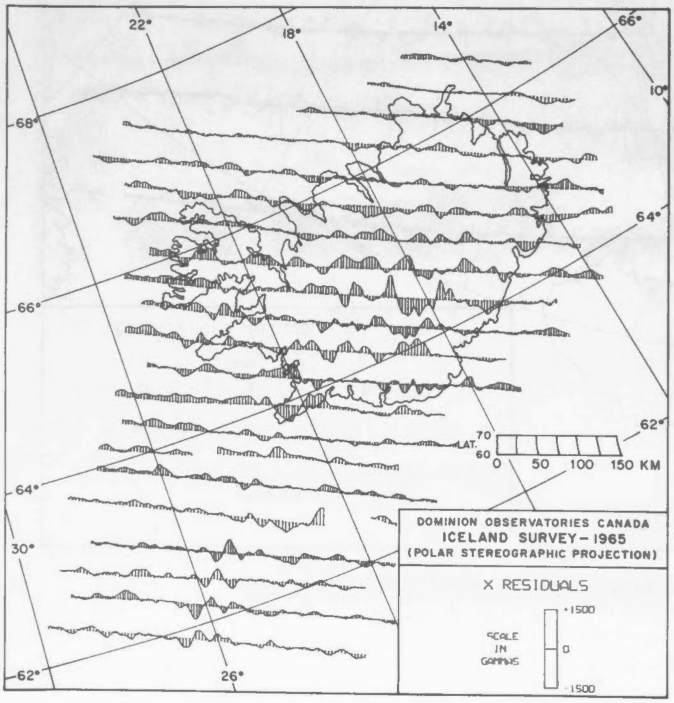

FIGURE 15. Residual profiles of geographic north component.

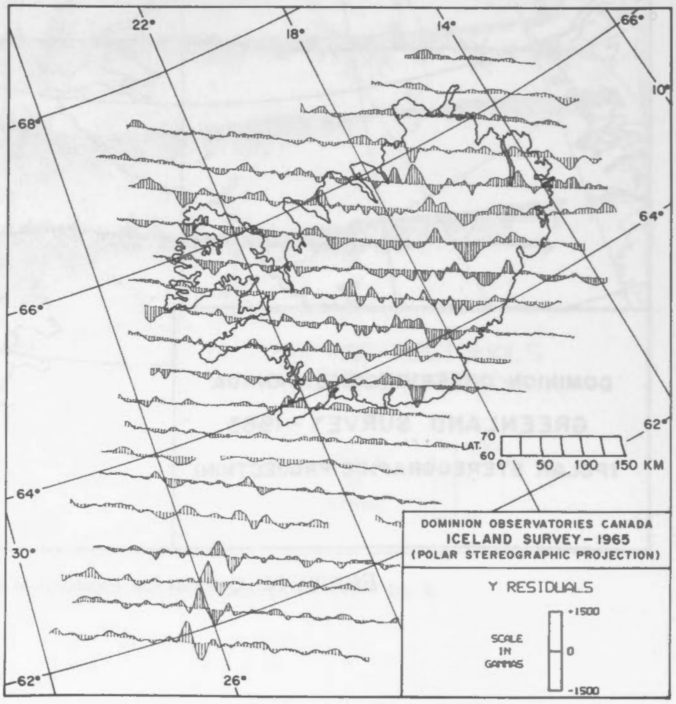

FIGURE 16. Residual profiles of geographic east component.

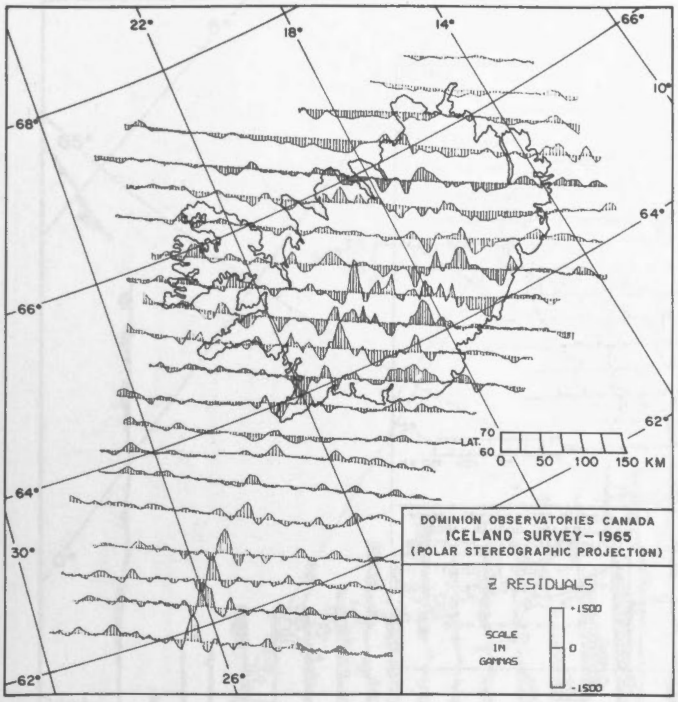

FIGURE 17. Residual profiles of vertical downward component.

