AEROMAGNETIC DATA

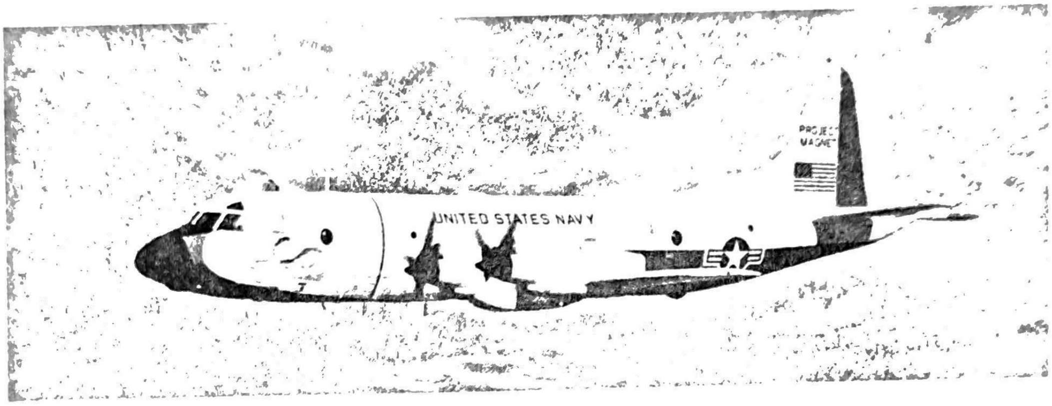
1980(SE-R)

DATA ANNOUNCEMENT

PROJECT MAGNET: Airborne Magnetic Survey of the U.S. (1976-1977)

The Data Center now has available scalar total magnetic intensity data for conterminous United States. These data were acquired by the U.S. Naval Oceanographic Office's Project MAGNET aircraft during survey operations from September 1976 through September 1977 using a metastable helium magnetometer. The centerfold map illustrates the geographical coverage of the data file.

The data were, in general, collected at altitudes (above ground level) of 500-700 m in nonmountainous terrain and 900-1,600 m in mountainous terrain. The typical interval of time between data records is 1 sec (approximately 0.1 km) and aircraft ground speeds were between 380-500 km/hr.



Project MAGNET aircraft

DESCRIPTION OF DATA

The file contains approximately 650,500 data points. The data are uncorrected for temporal magnetic variations. Each record includes the following information:

	Character Nos.	Code	Description
	1-2	A2	*Line Number*
	3-4	I2	*Degrees of Latitude*
	5-7	F3.1	*Minutes of Latitude - implicit decimal point*
	8	A1	*Sign of Latitude - N/S*
	9-11	I3	*Degrees of Longitude*
	12-14	F3.1	*Minutes of Longitude - implicit decimal point*
	15	A1	*Sign of Longitude - E/W*
	16-21	I6	*Date - month, day, year*
	22-27	I6	*Time (GMT) - hours, minutes, seconds*
	28-32	I5	*Total Magnetic Intensity - in nanoteslas*
	33-37	I5	*Altitude - above ground in meters*
	38-40	A3	*Navigation Device - "ESG" for electrostatic gyro,* *"INS" for mechanical gyro*
Future field (Sep'80)	41-44	I4	*Elevation of local terrain - in meters (estimated for certain regions by U.S. Geological Survey from 30-sec terrain file).*

National Geophysical and Solar-Terrestrial Data Center, NOAA
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Your file Votre référence

January 9, 1989

Our file Notre référence

GS2685 – 1

Mr. Grant R. Cameron
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Dear Mr. Cameron:

In response to your letter requesting information on Project Magnet, I am enclosing an article by Dr. Serson (I believe it is the one he referred to) along with some other information, albeit old.

If you wish more up–to–date information, I can only suggest that you write to the U.S. Naval Oceanographic Office.

Yours sincerely,

Richard Coles

Richard L. Coles
Head, Geomagnetism

Encl.

Canada

AIRBORNE MAGNETIC SURVEYS FOR WORLD CHARTS

by

P.H. Serson

Dominion Observatory, Ottawa, Canada

Presented to

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ABSTRACT

Airborne magnetometers which measure the direction as well as the intensity of the earth's magnetic field are described briefly. The accuracy of airborne magnetic measurements is discussed in relation to the problems of representing the geomagnetic field by world charts. It is concluded that airborne surveys can increase the accuracy of magnetic charts even in regions with a reasonable distribution of accurate observations on the ground.

AIRBORNE MAGNETIC SURVEYS FOR WORLD CHARTS

by

P.H. Serson[*]

After the end of the second World War, airborne magnetometers for geophysical prospecting were quickly developed and put to use. The successful instruments measured the total intensity of the magnetic field by means of a field-sensitive detector of the fluxgate or saturated transformer type, the axis of which was automatically aligned parallel to the geomagnetic vector. These instruments give only the scalar magnitude of the field, and no provision is made for determining its direction. For theoretical investigations of the earth's magnetic field, and certainly for navigation, knowledge of the direction of the magnetic vector is more important than knowledge of its magnitude.

To measure the direction of the magnetic field, one must have a direction reference system, and the accuracy of the measurement can be no greater than the accuracy of the system. The direction reference system used in magnetic measurements on the ground is that defined by the vertical--the direction of gravity--and geographic north. On the ground, the vertical direction is given with great accuracy by a pendulum, such as a magnet hanging on a thread, a compass needle balanced on a pivot, or a level bubble. Knowing the vertical, geographic north can be determined by astronomical observations.

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In an aircraft in flight, however, a pendulum or level bubble does not indicate the direction of gravity, but rather the direction of the vector sum of the acceleration of gravity and the acceleration of the aircraft. In what appears to be smooth and steady flight, the aircraft actually undergoes accelerations large enough to deflect a pendulum or level bubble from the true vertical by angles of the order of 1°. To measure components of the magnetic field to 1 gamma, one must of course have a reference system accurate to the order of 0.1'.

One way of overcoming this difficulty in airborne measurements is to use a different direction reference system - one fixed to the stars, for example. A very simple and elegant method has been suggested by Gerard(1953). His proposal is to mount a small camera on the fluxgate of the prospecting type total intensity magnetometer, so that the optical axis of the camera is automatically aligned parallel to the magnetic vector. Photographs of the stars are then made periodically. By identifying the stars in the photographs, the orientation of the magnetic vector relative to the celestial sphere is determined. Knowing the time and geographical position of the observations, the magnetic declination and inclination can be computed. Gerard showed, by experiments on the ground, that his method was practical, except of course near the magnetic equator. He estimated that an over-all accuracy of 0.2° could be obtained in the air. As far as I am aware, the method has not been tried in the air.

The Ministry of Supply of the United Kingdom did considerable development of another method of measurement relative to astronomical bodies (Jarman, 1949). A total intensity magnetometer and a magnetometer measuring the component of field in the direction of the sun were flown in the same aircraft. These two measurements supply two of the three numbers necessary to define the direction and magnitude of the geomagnetic field. The flight would then be repeated, when the sun was in a different part of the sky, giving enough information to compute the usual magnetic elements. To our knowledge, no surveys were made by this method.

The two groups - in the United States and Canada - who are carrying out airborne surveys of the complete magnetic vector measure its direction with respect to the conventional reference system, that defined by the vertical and geographical north. Both groups use gravity to define the vertical, in spite of the fact that it is theoretically impossible to distinguish between the acceleration due to gravity and the acceleration due to motions of the aircraft. The reason gravity can be used is that in survey flying, one is not entirely ignorant of the motions of the aircraft. The forward speed is reasonably constant from hour to hour, and it is easy to show that the changes in speed which do occur, spread out over an hour, have little effect on a pendulum. A similar argument can be made with respect to the transverse velocity, if one is attempting to fly in long straight lines. It is accelerations with shorter periods, of the order of one minute, which cause the trouble. Their amplitudes are larger, and because of their short period they cannot be deduced from navigational information. The aircraft flies in such a way that the passengers, the pilot, and in fact most navigational instruments are not aware of these accelerations. There can also be accelerations with still shorter periods, of the order of one second, of which the passenger is aware, but these can be easily averaged out by a pendulum.

