THE POSITIONS OF THE MAGNETIC POLES

by Sir Harold SPENCER JONES, Sc. D., F. R. S., Astronomer Royal.

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A knowledge of the positions of the magnetic poles is important for the construction of magnetic charts of the polar areas. Charts giving the isogonals, or lines of equal declination, are needed for the purpose of air navigation over the polar regions, which is likely to become of increasing importance. The isogonals have a particularly complicated shape in the polar regions, because both the geographical pole and the magnetic pole are points of singularity, through which all the isogonals necessarily pass.

The magnetic pole can be defined as the point on the earth's surface at which the dip needle takes a vertical position, or as the point where the horizontal intensity of the earth's magnetic field becomes zero. The two definitions are, of course, equivalent. The first determination of the position of the north magnetic pole was made by Ross in 1831 in the course of a voyage to discover a North-West Passage. Observations having shown that he was in the vicinity of the magnetic pole and that the magnetic dip was increasing and was not far short of 90°, the party proceeded farther in the direction to which the compass was pointing and on 2 June reached a position at which the mean of several determinations of the dip was 89°59', and at which there was no observable directive force on a suspended magnet. The position was latitude 70° 5' N., longitude 96° 46' W., and was accepted as the approximate position of the north magnetic pole.

It was not possible for Ross to make any survey of the region in the vicinity of this point, and until the area has been given a magnetic survey in some detail it will not be possible to decide how near Ross may have been to the true position of the magnetic pole. The Canadian Arctic is a region in which there are considerable local magnetic anomalies, and the actual isogonals have complicated and distorted shapes. The position on the Boothia Peninsula where Ross observed a dip of almost exactly 90° may have been a local dip pole, where the effect of a local magnetic anomaly was superposed on the earth's magnetic field. In air navigation, with aircraft flying at a height of 10,000 ft. or more, the effects of local anomalies are very greatly reduced, and it is the true magnetic field of the earth, freed from local magnetic effects, with which we are concerned.

No further determination of the position of the north magnetic pole was made until the expedition of Amundsen in 1903. A temporary magnetic observatory was established on King William Island from November 1903 to May 1905, and a magnetic survey was made of a portion of Boothia Peninsula. A rediscussion of the observations subsequently made at Christiania (Oslo) gave the following determinations of the position of the magnetic pole :

From declination..................	70° 35' N.,	96° 10' W.
From horizontal intensity.......	70° 40' N.,	96° 05' W.
From dip	70° 40' N.,	95° 55' W.

so that a position of 70° 40' N., 96° 05' W. can be assumed. The separate results from declination, horizontal intensity and dip are concordant, which indicates that the observations were consistent, but there still remains the doubt whether the results may be influenced by a considerable local magnetic anomaly.

The comparison of the position obtained by Ross and Amundsen might suggest a small displacement of the magnetic pole between 1831 and 1904. There is no reason why the secular change of the earth's magnetic field should not produce a progressive change in the position of the magnetic pole. It would, indeed, be surprising if this were not the case. At any point of the earth's surface the intensity and direction of the earth's magnetic field gradually change. If at some place the mean value of the dip is 90° this year, it will be slightly different from 90° next year. Because, moreover, of the diurnal, seasonal and slower variations, the position at which the dip is exactly 90° will change from day to day, quite apart from the slow secular change. From this point of view the magnetic pole should be considered as an area with a radius of the order of 40 or 50 miles, rather than as a definite point. The best position of the magnetic pole which can be assigned at any particular epoch is the centre of this area. As the position assigned by Ross was derived from observations on a single day, it may have been at any point within such an area, and it is not legitimate to draw any conclusions about the motion of the magnetic pole from a comparison of the positions assigned by Ross and Amundsen. In default of any reliable information about the motion of the north magnetic pole, the Ross-Amundsen position has been generally adopted in the construction of world magnetic charts.