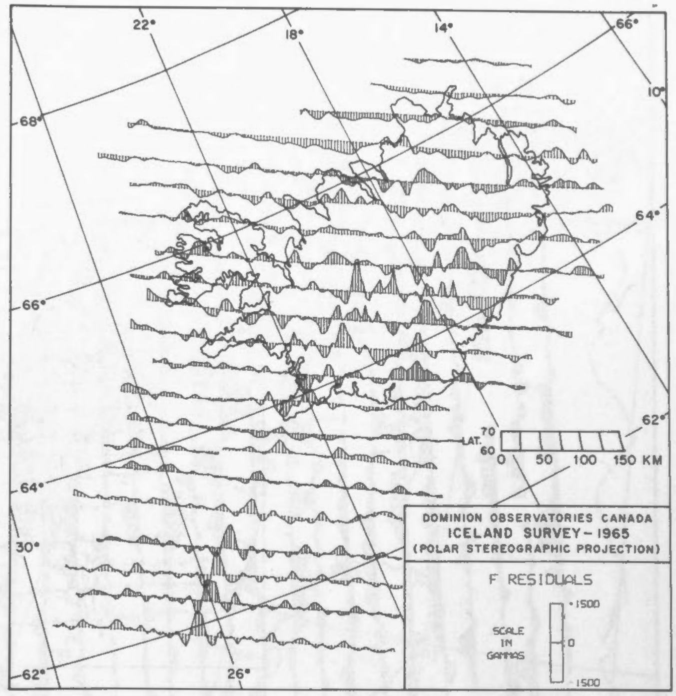

FIGURE 18. Residual profiles of total magnetic field intensity.

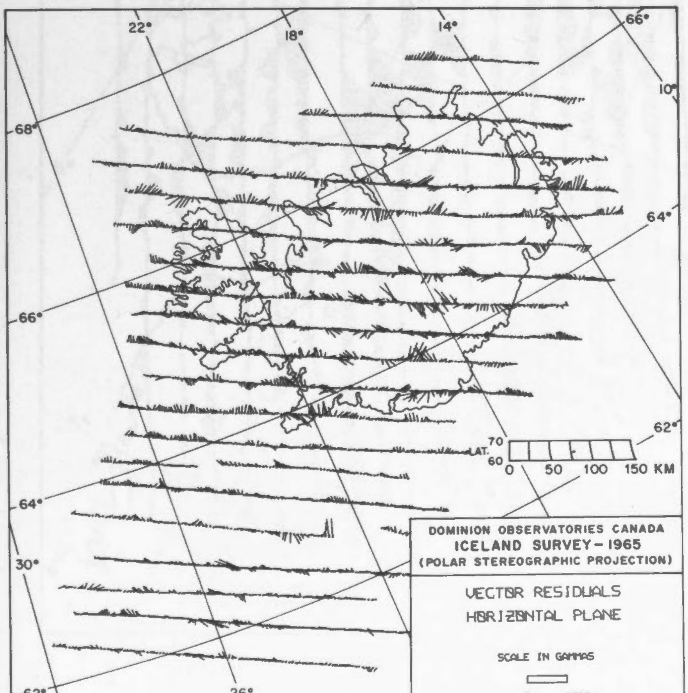

FIGURE 19. Projection of total residual vector onto horizontal plane.

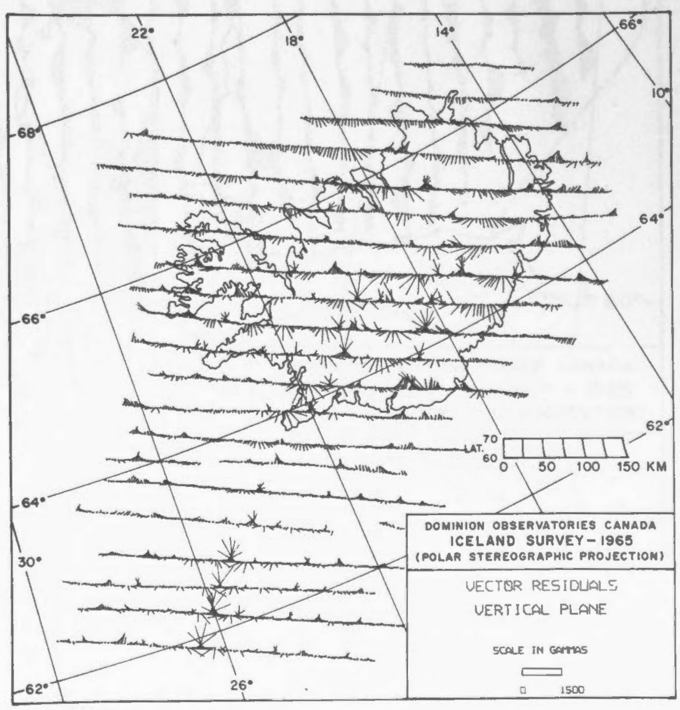

FIGURE 20. Projection of total residual vector onto vertical plane passing through the flight track.

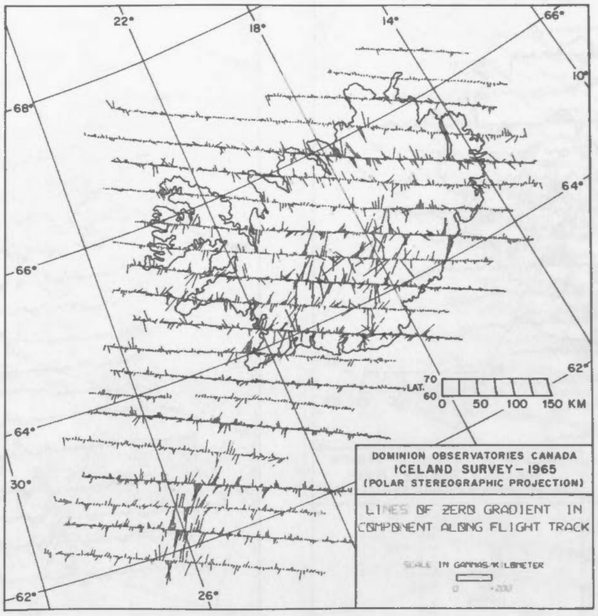

FIGURE 21. Contour line segments of the magnetic component along the flight track.