The United States instrument was developed by the Naval Ordnance Laboratory [illegible], and is now operated by the U.S. Navy Hydrographic Office [Schonstedt and Irons, 1953]. A fluxgate detector is automatically aligned parallel to the magnetic vector and the total intensity is recorded, as in the [illegible] magnetometer. Two angles are recorded which define the direction of the axis of the fluxgate with respect to a vertical and the fore-and-aft axis of the aircraft. These angles correspond to inclination and magnetic heading, except in high magnetic latitudes, where a different configuration of the instrument is used. A third angle indicating the azimuth of the fore-and-aft axis of the aircraft is recorded by astronomical observations made with a periodically operated periscope.

All these angles are affected by the accelerations of the aircraft, and instantaneous measurement, with a useful accuracy, of the direction of the magnetic vector is not possible. However, provision is made for automatically recording the average value of each of the angles, with the averages computed over an interval of 100 seconds. This interval is chosen as being close to twice the natural period of the aircraft, with the aim of averaging out effects due to accelerations with this natural period. The results of the United States instruments are thus a continuous record of total intensity, with values of declination and inclination taken at regular intervals. The declination and inclination angles do not describe the direction of the vector at a point, but represent the direction averaged over a distance of 10 km or so.

In the Canadian instrument, a different approach is adopted [Serson, Mack, and Whitham, 1957]. The magnetic measurements are made with respect to a stable reference system, the effects of aircraft accelerations having been removed in a section of the instrument distinct from the magnetometer itself. Thus continuous recording of any component of the field is possible, and a complete description of the magnetic vector at any point on the flight path is obtained.

The magnetic measurements are made on a platform which is controlled by gyroscopes and accelerometers in such a way as to make it behave much like damped pendulum with a natural period of 6 to 7 minutes. A simple pendulum with this period would be 35 km long. Since the smoothing effect of a pendulum is proportional to the square of the period, it will be seen that this system should be more efficient in removing the effects of periodic acceleration than the American system, where the smoothing varies linearly with the averaging interval. The gyrostabilised platform has a further advantage in that corrections can be automatically introduced for changes in speed of the aircraft and for moderate changes in the direction of flight. These advantages are obtained at the cost of a considerable increase in the complexity of the instrument. The azimuth reference is a free gyroscope. Astronomical observations are made at regular intervals in flight to determine its precession, by means of a periscope which is stabilised with respect to the stabilised platform.

The magnetic elements recorded by the Canadian instrument are D, H, and Z. These were chosen rather than (D,I,F) or (X, Y, Z) for reasons of instrumental convenience, and because they are the elements from which charts are usually constructed. As well as recording D, H, and Z as continuous profiles, the instrument also supplies automatically computed averages of D, H, and Z, the averages being taken over 5-minute intervals of time. The purpose of this averaging is to assist in handling the data.

How accurate are airborne measurements of the complete magnetic vector? The error of an airborne measurement as plotted on the charts may be considered as the sum of 5 independent errors of the following types:

(a) Errors in measuring the magnetic field at the magnetometer with respect to the direction reference system.

(b) Errors in the direction reference system.

(c) Errors due to changes in the magnetic field of the aircraft.

(d) Errors due to transient changes in the magnetic field.

(e) Errors in geographical position.

Errors of the first type are purely instrumental. By good design and careful calibration they can be held to the order of 10 gammas, which is negligible compared to other errors to be discussed.

Errors in the direction reference system are difficult to evaluate. The theoretical response of the system to accelerations of the aircraft can be calculated, but these accelerations vary widely, depending on the dynamic characteristics of the particular aircraft, the setting of the aircraft controls, and the degree of turbulence of the air through which it is flying. In the United States instrument, where the effect of these accelerations is reduced by averaging the observations over a discrete interval, the effectiveness of the averaging depends on how well the interval approximates an integral number of periods of the accelerations. It is estimated that under good conditions the probable error in the direction of the vertical resulting from the averaging is 0.1°. Expressed in gammas, the corresponding error in X and Y would vary from zero at the equator to 100 gammas at high latitudes, and in Z from 50 gammas at the equator to zero at the poles. In the Canadian instrument, the probable error in the determination of the vertical is estimated at 2', resulting in errors of 30 gammas in X and Y at high latitudes, and 15 gammas in Z at the equator. Both instruments claim a probable error of 0.1° in azimuth, producing errors ranging from 50 gammas at the equator to zero at the poles.

Inside a four-engined aircraft, where these instruments are carried, there are normally present fields of the order of a few hundred gammas due to direct currents in the aircraft electrical system and to ferromagnetic parts of the aircraft. These fields can be greatly reduced by modifying the wiring of the aircraft and removing magnetic parts. Any remaining permanent and induced magnetic fields can be compensated, as in compensating the compass of a ship. The United States Navy Hydrographic Office has two aircraft permanently assigned to making magnetic surveys which have been modified in this way. It is specified that the residual aircraft fields after compensation shall be less than 5 gammas. The Canadian group has been less fortunate in that it has no permanent aircraft, but hires an airplane for a few months each year. No de-gaussing or compensation of the aircraft is possible. The magnetic fields of the aircraft are determined four times during a survey by special calibration flights, and corrections are applied to the observations after the survey. It has been found that the large fields of the unmodified aircraft change considerably during a survey, with the result that there is an uncertainty, of 30 to 50 gammas, in the corrections to be applied at any time.

It is concluded that the operational accuracy of the two instruments is about the same, ranging from 50 to 100 gammas. This is the probable error of a single determination of the magnetic vector at a particular time and place.

Magnetic charts are intended to show the main field, and the effect of transient disturbances should be removed from the observations. When a few days of observations at a ground station are available, corrections according to the records of permanent observatories can be made with considerable confidence, because it can be checked that the corrections are having the desired effect. Such a check is not possible in the case of airborne observations. Near the zone of maximum aurora, the best that one can do is to estimate the probable error of the survey results due to transient disturbances. For example, during a survey of Central Canada lasting one month in 1955, the probable error of an observation due to time variations in the field was estimated at 30 gammas.

No matter how accurately a magnetic observation is made and corrected to epoch, if it is plotted in the wrong location on a chart, the chart will be in error. From an examination of world charts, one would not expect this to be a serious problem. The gradients in the components shown are usually of the order of 10 gammas per km, and at most about 40 gammas per km. With careful navigation and analysis of the data after completion of a flight, it is usually possible to determine the geographical position of the aircraft with a probable error of 5 km. The resulting error in the chart would be expected to be of the order of a few 10's of gammas.

However, the first fact to impress one who examines the results of airborne surveys is that the local gradients in the magnetic field, even at altitudes of many km, are many times larger than the regional gradients shown by magnetic charts. It is this fact which makes it difficult to test the over-all accuracy of airborne measurements. The obvious procedure of flying over a magnetic observatory to check the airborne values practically never gives satisfactory results. Because the gradients at observatories are in general so large, the aircraft must be flown directly over the observatory and at a very low altitude. These conditions are incompatible with making accurate measurements of the direction of the magnetic vector in the air. It has in fact proved very difficult to find locations where the gradients are sufficiently small for calibration and determination of the aircraft fields in the air, even without requiring the presence of a permanent magnetic observatory.

Analysis of the accuracy of airborne magnetic surveys in Canada has shown that moderate errors of a few km in navigation and plotting of the observations are responsible for the largest source of error in the results as plotted on the charts. These errors are of the order of 100 to 150 gammas. It is considerations of this sort which have led to rather conservative claims of the accuracy of airborne aurveys, rather than questions of instrumental techniques.

In view of the accuracy of the order of 100 gammas claimed for airborne magnetic measurements, and the fact that an accuracy of one gamma has been the aim in measurements on the ground since the time of Gauss, it has been argued that world charts should be based primarily on measurements made on the ground. Airborne observations would be used only in regions where ground observations are impossible. I propose to show that this view is quite mistaken. At the same time, I would like to make clear some of the limitations of magnetic charts. The discussion will seem trivial to many who had had to construct charts from inadequate data, but a review of the recent literature will show that serious misconceptions are current.