In connection with the prepation at the Royal Observatory, Greenwich, of the Admiralty world magnetic charts for epoch 1922, I undertook a revision of the charts for the polar regions. The observational data for these areas are rather scanty and differ considerably in epoch, and there is little reliable information about secular change. The complicated shapes of the isogonals make interpolation difficult. It occurred to me that a more reliable interpolation could be made by first plotting the projected lines of magnetic force. At any point on such a line, the direction in which the magnet points is tangential to the line. These projected lines of force must all pass through the magnetic pole, but have no relation to the geographical pole ; thus they have only the one singular point, instead of the two singular points of the system of isogonals. The interpolation between the observations became fairly straightforward and the projected lines of force were drawn without difficulty, all being made to pass through the magnetic pole as located by Amundsen. The angles between these lines and the meridians at a number of points along each line were then read off, and provided the material from which the isogonals themselves could be constructed. The values of the declination read off from this chart were compared with the observations. In the published account of the investigation I remarked : "It will be seen that the revision has considerably reduced the residuals which, however, are still systematic in their value. It does not seem possible to reduce them further whilst adhering to the position which has been adopted for the magnetic pole. A better fit could have been obtained if a position about 2° farther north had been adopted." This was, as far as I am aware, the first suggestion that the Amundsen position did not, at that epoch, fit in with the earth's general magnetic field.

In 1923 Dyson and Furner made a harmonic analysis of the earth's general magnetic field using the data from the Admiralty magnetic charts for epoch 1922, for declination, horizontal intensity and dip, prepared at Greenwich. The method of analysis first devised by Gauss was used. If it is assumed that the earth's magnetic field is derivable from a potential function, which can be expressed by means of a series of spherical harmonics, then, by differentiation, expressions for the north, east, and vertical components of the field at any point of the earth's surface can be obtained. By reading off from the charts the values of declination, horizontal intensity and dip for the intersection of the 10° meridians and parallels, the north, east and vertical components of the field at these points can be calculated. Comparing the observed values with the theoretical expressions, the coefficients of the harmonic terms can be calculated by least squares. The coefficients in the expressions for the north and east components should be in agreement, within the limits of their probable errors; this provides a check on the validity of the representation. The agreement proved to be satisfactory. The coefficients in the expressions for the vertical component will only agree with those derived from the north and east components if the magnetic field of the earth is due to causes originating within the interior of the earth. If a part of the earth's field is of external origin, the coefficients derived from the vertical component will differ from those derived from the north and east components, and a separation of the total magnetic field of the earth into parts of internal and external origin becomes possible. Dyson and Furner concluded that the coefficients were in agreement within the limits of observational uncertainty, and that there was therefore no evidence that any part of the earth's field was of external origin.

The coefficients having been determined, it becomes possible to compute the components of the earth's field at any point of the earth's surface and to compare the computed values with the observed values. In the north and east components the computed values generally agreed with the observed values within about 0.005 gauss. There were a few larger discordances, mainly in high latitudes, where the chart data are uncertain and not too reliable. There were also a number of areas within which the differences between the observed and computed values were of a systematic nature. This is not surprising, as a good deal of smoothing of scattered observational values is involved in the construction of the charts, and, further, the data are brought forward to a common epoch by the application of corrections for secular change, which may differ from their true value in the same sense over a considerable area. The power of the harmonic analysis lies in the fact that the values of the earth's field in areas where there have been plenty of observations and where the uncertainties are small can be used to give a close approximation to the field in other areas where observations are scanty and unreliable. In particular, it is possible to compute the positions of the points where the horizontal intensity is zero, *i. e.* of the magnetic poles. In this way Dyson and Furner obtained the following positions:

North magnetic pole: lat. 75° N., long. 100° W.
South magnetic pole: lat. 71° S., long. 151° E.

The position of the north magnetic pole is well to the north of the Ross-Amundsen position; but the position obtained for the south magnetic pole falls amongst several rather discordant positions assigned by observation, so that it cannot be said that for this pole there is any serious discordance. The question arises whether the difference between the computed and observed positions of the north magnetic pole is significant or whether it can be attributed to errors in the harmonic coefficients due to the uncertainties in the chart data. In the vicinity of the north magnetic pole the curves of equal horizontal intensity are elongated ellipses, whose longest axes are roughly in the N.N.W.-S.S.E. direction, the ratio in length of the major and minor axes being about 3 to 1. The rate of change of horizontal intensity near the magnetic pole is about 0.0035 gauss per degree of latitude, or, say, about 0.010 gauss in three degrees of latitude. Comparison with the discordances in other regions suggests that a discordance of as much as 0.010 gauss is about the maximum that would be expected. It is true that the chart and computed values ir some cases appreciably exceed this amount in latitudes higher than

60° N. and S., but this is the consequence of the scantiness and uncertainty of the observational data in the polar regions. The areas between latitude 60° and the geographical pole have small weight in the determination of the harmonic coefficients. The conclusion is that the discordance between the computed position of the north magnetic pole and the Ross-Amundsen position is greater than would be expected as a consequence of the general uncertainty in the chart data, and that the true position of the pole is likely to be at least 2° and possibly as much as 5° to the north and somewhat to the west of the accepted position. In the vicinity of the south magnetic pole the curves of equal horizontal intensity are much less elongated, and the rate of change of horizontal intensity is about 0.007 gauss per degree of latitude.

