Analysis of Long Magnetic Profiles

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Abstract

Mobile recording magnetometers were developed during and after World War II. These new instruments have permitted the recording of long magnetic profile lines. These long magnetic profiles have clearly shown that two distinctly different types of anomalies occur. Many local anomalies are found with amplitudes up to a few thousand gammas and widths up to a few hundred kms. Very large regional anomalies are found with amplitudes of tens of thousands of gammas and widths of several thousands of kms. There are no noticeable anomalies between these two types.

It is suggested that world magnetic charts made to a scale of less than 1/30,000,000 should be smoothed so as to eliminate the effect of all local anomalies on the isoline shapes. The characteristics of local anomalies could be indicated on the chart by a color coded scheme which in effect would indicate a chart error which might be expected because of local anomalies in the area.

1. Introduction

Recordings of time variations in magnetic components have been made nearly continuously in many magnetic observatories since the introduction of photographic recording at the Royal Observatory, Greenwich, in 1847.

These early continuously recording instruments were not mobile so they could not be used to obtain recordings of magnetic field variations as a function of distance or location.

Because there were no mobile recording magnetometers in the early days, all magnetic charting had to be done from spot measurements. Each measurement was rather laborious to make so there was a tendency to space them very far apart. Since the detailed picture between measured points was not determined, it was not known whether the measured points themselves represented good average values for that area or whether they might be anomalous values.

In the early days of geophysical magnetic prospecting, ground magnetic measurements were often made at close spacings so that local anomalies were known to exist, but such surveys never covered very large areas because of the expense and time required to make such surveys. The area covered was generally much too small to reveal the relationship between strictly local effects and broader regional anomalies.

No doubt the first mobile magnetic instrument was the marine compass. These were not, of course, recording instruments and in any case could not have given very useful detailed information because of poor navigation and heading controls.

The advent of recording mobile magnetometers, which proved to be a real significant breakthrough for magnetic surveying, had to await the development of electronic magneto-
meters.

During World War II the fluxgate was highly developed for use in aircraft for submarine detection and was later modified for geophysical exploration (Jensen, 1946; Muffly, 1946; Rumbaugh and Alldredge, 1949). Hope (1964) points out that in the USSR, the first aeromagnetic survey flight was made in 1936, with an airborne magnetometer developed by A.A. Logachev. These geophysical instruments record the magnetic total field intensity continuously along the flight line with a sufficiently small base line drift to permit the accurate magnetic contouring of areas crisscrossed by the magnetometer.

In this application it was customary to develop areas a few hundred miles square in great detail so that most flight lines were not more than a few hundred miles long.

These lines were still too short to clearly show how local magnetic anomalies blended into the truly world wide regional anomalies clearly shown no world charts. The same kind of magnetometer was successfully adapted for towing in a fish behind ships.

Gradually both the ship-towed and the airborne fluxgate magnetometers were used to obtain very long magnetic profiles which began to reveal the nature of the anomalies between the strictly local type and the very long regional type. The proton precession magnetometer slowly replaced the fluxgate instrument in ship-towed installations.

The fluxgate airborne magnetometer was later further modified so that the entire magnetic vector could be determined (Schonstedt and Irons, 1955). It is this instrument which has been used so successfully on many around-the-world survey flights by the U.S. Oceanographic Office on project Magnet (Byrnes, 1960). P. Serson in Canada has developed a comparable instrument.

These new mobile recording magnetometers have marked the beginning of a new era in magnetic measurements as was foreseen by Vestine (1947), nearly twenty years ago, when he wrote “...high speed world surveys, such as might be made by airplanes, with complete coverage of the earth in a year or two and repeated every decade, are the hopeful dreams of those responsible for future isomagnetic charts.”

2. General Results

One of the earliest very long magnetic profiles was obtained in 1947 on project Volcano. Figure 1 (Alldredge and Keller, 1949) shows the magnetic total field intensity from Adak Island to Kwajalein Atoll as recorded by a fluxgate instrument at a flight altitude of approximately 1,000 feet. The broken line represents data taken from the 1947 U.S. Hydrographic Office Chart No. 1703. The zero line of the data taken on this survey was arbitrarily adjusted to provide a good average agreement with the hydrographic chart data in the area between Wake and Midway Islands.