Magnetic charts are often accepted as a true picture of the field with an accuracy comparable to the observations used in their construction, and the users are upset to find large differences between charts produced by different agencies. For a hundred years, spherical harmonic analyses of magnetic charts have been made, partly to investigate the origin of the field, but mainly to test the consistency of the charts and to aid in extending the contours into regions where observations are scarce. Now we find the coefficients from these analyses being used to compute magnetic fields at heights of a hundred km above the earth, for comparison with rocket observations, with physical significance ascribed to differences of a few tens of gammas. As another example, we find elaborate spherical harmonic analyses of the main field based only on observations at the 200 badly distributed permanent magnetic observatories, with the implication that by using only the most reliable information, a better representation of the geomagnetic field will be obtained.

To discuss the accuracy of magnetic charts, one must know the purpose of the chart. There are three possible views of what a chart represents. First, it may be considered as simply a graphical representation of the observations available to the chart maker. Then the accuracy of the chart is simply the accuracy of the observations. A magnetic chart viewed this way would have a very limited use. A table of the original observations would be more valuable.

Secondly, a magnetic chart can be considered as a prediction of the values which would be obtained if observations were to be made at any point. This is the sense in which magnetic charts are most used - in navigation, for instance. Here the accuracy of the chart is the measure of the success with which it performs the prediction. If one has the appropriate statistical information about the magnetic field, and knows the geographical distribution of the observations and the way they were used by the chart maker, this accuracy can be computed.

A third view of a magnetic chart is that it should present an ideal field, which is fitted to the available observations by the method of least squares, for instance. An example is the field given by a spherical harmonic analysis. The accuracy is presumable given by the residuals of the solution. Unless the observations are evenly distributed, and the number of observations is many times larger than the number of coefficients in the solution, this accuracy has little relation to the usual meaning of the term.

Let us discuss the accuracy of magnetic charts as predictions. Airborne surveys give us the opportunity for the first time to examine the geographical variation of the magnetic components in detail and with large samples of data. Figure 1 is an example of continuous profiles of D,H, and Z recorded at an altitude of 3.6 km over central Canada. The profiles begin in the upper left corner of the diagram, and are read from left to right, continuing downward, as a printed page is read. To prevent the profiles from running off the diagram, straight line approximations to the profiles have been subtracted before plotting.

It is often given as one of the advantages of airborne magnetic measurements that they are unaffected by local anomalies because of the altitude of the observations. It is true that most of the anomalies of interest to the geophysical prospector disappear - those a few km in breadth due to rocks near the surface. However, there remain many anomalies of several hundred gammas' amplitude and up to 100 km wide. These are still local anomalies in the sense that they are too small geographically to be shown on world charts.

It will be noticed that the anomalies are fairly evenly distributed along the flight path. One cannot readily pick out anomalous regions. In fact, profiles very similar to this are obtained in any part of Canada, with no obvious difference in the degree of disturbance, whether they are obtained over the Precambrian rocks of the Canadian Shield, or over the plains where the sediments are several km in depth.

If there are any who suspect that these anomalies originate in the instrument rather than in the geomagnetic field, I should point out the phase differences between the anomalies in the different components. The fact that D decreases before a maximum in Z is reached, and increases after the maximum in Z is passed, indicates that the aircraft is flying toward the west. If the variations were due to errors in the direction reference system, an increase in Z would be accompanied by a decrease in H. In fact, at this particular latitude, the change in H would be 6 times greater than the change in Z, and the records show about the same amplitude of disturbance in all three components.

Figure 2 shows profiles of D,H, and Z, again with linear approximations subtracted, obtained at a height of 3.0 km over the ocean. This flight was from Honolulu directly south to Christmas Island, near the equator, and the results are typical of profiles we have recorded over both the Atlantic and the Pacific. The average depth of the ocean here is about 5 km. The profiles are very similar to those measured over Canada, except that the amplitude of the anomalies is somewhat smaller. Notice the large anomaly over Christmas Island.

What are the consequences of these results from the construction of magnetic charts? Two conclusions are immediately obvious. First, one cannot produce a chart giving the components of the magnetic field at any point to an accuracy of 100 gammas unless one has observations at very closely spaced locations. Secondly, an observation at a single point is likely to differ by several hundred gammas from the average field in the vicinity, and a chart constructed from widely spaced observations will contain errors of this magnitude.

To discuss these questions quantitatively, many thousands of kilometers of airborne profile have been analysed statistically (Serson and Hannaford, 1957). The upper part of Fig. 3 shows the result of such an analysis of north-south flights in central Canada, expressed as autocorrelation functions of D,H, and Z. The lower part of the figure gives much the same information in a more easily explained form. Here the root-mean-square change in a component, in gammas, is plotted as a function of the distance τ, in kilometers, over which it is measured. The profiles were recorded at an altitude of 3.0 km, and linear approximations were subtracted from the profiles before the analysis was made. The probable change in any component over a distance of 30 km, not including the regional gradient, is about 200 gammas. Over smaller distances, the change is proportionally less, but over distances greater than 30 km, the probable change is still of the order of 200 gammas. This shows that in the spectrum of the anomalies there are no wavelengths exceeding 100 km. The reason that the function for Z continues to increase is that the Z-profiles were gently curved, and did not fit the straight line approximations.

Figure 4 shows the same functions for east-west profiles obtained at an altitude of 2.5 km over the Atlantic Ocean east of Bermuda. The depth of the water was practically constant at 5.5 km. They are very similar to those obtained in Canada, except that the amplitude of the anomalies is about one third as large.

From this information, the accuracy of a magnetic chart, considered as a prediction of the field at any point, can be calculated. The upper part of Figure 5 illustrates the first case considered, when the map maker interpolates linearly between observations at points equally distributed a distance 'p' apart. In the second case, shown in the lower part of the diagram, he interpolates between points representing the mean of many observations, taken over intervals of length 'a'. Figure 6 shows the root-mean-square error of charts of H and Z over central Canada, plotted as a function of p, the distance over which interpolation is made. The curve (a) shows the r.m.s. error for interpolation between observations at points a distance p apart. Curve (b) shows the r.m.s. error when interpolation is made between averages taken over an interval of 30 km; curve (c) when averages are taken over 90 km. It will be seen that smoothing of the observations does not increase the accuracy of the chart significantly. In fact, the special case considered here of interpolation along the flight lines favours smoothing, and it is more likely that in general smoothing cannot reduce the error of a chart at all. Notice that smoothing increases the chart error if the smoothing interval exceeds the interpolation interval.

It is concluded that, for Canada at least, a chart based on observations 200 km apart will show the magnetic field at any point with a r.m.s. error of 200 gammas. As the density of observations is increased, the accuracy of the chart does not increase very much until the observations are less than 50 km apart. For the deepest part of the oceans, the conclusions are the same, except that the errors are one third as large.

The objection can be made that computing errors in this way is being unfair to magnetic charts - that a chart is not intended to show the value of the magnetic field at any point, but rather a smoothed version of the field. Even though the chart is based on widely separated observations each of which is likely to differ from the ideal field by a few hundred gammas because of local anomalies, it would be maintained that these differences are of a random nature and their influence would be greatly reduced by the smoothing. This argument cannot be answered quantitatively without a clear definition of the nature of the smoothed field. To give an example, suppose that we have magnetic observations at 1000 points evenly distributed over the surface of the earth. If we perform a spherical harmonic analysis with terms up to degree and order 6, we must solve for 48 coefficients. We have 20 times as much information as required, or 60 times if we use all three components and assume the field to be of internal origin and derivable from a potential. The effect of local anomalies on the observations will be made negligible, but the result is a grossly simplified picture of the geomagnetic field. Such a picture is unsatisfactory even for navigation by compass, not to mention computing fields at an altitude of a few hundred kilometers. Important features, many thousands of kilometers broad, will not be indicated at all. This is surely not the best way to use 1000 observations.

Smoothing can help only when we have many more observations than we need to show the desired detail, and hundreds of observations can be sacrificed for the general good. A superabundance of observations is exactly what is produced by airborne magnetic surveys. In fact, handling the masses of data is one of the main problems. The Canadian airborne magnetometer produced an infinity of observations. The number produced by the United States instrument is somewhat smaller, but still large in relation to the scale of world charts and the detail which can be shown.