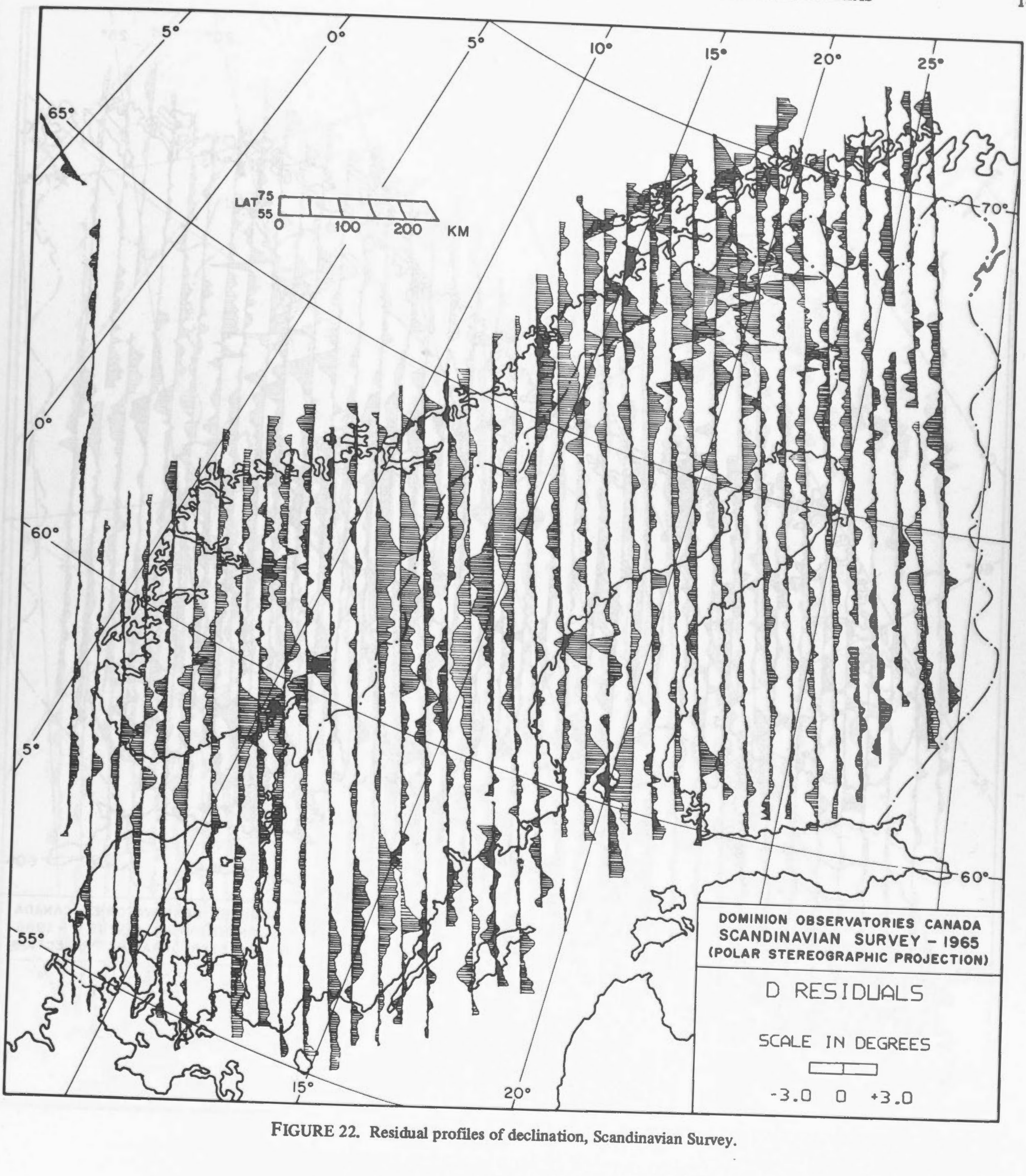

FIGURE 22. Residual profiles of declination, Scandinavian Survey.