A comparison between the broken line and an imaginary smooth line representing the solid curve of Figure 1 with local anomalies removed, indicates a discrepancy between these two sets of data. The discrepancy is as large as 400 gammas south of Wake Island and as large as 1000 gammas near Adak.

Large discrepancies as indicated above were surprising since this flight line was in an
area where very few measurements had been made earlier. In fact this flight was one of the first extensive magnetic measurement programs over open sea areas since the non-magnetic ship CARNEGIE was lost in 1929. More recent very extensive measurements by project Magnet and by the ship ZARYA, should greatly improve the magnetic charts in the ocean areas.

Perhaps the most striking feature which has been discovered by ship-towed magnetic records, is that of large horizontal displacements in the floor of the ocean. Vacquier, Raff and Warren (1961) have found discontinuities in the north-south pattern of magnetic anomalies in the Northeast Pacific along the Murray, the Pioneer, and the Mendocino faults. By fitting the magnetic anomaly pattern across the faults a combined displacement across the Mendocino and the pioneer faults of about 800 nautical miles was found. The offset at the Murray fault suggests a right-lateral displacement of about 84 nautical miles.

Using a similar method Vacquier and Von Herzen (1961) have suggested that the mid-Atlantic ridge has been displaced in several segments by as much as 110 nautical miles. This type of research could not have been accomplished without continuous recordings of the magnetic field over long distances.

The above conclusions regarding large geologic displacements were possible because of the distinct linear trend of magnetic anomalies which were found. Many places where magnetic surveys have been made do not exhibit linear trends. On the other hand, there are a few areas such as in the Northeast Pacific cited above, where a very distinct linear pattern is found in the local anomalies. In the Northeast Pacific the anomalies trend toward the North to Northeast direction and have a typical width of 20 to 30 n.m. and a length up to several hundred n.m.

Hope (1964) calls attention to several other examples of large linear trends exhibited by magnetic anomalies near the Boothia Arch, and in the Kurile-Kamchatka island arc. He calls these crustal macranomalies. He points out that tectonic activity of a compar-
able size-range has a marked linear tendency (geosynclines, oceanic troughs, island arcs, mountain ranges) and hence any associated magnetic effects would be expected to have a linear trend.

Although these large linear trending anomalies are important features of the crustal field still they are usually much too narrow to be preserved on world magnetic charts.

Heirtzler (1961) has made a valuable contribution to magnetic surveying by making available detailed magnetic profiles taken during a 40,000 n.m. voyage of the Vema in 1959-60.

In the older magnetic world charts there are a few examples where extreme curvatures in isomagnetic lines were included in a few remote places of the earth. In one such example, it was found that the extreme curvature was included to accommodate, a single track of widely spaced measurements made east and northeast of Greenland. Since the advent of the airborne magnetometer, surveys have been systematically made of more than half of the Arctic Ocean (King, Zietz and Allredge, 1964). These new surveys show many anomalies distributed over the Arctic area in addition to the one shown by the isolated extreme curvature in the earlier charts indicating that either more sharp curvatures should be included or else the few that are there should be removed. The anomaly size that should be included in a magnetic chart will, of course, be determined by the scale of the chart. Most local anomalies can not be included on world magnetic charts which are normally made at a scale of about 1/33,000,000.

This last point as well as the distribution of anomalies which were found on a very long flight line are shown in Figure 2 (Allredge, Van Voorhis, and Davis, 1963). This composite around-the-world magnetic profile was obtained by piecing together parts of several different around-the-world flights so as to form as nearly a straight path as possible. All of the data used were taken by project Magnet of the U.S. Naval Oceanographic Office. The average flight altitude was approximately 9000 feet. The magnetic profile shows the difference between the observed values of the total field intensity and

![Fig. 2. Around-the-world profile showing both position and nondipole field. The horizontal scale is linear in distance along the flight path which was at an altitude of approximately 9,000 feet.](image)
the total field intensity of a centered dipole.

From the dimensions of the local perturbations compared to the large regional variations it is immediately apparent that only the details of the latter can be included in world charts. On the other hand, it should be possible and desirable to include some information regarding the local anomalies by some form of color coding on the charts denoting their amplitude and width.