Figure 7 shows a continuous profile of Z over the Pacific Ocean. The 5-minute average values computed by the instrument are also shown, as X's plotted at the center of their respective intervals. If some of the averages do not look very convincing, it is due to errors in making the diagram rather than the errors in the information. We mentioned that the airborne magnetometer produces an infinity of observations. Since we are charting the magnetic field in two dimensions, what we really want is a double infinity of observations, but this is not economically practicable. It will be noticed that by smoothing the profiles over 200 km or so, most of the local variations are eliminated. It is a fortunate coincidence that line-spacings of a few hundred km are practical. The cartographer can take means of the 5-minute averages, obtaining hourly averages as shown by the circles, for example, giving him an isotropic distribution of field values to contour.

There are of course more elaborate methods of smoothing than the simple linear averaging we have discussed. It has been shown (Serson and Hannaford, 1957) that if the criterion of accuracy of a magnetic chart is the closeness of representation of the field at any point, the use of the more elaborate methods is not justified. If, however, one had a definite aim, such as the production of a spherical harmonic analysis to degree and order 'n' where 'n' is known, an optimum mathematical low-pass filter can be devised, following the theory of Wiener (1949), which would make better use of the observational material.

This, then, is the most important advantage of airborne observations as against ground observations - that data is obtained in such profusion that it can be smoothed without discarding important features of the field. A more obvious advantage is that surveys can be planned to give a systematic coverage of areas where it would be impossible by other methods. Figure 8 shows the distribution of airborne observations available to the cartographer in 1960. Parallel lines have been flown some 100 to 200 km apart. In the central region the lines are on integral degrees of latitude. With a uniform coverage like this, the cartographer can state exactly how he has drawn his map, what degree of smoothing is involved, and can assign a probable error to the result. This figure represents 6 surveys, each lasting 1 or 2 months, made at intervals of about a year. It shows some 200,000 miles of flying, representing about $500,000 in aircraft expenses.

This considerable accomplishment fades into the background when we turn to Figure 9. It shows the tracks which the United States Navy Hydrographic Office plans to fly in its airborne survey of the oceans of the world. The lines are 300 to 400 km apart, and cover all the ocean areas accessible to the aircraft available at present. There are gaps, however, notable in the Indian Ocean and Antarctic regions. There are now in operation, by commercial airlines and military organizations, aircraft with ranges much greater than those available to magnetic surveyors. One difficulty is that many of these aircraft require large landing fields, and these have not yet been built near the difficult regions, particularly in the southern hemisphere. However, aircraft with ranges approaching 10,000 km but still able to use small airports are being built in quantity. One which is ideally suited for magnetic surveys has no direct currents in its electrical system, and practically negligible magnetic fields as it comes from the factory. There is at present no technological difficulty in carrying out airborne magnetic surveys in any part of the world. It is only a matter of money - 4 or 5 million dollars to buy such an aircraft. We can only wait patiently for these aircraft to become sufficiently obsolete to be assigned to scientific research.

If the whole world were covered with airborne magnetic surveys in lines 300 km apart, it would be profitable to carry a spherical harmonic analysis out to the 100th degree and order. This would involve some 10,000 coefficients.

A few years ago, Zmuda(1958) showed that one could solve for the usual spherical harmonic coefficients from total intensity information alone. From the coefficients, any component of the field could then be calculated. It has been suggested that since total intensity can be measured in an aircraft more accurately than the components of the field, a world survey might be based on total intensity observations alone. The complexity of the computation involved in carrying out the analysis to a useful number of terms is formidable, but is perhaps not an important consideration with modern computing techniques.

There are three practical objections to this proposal. First, until the earth was uniformly covered with total intensity surveys, no information concerning the components of the field could be calculated with any degree of assurance. The results of three-component airborne surveys, on the other hand, are immediately useful, and can be combined with the results of surveys carried out by different methods by the various national agencies.

Secondly, total intensity airborne surveys are subject to all the sources of error we have indicated for three component surveys, excepting the error in the direction reference system. These other errors are comparable to, and often larger than, the errors in direction. It is doubtful that a world chart of total intensity obtained by flying lines 300 km apart would be significantly more accurate than charts of the components measured by present techniques in the same survey. Thirdly, large scale aeromagnetic surveys are expensive, and the problem of measuring components to a useful degree of accuracy has been solved. Therefore, it is wasteful to discard two thirds of the information available in making an analysis of the earth's field. However, this approach may be very useful in connection with satellite observations, where the measurement of components would be more difficult than in an aircraft. A few satellites could cover the earth with observations in a very short time, at altitudes where the field can be assumed to be representable in a reasonable number of spherical harmonics.

Now that it is feasible to survey the world in a few years, the need for accurate knowledge of secular variation becomes much less critical for the production of charts of the main field. However, secular variation still has great theoretical interest, and we should inquire whether airborne observations can help in its determination. From what has been said about the effect of small errors in geographical position, it will be seen that it is quite hopeless to attempt to deduce secular change by comparing observations at points from surveys a few years apart. Knowledge of secular variation will depend for many years on the results of magnetic observatories and carefully reoccupied field stations. There are still large areas with no observatories or field stations, and here the airborne magnetometer can help. It is assumed that the features of the secular variation field are much broader than those of the main field. Thus the airborne data can be very heavily smoothed, averaging all observations in a large area, and a comparison of surveys made 5 to 10 years apart should reveal much information about the secular change which is now unobtainable. Smoothing of this sort will not remove systematic errors in the observations. It may seem pointless to worry about systematic errors of tens of gammas in measuring a function with a noise level of hundreds of gammas. But it should be kept in mind by those responsible for airborne surveys that such systematic errors may be important in future uses of the data.

Surveys by non-magnetic ship have not been mentioned. Obviously many of the arguments in favour of airborne surveys will apply equally to seaborne surveys. When magnetic observations are made continuously, or practically continuously, in a moving vehicle, a great advantage is obtained for the production of charts by sampling the field at many locations. This advantage outweighs the reduction in accuracy of a single observation due to the difficulty of measurement in a moving vehicle.

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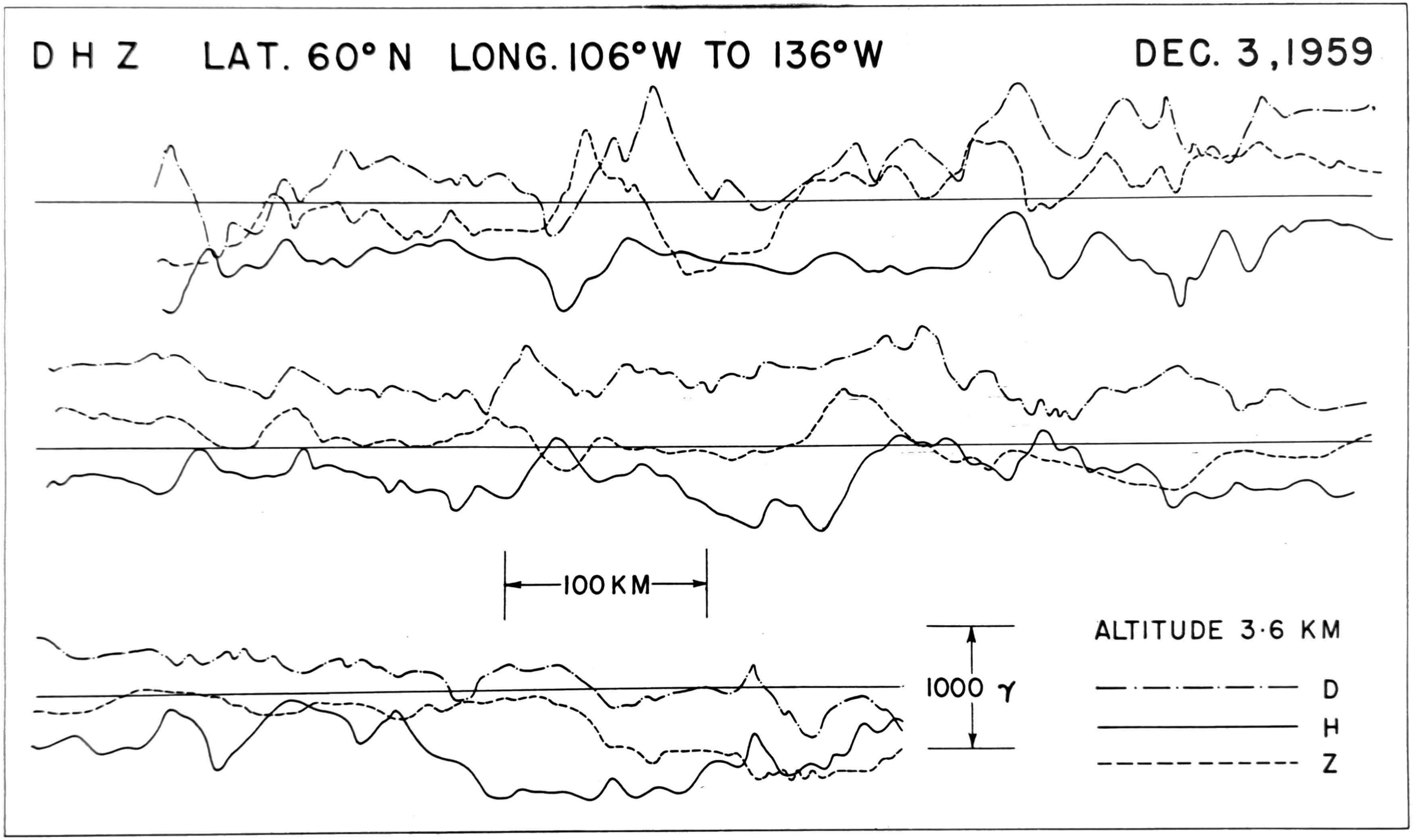