In 1943, I carried out, in collaboration with Mr Melotte, a harmonic analysis of the data on the Admiralty magnetic charts for epoch 1942. The analysis was restricted to the portion of the earth's surface between latitude 60° N. and 50° S., in which the data are most reliable. They were weighted, in making the analysis, according to their general consistency. Separate solutions were made first for a spherical earth (as in the analysis of Dyson and Furner) and then taking into account the spheroidal figure of the earth. The computed positions of the magnetic poles on the two assumptions are as follows :

	Spherical earth	*Spheroidal earth*
North magnetic pole.......	lat. 77° N., long. $103\frac{1}{2}$° W.	lat. 76° N., long. 102° W.
South magnetic pole	lat. 71° S., long. $150\frac{1}{2}$° E.	lat. 70° S., long. 150° E.

Comparison between these results and those of Dyson and Furner suggest that the north magnetic pole has moved in the course of 20 years through about 2° in a direction somewhat west of north. If there is a real systematic difference between the spherical harmonic representation and the true field of the earth in the polar area, it should be common to the data for the two epochs. The positions for the south magnetic pole derived from the two analyses, on the other hand, are in close agreement, and there is no indication of any movement of this pole. The assumption of the spheroidal earth should give the better positions for the poles ; it places the north magnetic pole not so far north as the assumption of a spherical earth.

The discordance between the observed and computed positions of the north magnetic pole made it desirable that the position of the pole should be redetermined. Not long after this conclusion had been reached, a series of polar flights of the Lancaster aircraft *Aries* by the Empire Air Navigation School, Shawbury, was planned, and these flights offered an opportunity for some check on the positions to be obtained. The Commandant of the Empire Air Navigation School agreed that such observations as were possible in conjunction with the other objects of the flights and with equipment that was available should be undertaken. The aircraft was fitted with five different patterns of non-stabilised compasses, with two gyro-stabilised compasses of different patterns, with an astro-compass and directional gyroscope, with a flux-valve dip-meter, and with a three-axis flux-valve magnetometer. The dip-meter and the magnetometer were not of types to give highly accurate measurements, but were the best available at the time.

In the vicinity of the magnetic pole, the directive force on the compass is small and the oscillations of the compass become rather large. During the actual flights the non-stabilised compasses were found to give reasonably good indications down to an intensity of the horizontal field of 0.02 gauss, and the gyro-stabilised compasses down to 0.03 gauss. But even at smaller fields pretty consistent results were obtained, in spite of large oscillations, by taking the means of a number of readings.

Of the various flight made, two were of special interest. One of these started from Goose Bay (approx. position 53° N., 60° W.) and proceeded to Boothia Peninsula, passing over Amundsen's position of the magnetic pole, then northwards to a point (73° 7' N., 97° 7' W.) at the north-east corner of Prince of Wales Island, then returning over the Boothia Peninsula and on to Montreal. The other was the return flight from Whitehorse in north-west Canada to Shawbury, passing almost over the computed position of the magnetic pole. Of lesser interest, from the magnetic point of view, was a flight from Iceland to the geographical north pole and back. An astro-compass and a directional gyroscope were used for determining the course of the aircraft and to derive the compass variation (declination). The mean declination obtained from the several compasses was compared with the values read from standard charts based on the Amundsen position of the north magnetic pole and with values read from special charts prepared at the Royal Observatory, using the data derived from the harmonic analysis.

On the first of these flights, as the aircraft passed across the Amundsen position of the magnetic pole, there should have been a rapid change in the direction in which the compass needles pointed, if the magnetic pole was still in that position. In spite of the small directive force on the magnets their behaviour was on the whole very consistent and no such swing was observed; there was very little change in the observed declination. The conclusion is that the magnetic pole was not reached on this flight. On the basis of the computed chart there should have been a moderate change in the opposite direction. The fact that such a change was not observed suggests that the true position of the pole is not as far north as the computed position.

On the second flight a rapid change of 180° in the declination was to be expected as the aircraft passed by the computed position of the pole. If the pole was in the Amundsen position a similar change would have occurred, but the change would have occurred gradually, along about 1200 nautical miles of track. The change actually observed fell between the two expected changes, but was much nearer the change that would have occurred if the aircraft had passed over the pole. The conclusion is again that the pole is between the Amundsen and computed positions, but nearer the latter.