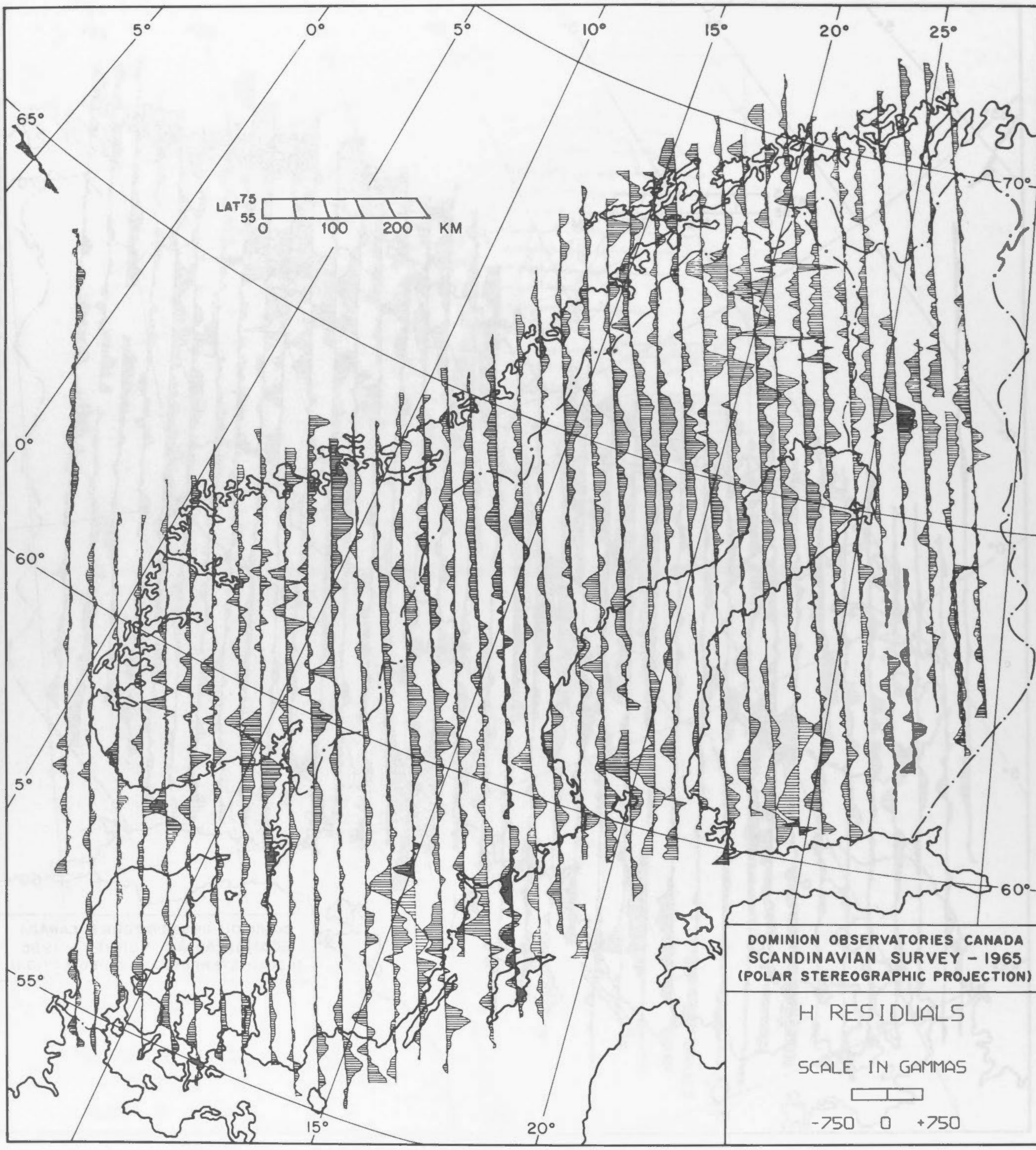

FIGURE 23. Residual profiles of horizontal intensity.

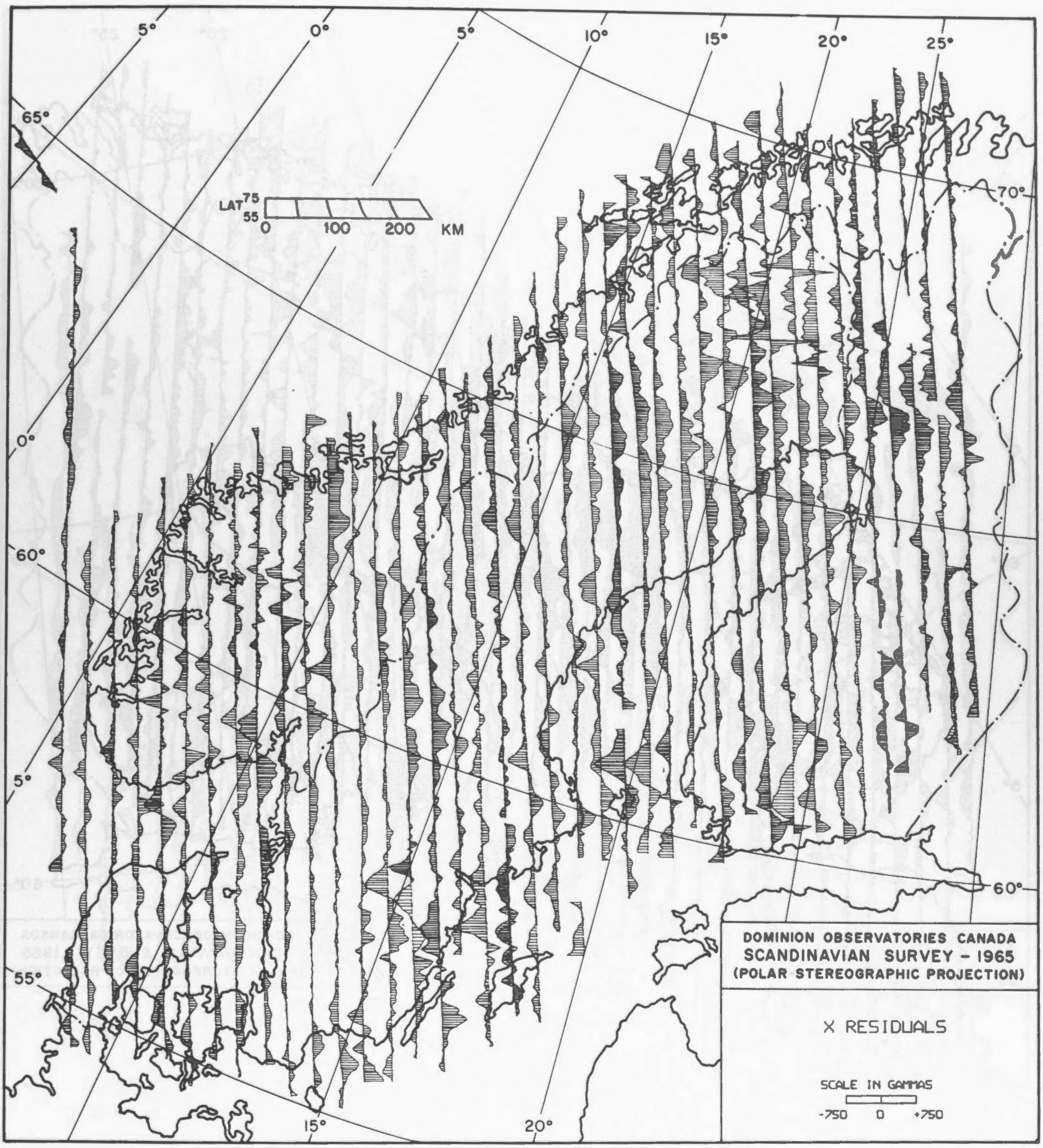

FIGURE 24. Residual profiles of geographic north component.