Figure 1 - Typical airborne magnetic profiles over central Canada. Regional gradients have been removed.

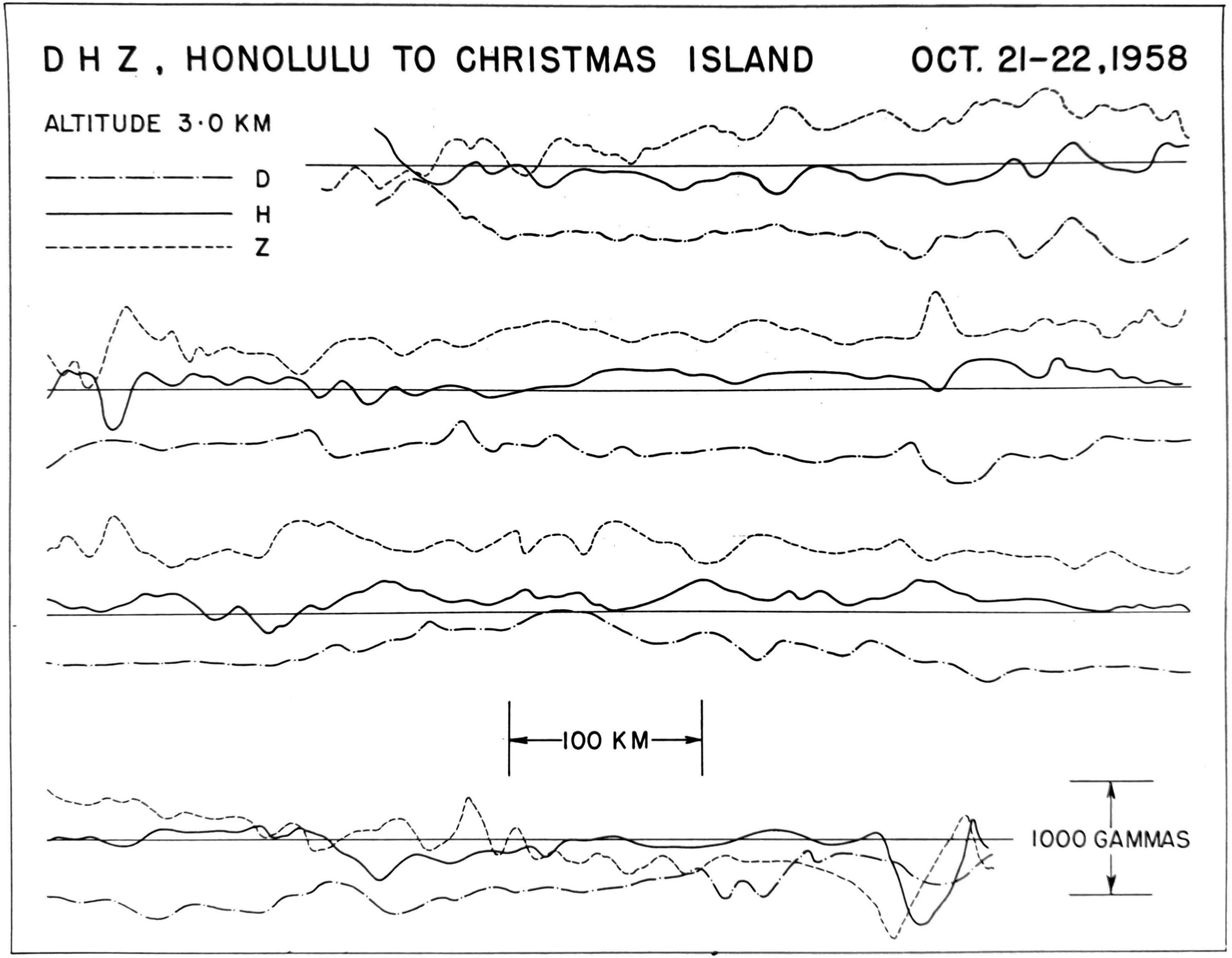

Figure 2 - Typical airborne magnetic profiles over Pacific Ocean. Regional gradients have been removed.

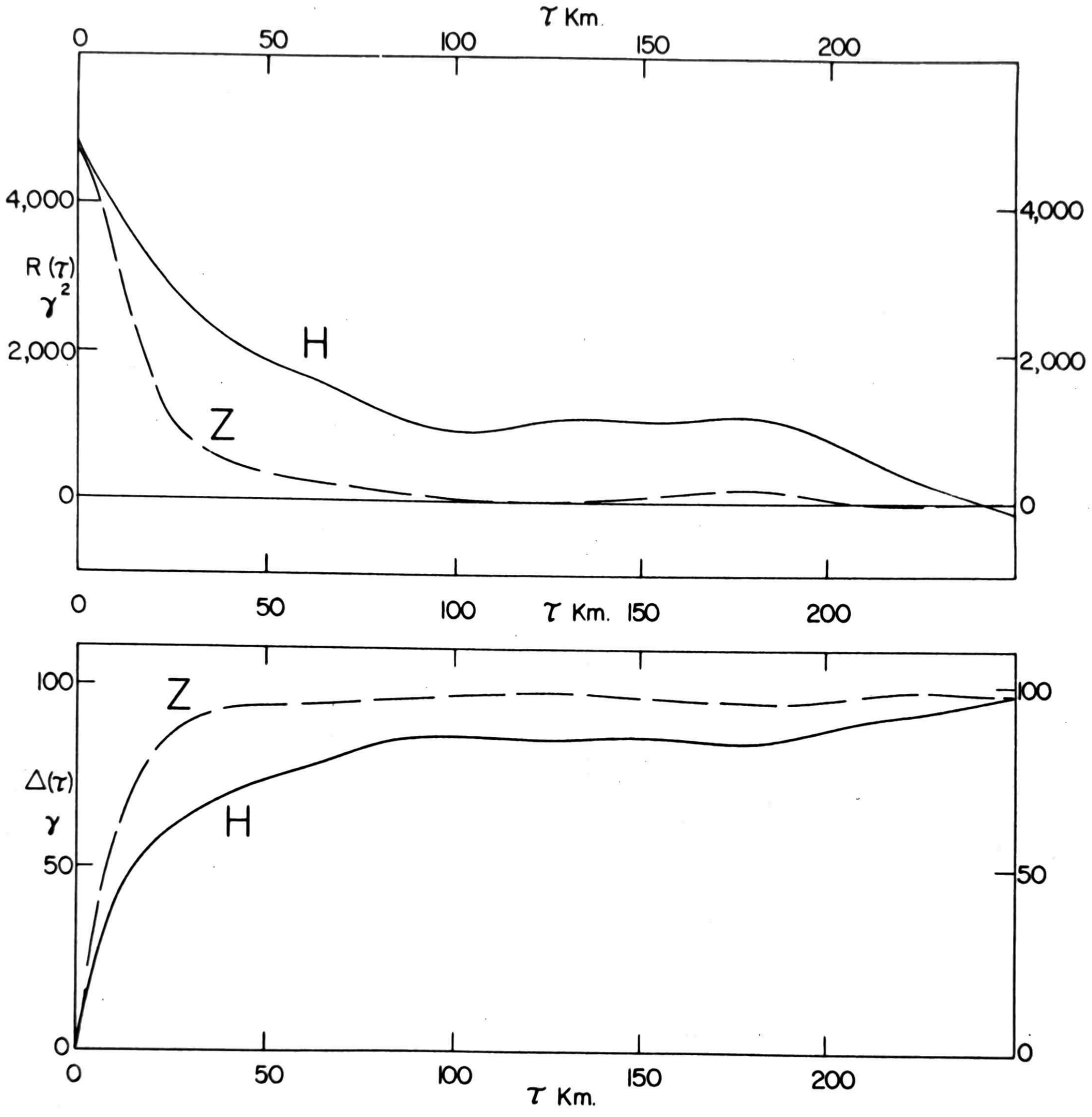

Figure 4 - Autocorrelation functions of magnetic profiles over the Atlantic east of Bermuda (above), and corresponding r.m.s. changes in components over distance τ (below).