It should generally be true that the sharpness of magnetic anomalies recorded in Figure 2 can be taken as a rough indicator of the depth of the magnetic sources, and the amplitude of the local anomalies should indicate something about the magnetic characteristics of the source material.

The following general ideas are suggested from an examination of Figure 2:

1. From the east coast of the United States to the vicinity of the mid-Atlantic ridge, the magnetic sources are at moderate depth and have only moderate permeability contrast.

2. Magnetic sources are very shallow over a region from about 40°W to Lisbon. These shallow sources are centered on the Azores and are associated with the mid-Atlantic ridge.

3. The profile over the entire Mediterranean Sea is nearly void of local anomalies except over Sicily and the toe of Italy. This probably indicates a great depth to basement rock.

4. The magnetic structure under the Arabian peninsula and along the coast of the Arabian Sea has very little susceptibility contrast and is quite deep.

5. Deep magnetic sources with high susceptibility contrasts are indicated under India.

6. Across the Bay of Bengal, Viet-Nam, and the South China Sea, the sources are shallow but of low susceptibility contrast.

7. From Manila to Tokyo, the susceptibility contrast is moderate and very shallow.

8. Across the entire Pacific from Tokyo to Portland via Adak, the sources are shallow. The structure of the magnetic basement from the Aleutian trench to Portland is broken up into small, quite regular pieces. The pattern from Tokyo to Adak is less regular. Two major seamounts were apparently encountered in this area. Very large, slightly deeper sources are apparent in the vicinity of the Aleutian Island arc.

9. The major magnetic sources across the United States tend to be very deep, with a great many shallower intrusions.

3. Spectral Analysis of Long Profiles

Serson and Hannaford (1957) were the first to apply spectral analyses to long continuous (or nearly continuous) magnetic profiles.

They have made autocorrelation and related root-mean-square (r.m.s.) change studies in the components $D$, $H$ and $Z$ over three north-south flights in Western Canada totaling 3,600 Km in length and over two east-west flights totaling 2,400 km over the Atlantic Ocean east of Bermuda. All flights were made at an altitude of 3 km above sea level.
The magnetic profiles resemble gentle curves with wavelengths of a few thousand Km, on which are superimposed local anomalies (noise) of a much shorter wavelength which are the largest source of errors in magnetic charts.

Serson's and Hannaford's main purpose was to analyze the noise so they first eliminated the smooth background field by assuming it to be a linear function of horizontal distance. This simplification resulted in uncertainties in the autocorrelation results for large intervals (for large values of $\tau$ or long wavelengths.) This means that their analysis can not give any information regarding very long wavelengths typical of sources within the core. In fact the length of the original profiles were too short for this purpose.

Figures 3 and 4 show autocorrelation functions and r.m.s. changes in components for magnetic profiles over Western Canada and the Atlantic Ocean east of Bermuda respectively. Over land there is little correlation between values more than 50 km apart in $D$ and $H$. In $Z$, over land, the correlation at large values of $\tau$ is due to the poor fitting of the straightline approximation to the curved profiles. The low-frequency cutoff shows more clearly in the r.m.s. changes than in the autocorrelation functions.

Fig. 3. Autocorrelation functions of magnetic profiles from three north-south flights in Western Canada (above), and corresponding r.m.s. changes in components over distance $\tau$ (below) (after Serson and Hannaford, 1957).
The autocorrelation function of $H$ in Figure 3 definitely goes negative, indicating a maximum in the spectrum of the anomaly field at a Wavelength of about 200 km.

In Figure 4 the correlation at large values of $\tau$ in $H$ is caused by the same reason given for $Z$ in Figure 3. Here the $Z$ profiles were quite straight, while the $H$ profiles showed more curvature.

The amplitudes of these values show that the anomalies over the ocean, for these examples, are about one-third as large as those over land.

Serson and Hannaford have used their autocorrelation information regarding the noise or local anomalies to draw conclusions about the desired geographical density of observations in making surveys for magnetic charts. They conclude that when, as is generally the case, anomalies are the main source of error in magnetic charts, simple linear interpolation between point readings is likely to produce nearly as accurate a chart as any other method.