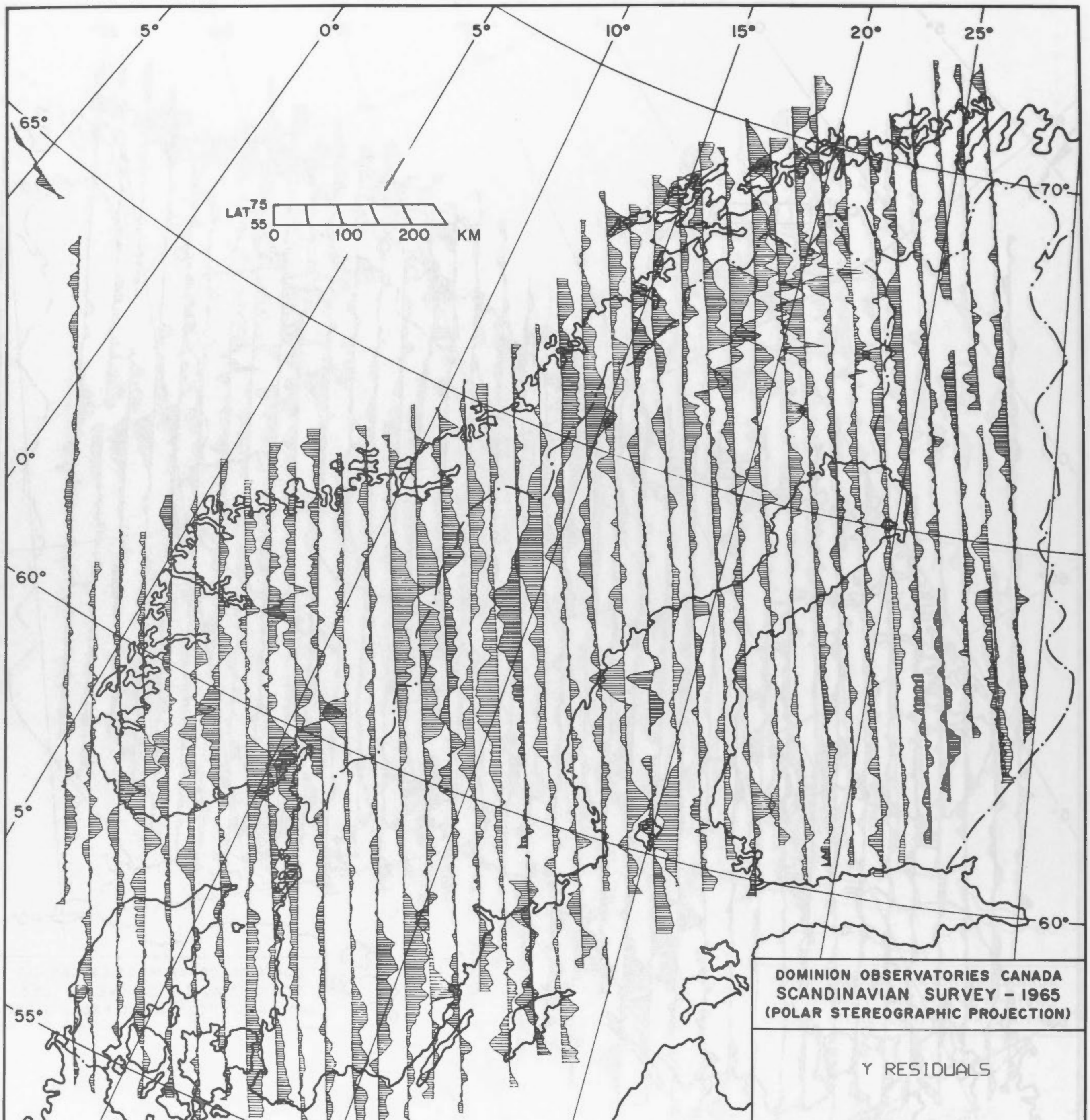

FIGURE 25. Residual profiles of geographic east component.