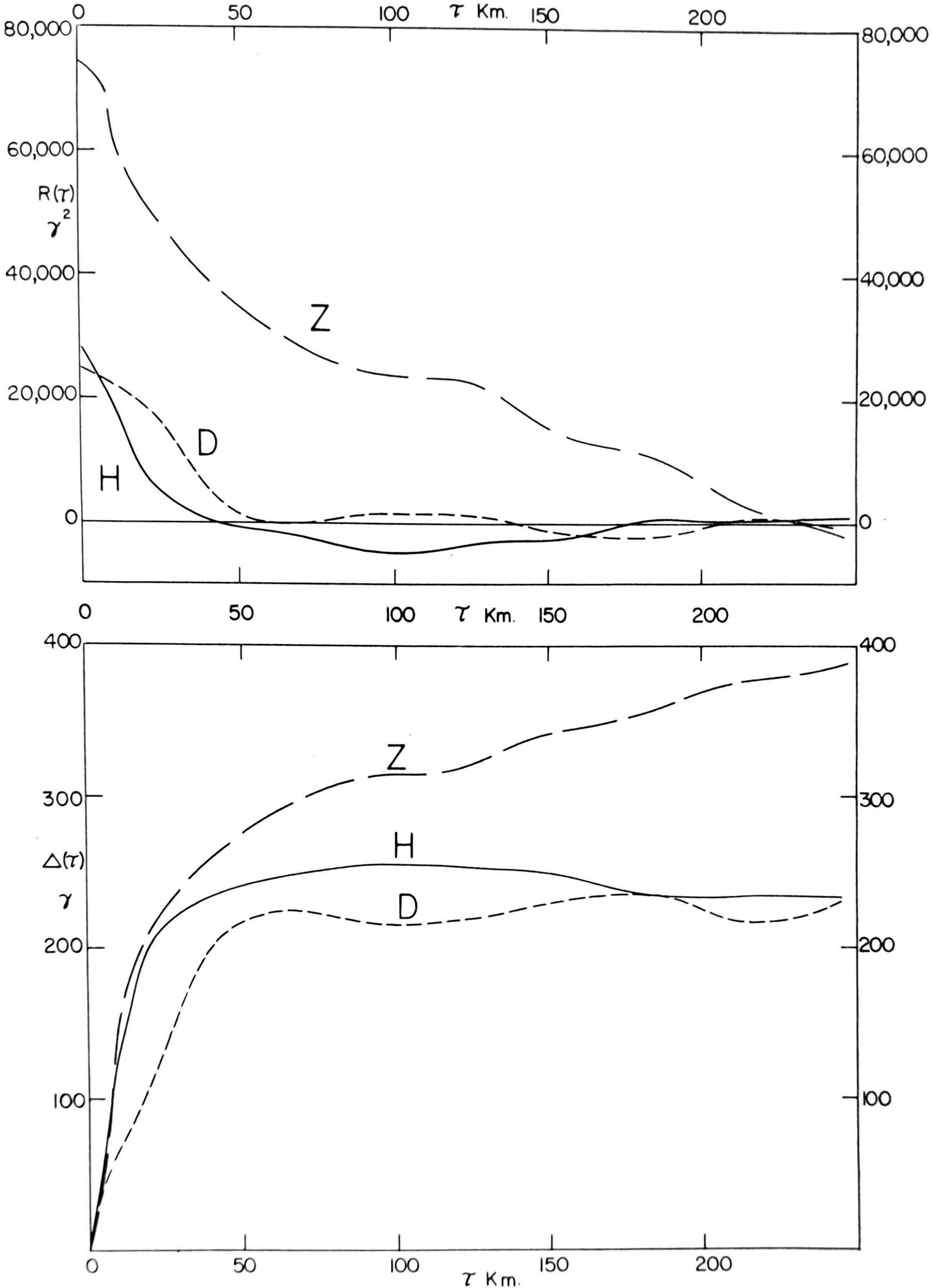

Figure 3 - Autocorrelation functions of magnetic profiles in central Canada (above), and corresponding r.m.s. changes in components over distance τ (below).

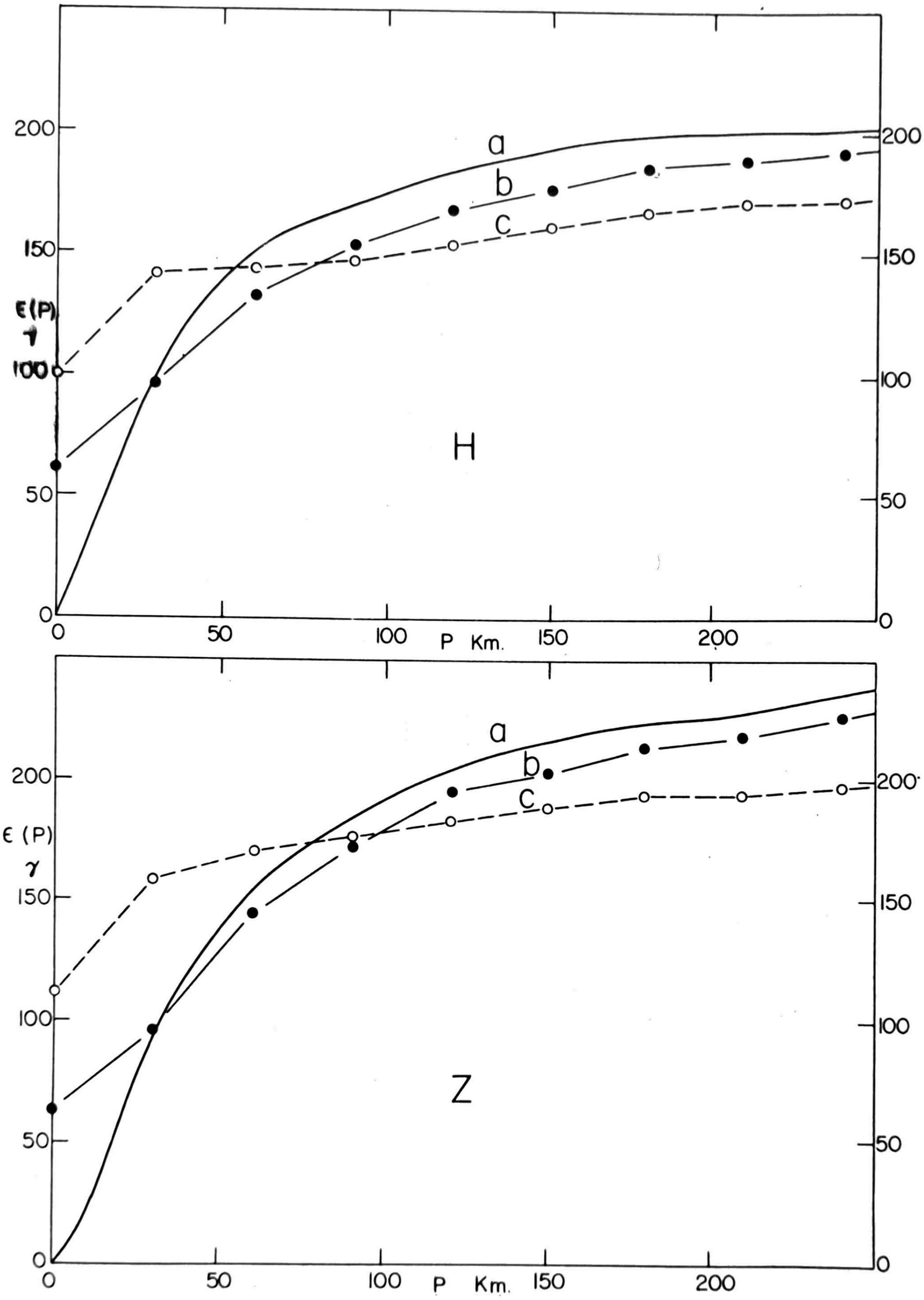

Figure 6 – R.M.S. errors in magnetic charts of central Canada for linear interpolation over interval p (a) between point observations; (b) between averages over 30 km; (c) between averages over 90 km.