In the construction of magnetic charts from airborne measurements, the main problem is in interpolation not along the flight lines but between them. For economy, the flight lines are usually spaced as far apart as is permitted by the desired accuracy. If linear interpolation is to be used, there is a slight advantage to smoothing or averaging the values along the flight line over a distance shorter than the interpolation interval.
before the interpolation is done. The spacing between flight lines is, however, too great
to permit smoothing before the linear interpolation is applied perpendicular to the flight
lines.

Serson and Hannaford further conclude that an airborne survey with lines 50 km
apart, costing five times as much as one with lines 250 km apart, will produce charts
only 35 percent more accurate and may, therefore, not be worth the extra trouble.

The above conclusions would be slightly modified if agreement could be reached to
the effect that world magnetic charts are not expected to reflect any of the local ano-
malies, but should show only the very wide regional effects usually attributed to very
deep sources. In this case, a smoothing procedure over a distance of several hundred
km would be called for and it would be admitted at the start that the r.m.s. error in
the chart would be equal to the r.m.s. amplitude of the local anomalies. If smoothing is
done along the flight lines as indicated above then there would be no need to space the
flight lines any closer than the smoothing interval along the flight lines. Deviations from
the smooth curve along the flight lines could be used to characterize the nature of the
local anomalies and could be color coded into the smooth chart as a measure of the local
errors to be expected.

When larger scale magnetic charts are contemplated encompassing single countries
or even smaller subdivisions, then very close spacing of survey lines may be indicated
so that in the largest scale charts all local anomalies would be shown.

Fortunately, there seems to be a very natural distinct division of anomalies into
local and regional varieties with a large gap in between, as discussed later, so that per-
haps only two kinds of charts are needed; those with and those without local anomalies.

It is suggested that since wavelengths less than 1.0 cm can not be readily depicted
on a chart and since, as discussed later, very few local anomalies have wavelengths
greater than 300 km any chart made to a scale less than 1/30,000,000 should not attempt
to depict local anomalies.

Serson and Hannaford did not take the Fourier transform of their autocorrelation
functions to obtain the more easily understood power spectra.

Bullard, Hill and Mason (1962) have made a power spectrum analysis of the total
field along an east-west profile 379 miles in length in the North Atlantic. Their results
are shown in Figure 5. This spectrum shows a peak in the power spectrum at a wave-
length of 55 miles with other minor peaks at 30 and 20 miles. When a harmonic analysis is
made of such a short line, there is always an implied fundamental wavelength equal to
the length of the line. The resulting amplitudes of the fundamental and other low order
harmonics are modified considerably by the method used to take out the general back-
ground trend. Much longer lines should be analyzed to obtain useful information about
wavelengths greater than 100 miles.

The longest magnetic profile which has been analyzed is that reported by Alldredge,
Van Voorhis and Davis (1963). Some general aspects of this profile which are shown in
Figure 2 were discussed earlier.
Since this profile is continuous around the world it is truly a periodic function so that a meaningful power spectrum can be obtained. For the analysis, values of $F$ were scaled to the nearest gamma once a minute of time along the track, giving a total of 6,112 observational values. At the aircraft's average speed of approximately 180 knots, this gave scaled values separated by about 3 n.m. along the flight path. Fourier coefficients up to order 2,000 corresponding to a wavelength of 10 n.m. were computed. The separate values of $A_n$ and $B_n$, the coefficients for the cosine and sine terms respectively, depend on the starting point of the analysis, whereas $R_n = (A_n^2 + B_n^2)^{1/2}$ is independent of the arbitrary starting point. $R_n$ is plotted against $n$ in Figure 6. This is the harmonic spectrum of the nondipole field. Figure 6 extends only to $n=1000$ because of the mechanical difficulty in extending the plot to order 2000. Between $n=1000$ and $n=2000$ the spectral components in general continue to decrease in amplitude. There are no coefficients greater than 3 $\gamma$ for $n$ greater than 1319, and no coefficients greater than 2 $\gamma$ for $n$ greater than 1660.

A change in the ordinate scale by a factor of 250 is made at order 20 so that we may properly show the small-amplitude, high-order terms. The most striking feature is the extremely rapid drop in amplitude as the order increases from 1 to 7. The values for $R_n$ up to order 12 are shown in Table 1.