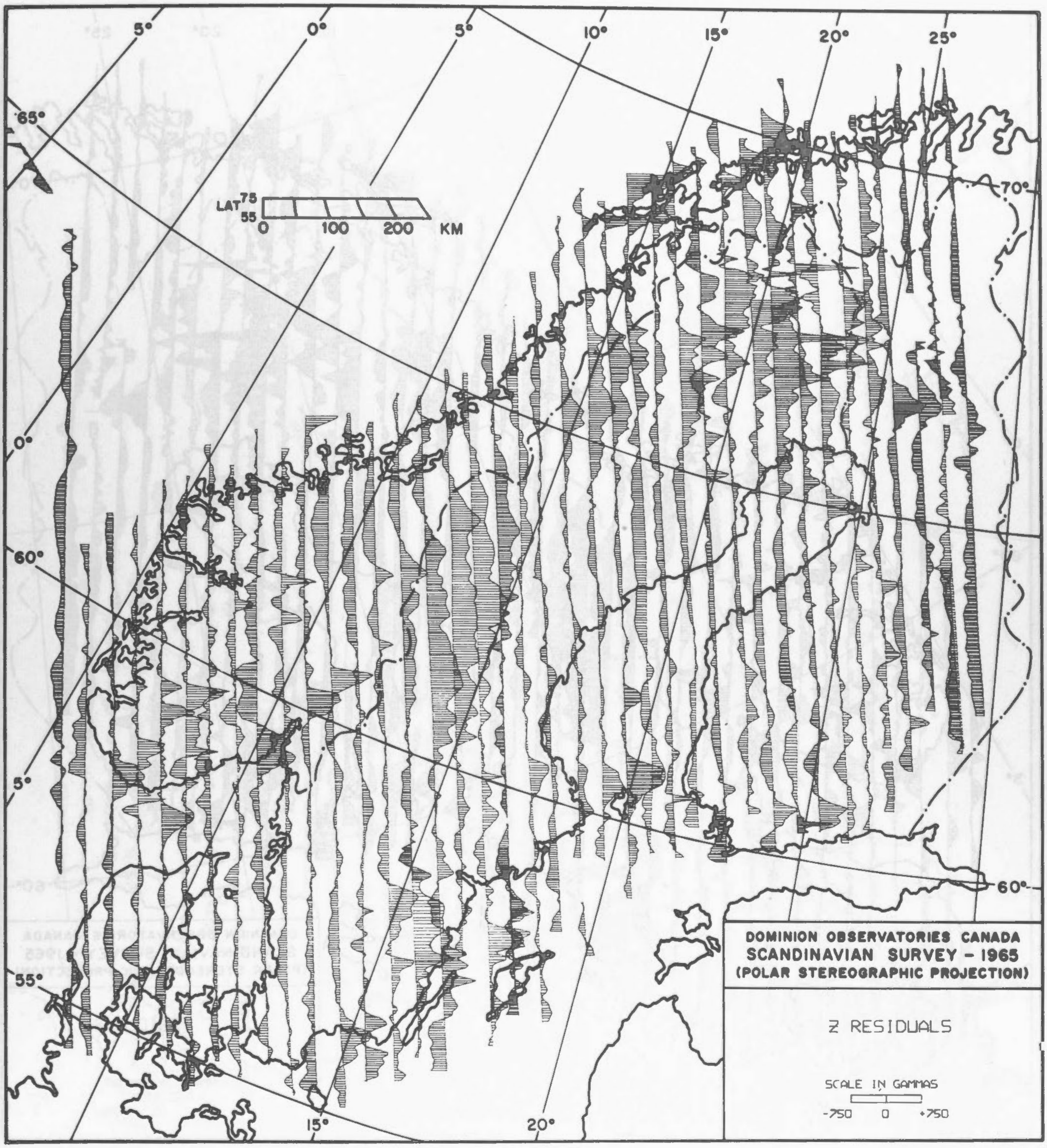

FIGURE 26. Residual profiles of vertical downward component.

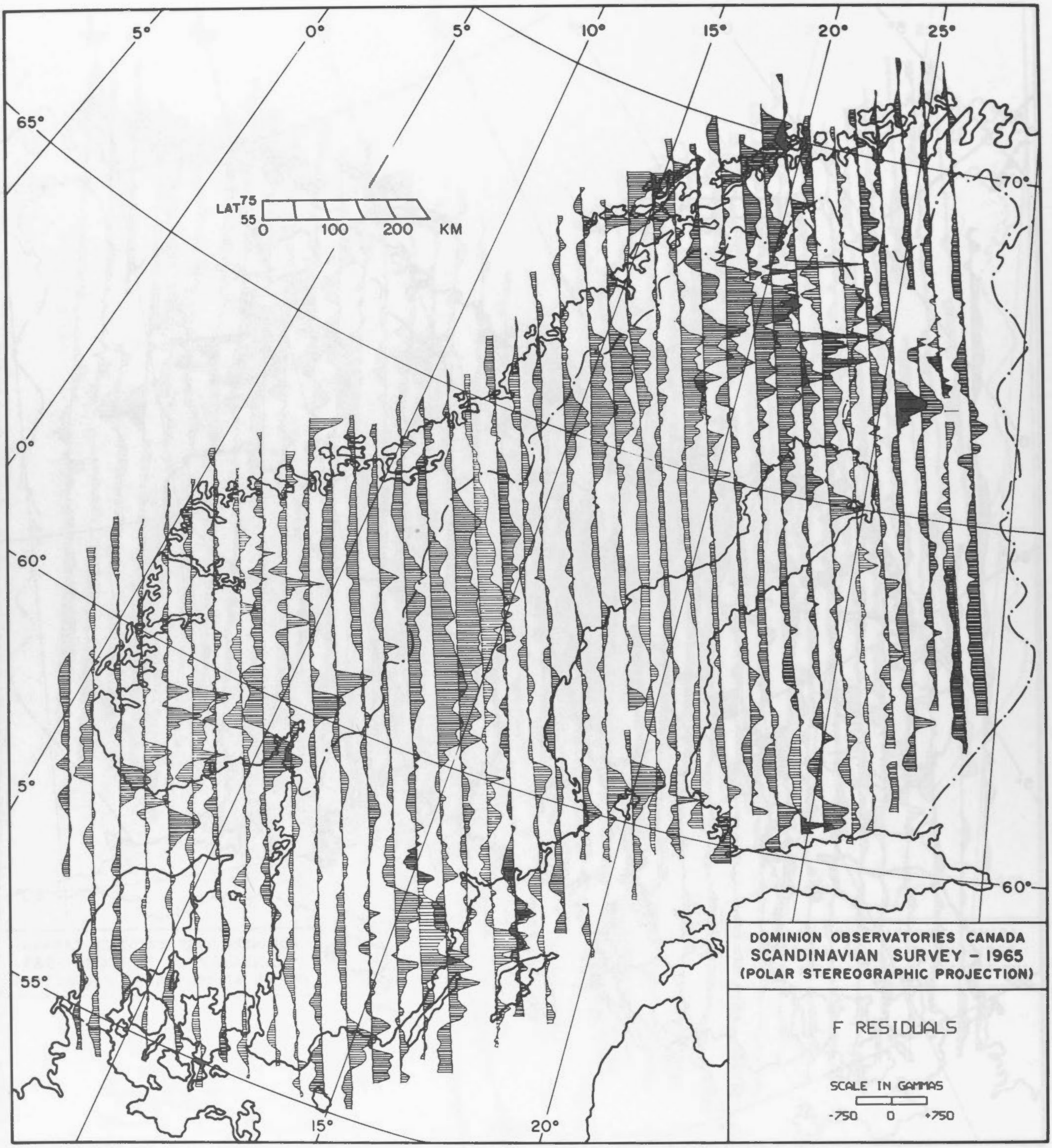

FIGURE 27. Residual profiles of total magnetic field intensity.