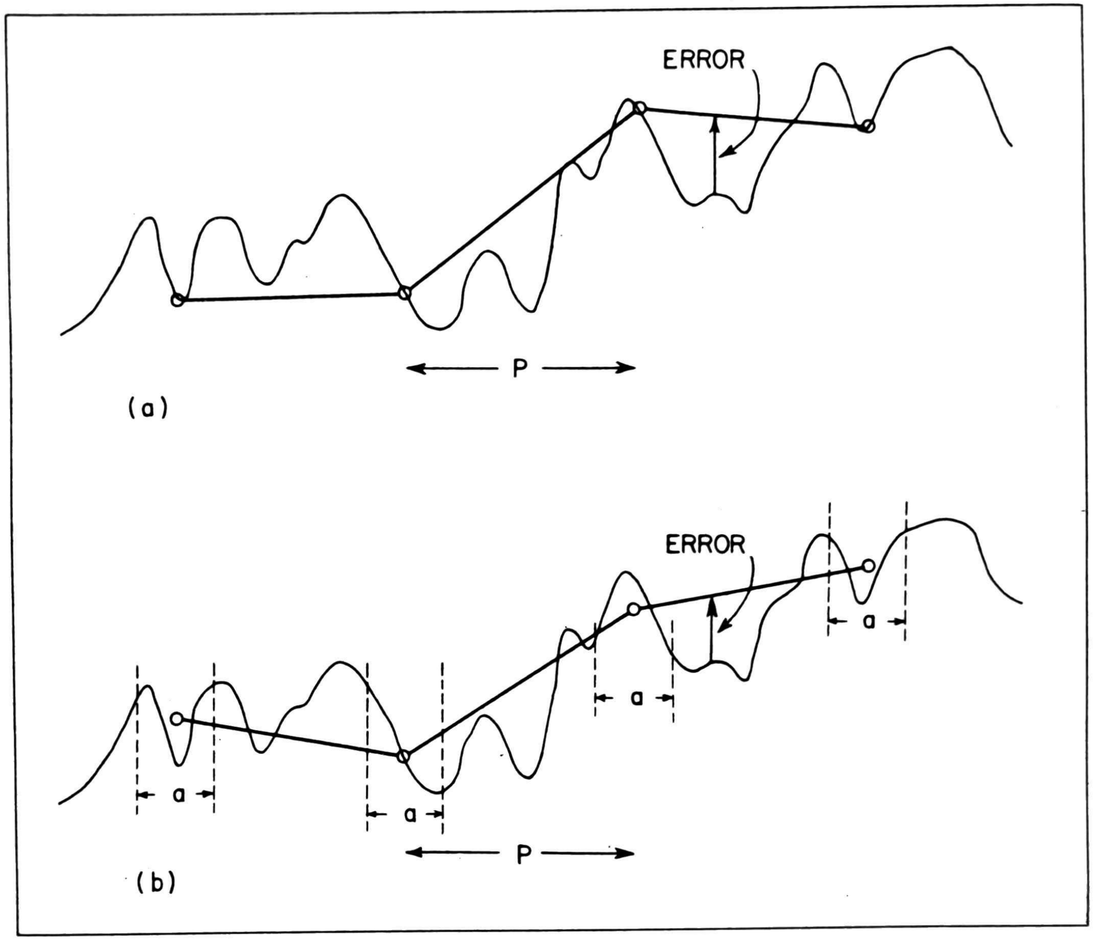

Figure 5 - Linear interpolation of magnetic observations (a) between point readings and (b) between averages over segments of the flight path.

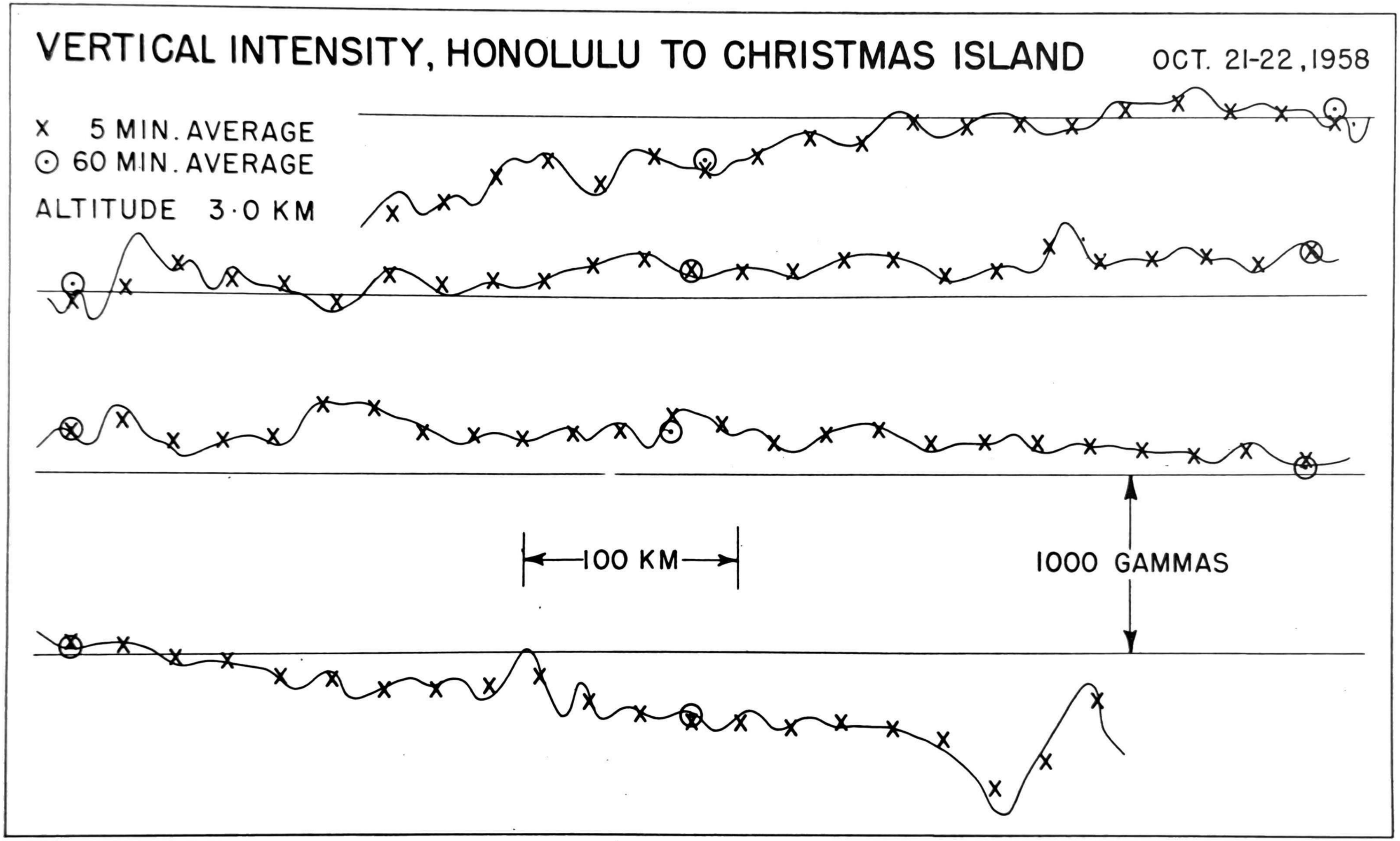

Figure 7 - Profile of vertical component over Pacific Ocean, showing 5-minute averages and 60-minute averages.