The flight to the north geographical pole showed changes in declination in the vicinity of the pole which agreed much more closely with the computed chart than with the standard chart.

The observations of dip, vertical intensity, and horizontal intensity did not give much conclusive information bearing on the position of the magnetic pole. These quantities vary rather slowly in the vicinity of the pole, and the differences to be expected on the two different assumptions about the position of the pole are not in general significant. In passing over the magnetic pole, the horizontal intensity should fall to a zero value. The magnetometer was used with the maximum sensitivity when the horizontal intensity was below 0.03 gauss. On neither flight did it fall to zero. The conclusion might be drawn that the true position of the pole is somewhere between the Amundsen and computed positions. It is doubtful, however, whether this conclusion is legitimate, because a small error in tilt of only 1° would produce an apparent horizontal intensity of the order 0.01 gauss, since the vertical intensity is about 0.59 gauss at the pole.

The *Aries* flights, while not providing conclusive evidence, afford strong support to the view that the magnetic pole is probably between the Amundsen position and the computed position, but nearer the latter. It is not possible to decide from these flights whether there has actually been motion of the magnetic pole, or whether the position assigned by Amundsen was merely a local dip pole, produced by the superposition of a local magnetic anomaly on the true field of the earth.

Since these flights were made in 1945 some still more definite information has been provided by observations made by the Surveys and Engineering Branch of the Dominions Observatory, Ottawa, in conjunction with the Geodetic Service. In recent years a network of magnetic stations has been gradually extended in the Canadian Arctic north of latitude 60°. Over 200 stations north of this latitude have been added since 1943, and there is now a pretty good coverage up to latitude 70°. Results of observations made on various repeat stations across the northern part of Canada had suggested to the Dominions Observatory that the magnetic pole was travelling in a northward direction. The convergence of the isogonal lines within the region extending to some 10° south from the magnetic pole gives an approximate position of the pole, and the secular change in the directions of the isogonals gives an indication of whether or not the pole is fixed in position.

During the summer of 1946 observations were extended farther northwards in connection with Exercise Musk-ox and the Eastern Arctic Patrol. Observations were secured at Denmark Bay, Victoria Island, and at Fort Ross, Somerset Island. On the basis of the additional information obtained, the Dominions Observatory announced in May 1947 a provisional position of the north magnetic pole at latitude 73 1/4° N., longitude 94 1/2° W., on Somerset Island.

During the summer of 1947 further information has been obtained with the aid of amphibious aircraft of the Royal Canadian Air Force. Magnetic observations were made at ten stations throughout the North-West Territories, surrounding the probable position of the magnetic pole. Thus, for instance, there were two stations on the eastern part of Victoria Island, two on Prince of Wales Island, one on King William Island, one on the east coast of Boothia Peninsula. Observations at a number of stations are necessary to decide whether the observed position of the pole is influenced by local magnetic anomalies. The results of these observations have not yet been published, but Dr C. S. Beals, the Dominions Astronomer, has informed me in a letter that the distribution of stations proved favourable, and that the observations indicate that the position of the magnetic pole is in the north-western part of Prince of Wales Island. The exact position is not given, but it cannot be far from latitude 73 1/2° N., longitude 100° W. This position is between the old position and the position derived from the harmonic analysis for a spheroidal earth, but rather nearer the latter position. It is in satisfactory accord with the conclusions derived from the *Aries* flights.

It is gratifying that the results obtained on these flights with somewhat improvised equipment have been so well confirmed. They show the value that could be derived from aircraft observations with more sensitive and accurate magnetic equipment. During the war the MAD (magnetic airborne detector) was developed in America for use in detection of submarines ; it measures the total field with a very high accuracy. Modifications of this equipment are in progress to enable three components of the field to be measured. If the *Aries* flights could be repeated, with such equipment installed, an important addition to our knowledge of the earth's magnetic field in the vicinity of the pole would result.

It seems to be now pretty well established that the north magnetic pole has moved more than 200 geographical miles in a direction somewhat west of north since its position was determined by Amundsen in 1905, or at the rate about five miles a year. The south magnetic pole, on the other hand, does not appear to have any appreciable motion ; its position needs to be more accurately determined by direct observation, and the most convenient means of making the observations would again be by the use of aircraft. It is to be hoped that this further addition to knowledge will be made at no very distant date.