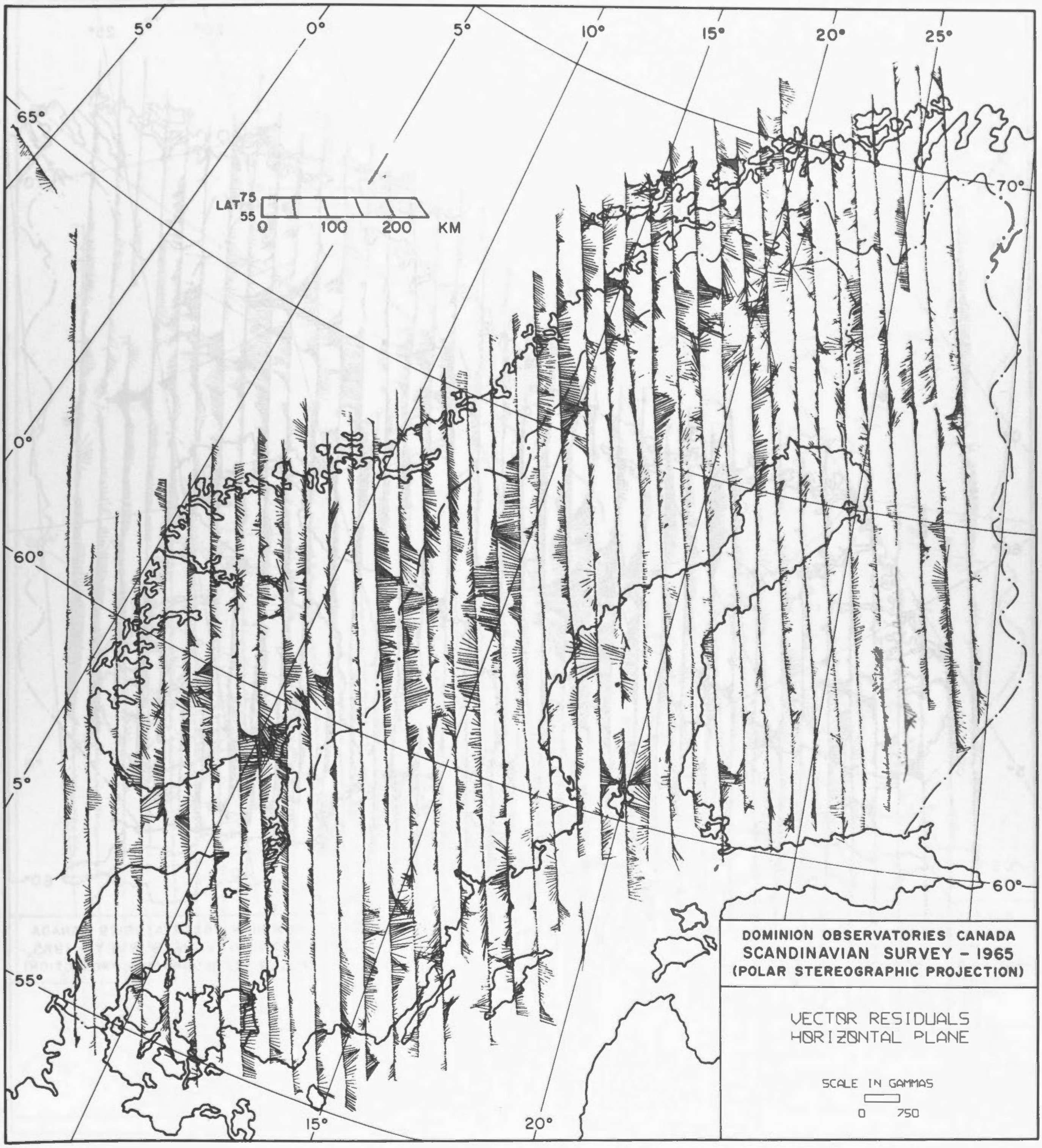

FIGURE 28. Projection of total residual vector onto horizontal plane.