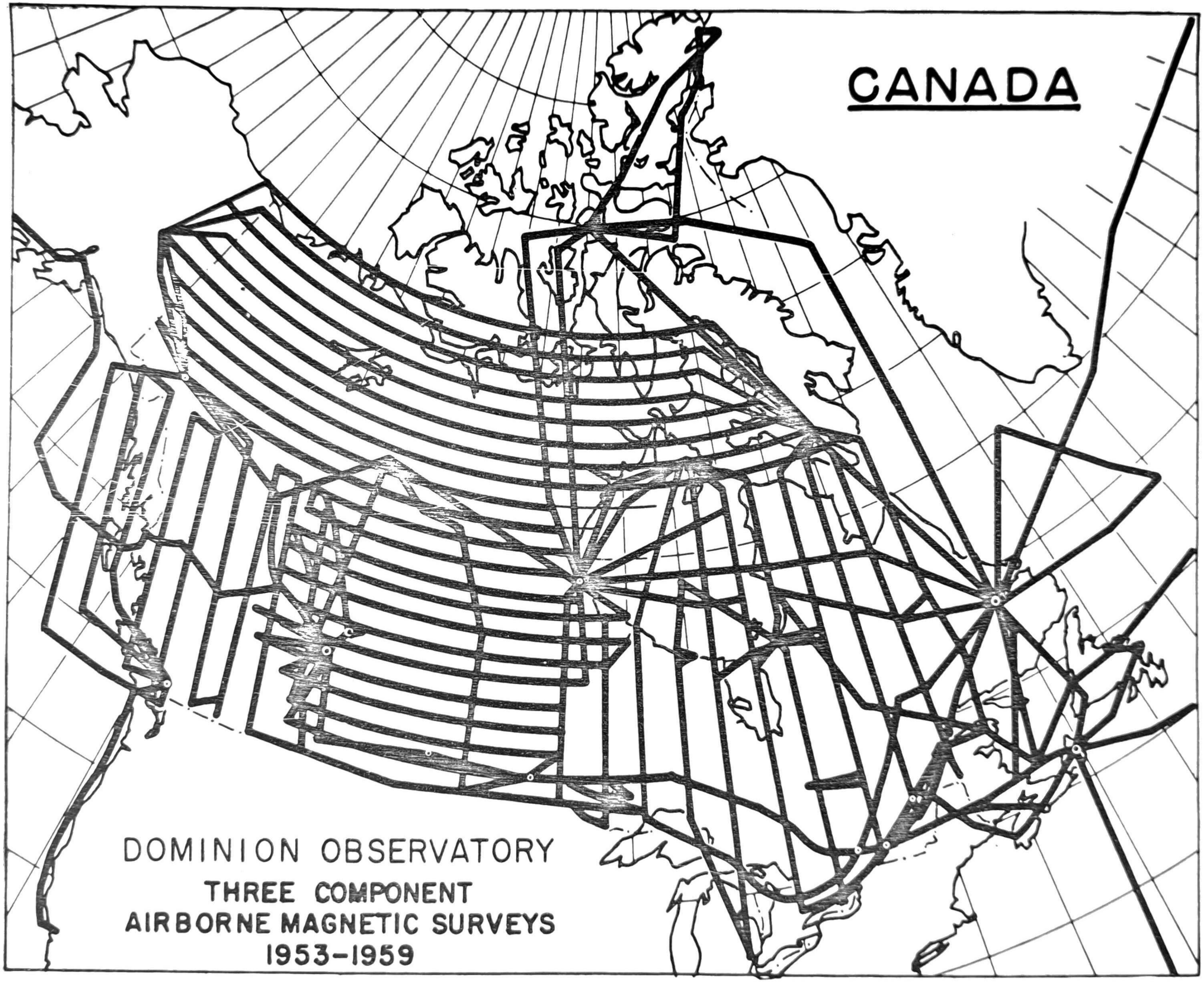

Figure 8 - Flight lines of three-component airborne magnetic surveys in Canada, 1953-1959.

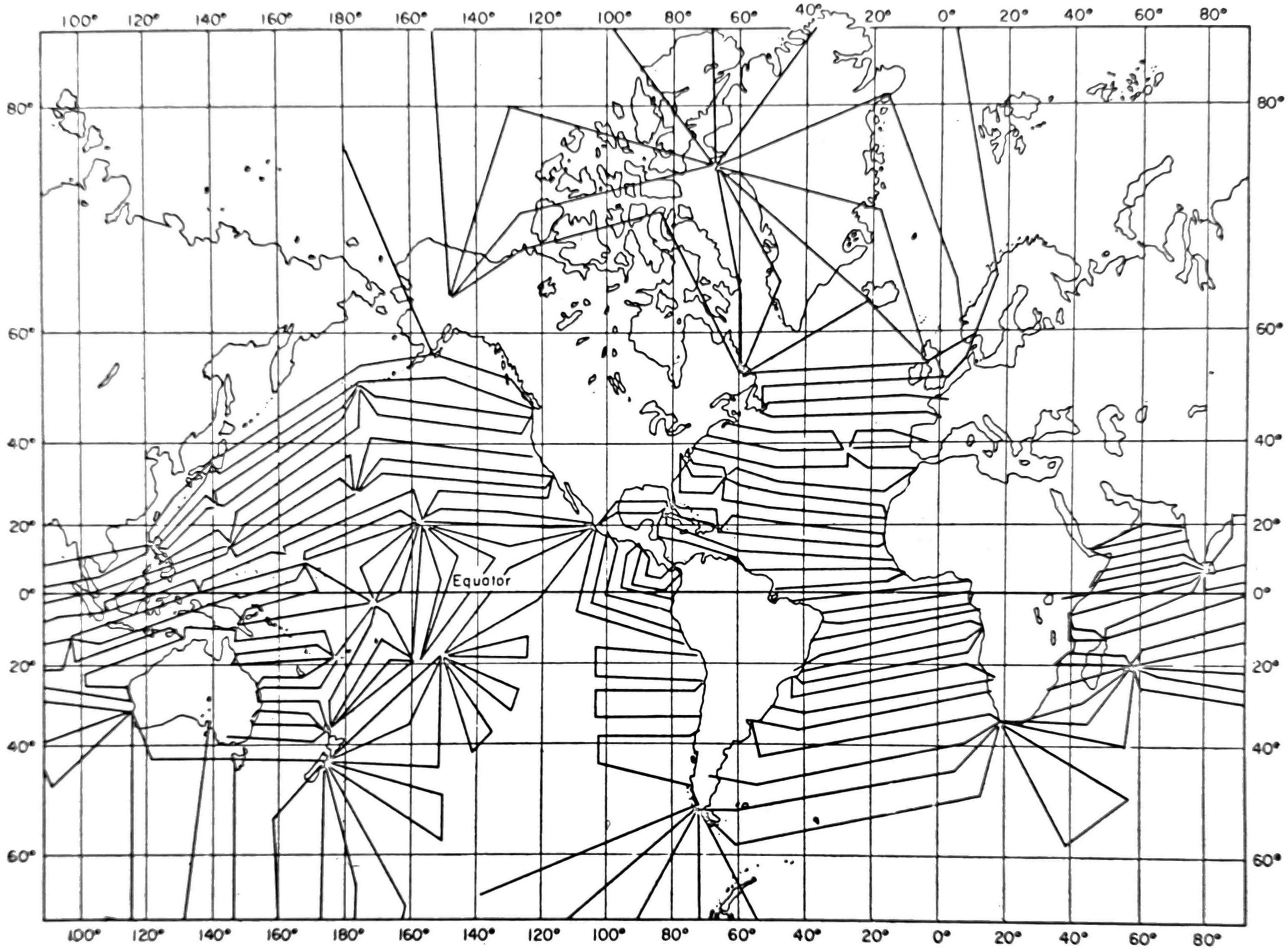

Figure 9 - U.S. Navy Hydrographic Office airborne geomagnetic survey plan Project Magnet.