It should be remembered that the dipole field was subtracted from the data before the harmonic analysis was made. When the dipole term if added the total field intensity at selected points will be as large as 60,000 gammas. None of the coefficients in Table 1 of order greater than six has an amplitude any larger than 0.07 percent of the peak total field intensity.

This striking result makes it clear why early spherical harmonic analyses of the earth's field which seldom were carried beyond order six were so successful.

Since local anomalies may have amplitudes up to a few thousand gammas and
widths of several tens of miles, one might have expected to find a peak in the harmonic analysis at a wavelength of several tens of miles, but such was not observed. In fact no single harmonic above order 200, which corresponds to a wavelength of 100 n.m., has a coefficient greater than 14 gammas. At first this seems to contradict Bullard's findings.

Table 1 Harmonic Amplitudes

<table>
<thead>
<tr>
<th>Order ($n$)</th>
<th>$R_n = (A_n^2 + B_n^2)^{1/2}$ (gammas)</th>
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<tbody>
<tr>
<td>0</td>
<td>3442.8</td>
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<tr>
<td>1</td>
<td>5295.4</td>
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<tr>
<td>2</td>
<td>4464.6</td>
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<tr>
<td>3</td>
<td>2430.3</td>
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<tr>
<td>4</td>
<td>319.9</td>
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<tr>
<td>5</td>
<td>204.0</td>
</tr>
<tr>
<td>6</td>
<td>191.9</td>
</tr>
<tr>
<td>7</td>
<td>39.5</td>
</tr>
<tr>
<td>8</td>
<td>42.0</td>
</tr>
<tr>
<td>9</td>
<td>11.5</td>
</tr>
<tr>
<td>10</td>
<td>37.4</td>
</tr>
<tr>
<td>11</td>
<td>34.5</td>
</tr>
<tr>
<td>12</td>
<td>26.2</td>
</tr>
</tbody>
</table>
of Figure 5 which indicates several power spectra peaks with wavelengths less than 100 n.m.

This apparent inconsistency is understood when the two analyses are compared in detail. Bullard's analysis assumed a fundamental periodicity of 379 miles (length of profile used). This meant that his entire profile must be accounted for by harmonics having wavelengths given by

\[ \lambda = \frac{379}{n} \text{ (miles)}. \]

so that there are only three harmonics between wavelengths of 30 and 40 miles. In contrast with this the analysis of Figure 2 yields harmonics with wavelengths of

\[ \lambda = \frac{20,000}{n} \text{ (n.m.)}, \]

so that there are 166 harmonics between wavelengths of 30 and 40 n.m.

This finer look at the spectrum in the latter case provides many harmonics in a given band width which when added together can produce the resonance peaks which might be noted in a coarser analysis.

An attempt to see how this might work has been made by grouping the harmonics together to determine the 'energy' in a fixed wavelength width filter.

Fig. 7. Energy in 10-nautical mile wavelength intervals.
The wavelength width chosen is 10 n.m. Harmonic coefficients from order 2000 down to 1000 contribute to the wavelength band from 10 to 20 n.m. Harmonic coefficients from order 999 to 666 contribute to the wavelength band from 20 to 30 n.m. Above 450 n.m., there is only one harmonic order in any one 10-mile wavelength band. The ‘energy’ in a band is assumed to be the summation of the squares of all the coefficients within the band. This type of analysis yields the results of Figure 7. Two distinct wavelength groupings are clearly evident.

The extreme range of values in Figure 7 requires use of the log scale, which in turn partly obscures the extent of the minimum in the center. Starting at short wavelength end, the ‘energy’ remains nearly constant until a definite break is noted at a wavelength of about 100 n.m. A rough mean curve imposed on Figure 4 would lie below 625 $r^2$, from a wavelength of 125 to 2000 n.m. The corresponding amplitude is only 25 $r$.

Since the width of anomalies must generally increase as the source depth increases, this is strong evidence of a rather definite separation between two main regions which act as sources of magnetic anomalies.

It also makes it clear why the earlier spherical harmonic analyses of the earth’s field which generally did not exceed order six were so successful.

Note

The author apologizes for a mixture of units of length throughout this paper. The results were taken from the work of several authors who used different units and to redo the figures for this review did not seem justified.

References

Jensen, H., Operational procedure for the airborne magnetometer, Oil, and Gas J., 45, 80-83, 1946.