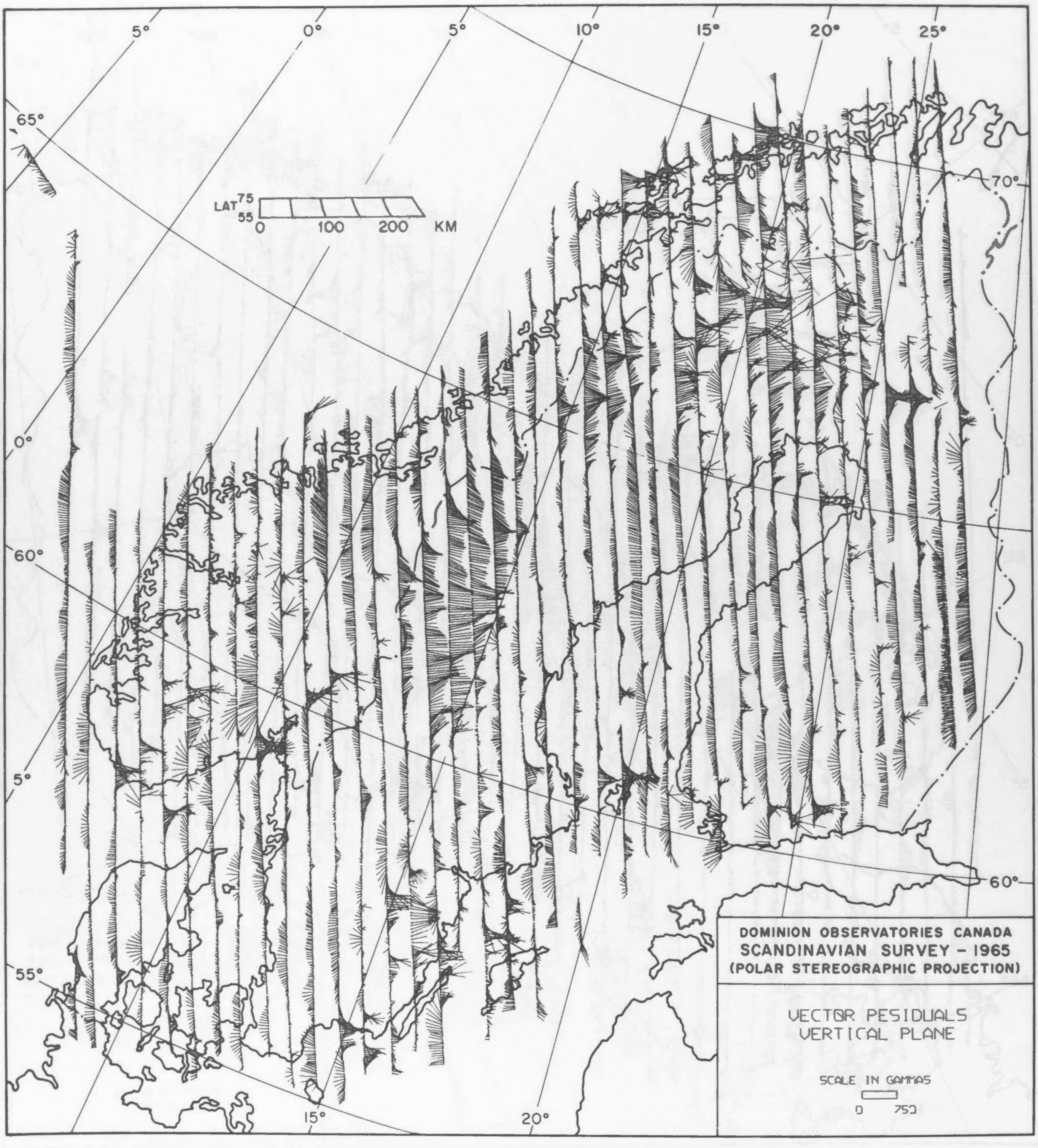

FIGURE 29. Projection of total residual vector onto vertical plane passing through the flight track.

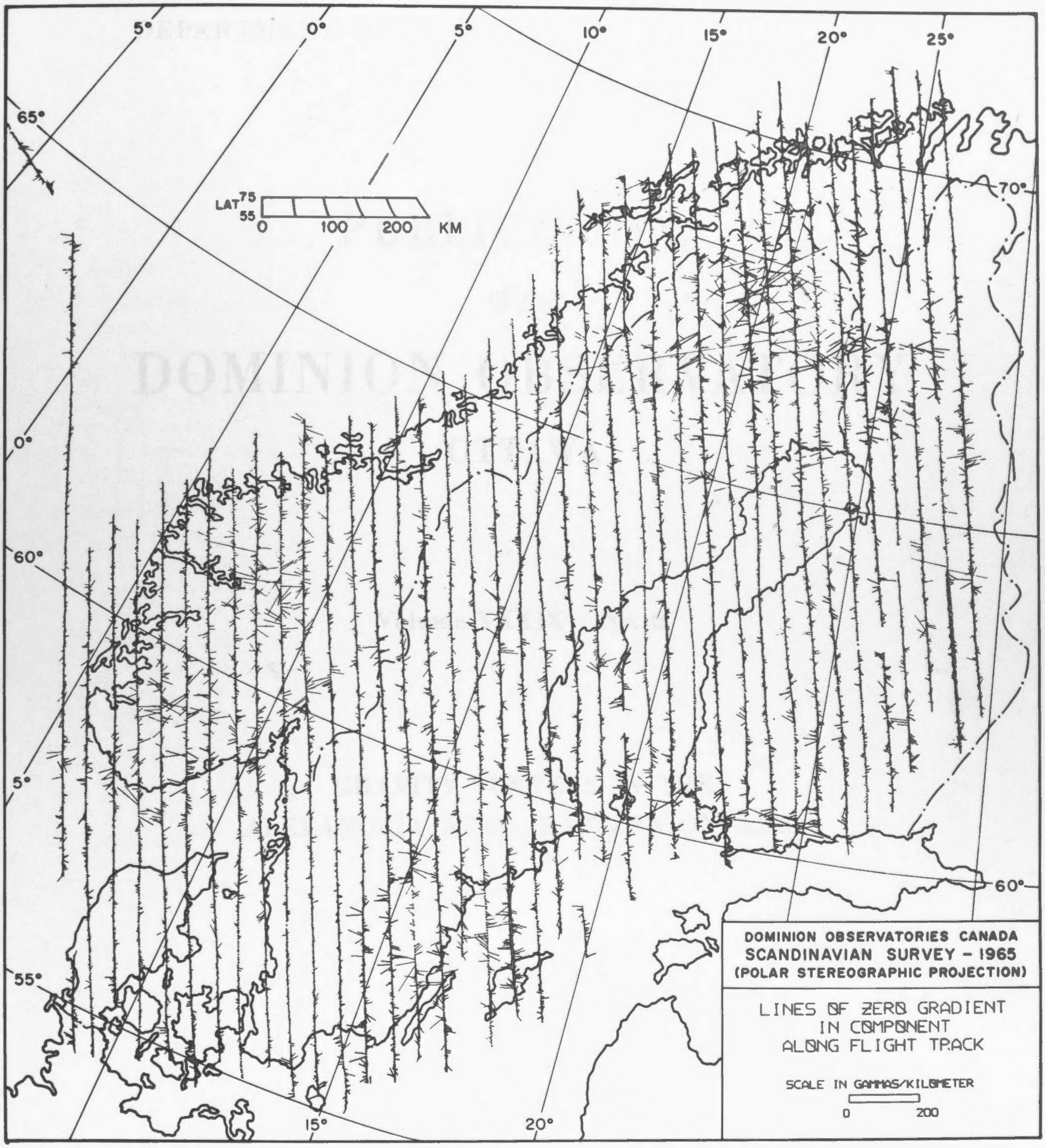

FIGURE 30. Contour line segments of the magnetic component along the flight track.