Standard Curves
for the
Magnetic Anomalies
due to Spheres

BY
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CONTENTS

SUMMARY .......................... 1
1. INTRODUCTION .................. 3
2. MATHEMATICAL DERIVATION .... 5
3. DISCUSSION ..................... 8
4. INTERPRETATION PROCEDURE ... 10
5. REFERENCES .................... 10

TABLE 1. Values of the true amplitude, profiles of ΔZ and ΔX 11
TABLE 2. Values of true amplitude, profiles of ΔH 11
APPENDIX 1. Programme listings and flow charts 28

ILLUSTRATIONS

Figure 1. Definition of axes ........ 4
Figure 2. Distribution of field components .... 4
Plate 1. Nomogram for determination of effective inclination ... 12
Plate 2. Magnetic anomalies over a sphere—Vertical component (Z) 13
Plate 3. Magnetic anomalies over a sphere—Horizontal component in the traverse direction (X) .... 14
Plates 4-13. Magnetic anomalies over a sphere—Horizontal component (H) ... 15-24
Plate 14. Nomogram for determination of the parameter C .... 25
Plate 15. Nomogram for determination of the radius of the sphere ... 26
Plate 16. Examples of the application of the curves for ΔZ .... 27
SUMMARY

Standard curves for interpretation of the magnetic anomalies due to spheres have been derived. The anomalies in the vertical component, and the horizontal component in the direction of the traverse, are each found to be represented by a single family of curves. The horizontal component is found to be not represented by a single family, and separate curves for each field inclination and traverse azimuth are presented. Curves for the anomaly in the total intensity were not computed.
1. INTRODUCTION

The relative merits of the various methods of magnetic interpretation have been discussed by Gay (1963, 1965). The advantages of the curve fitting methods are obvious, since a high proportion of the data is used. The use of the curve fitting method presupposes the availability of a sufficiently varied set of standard curves. Gay (1963, 1965) has published curves for infinite dykes and horizontal cylinders. However, it is generally accepted that many of the magnetic bodies found in nature are approximately spherical. Gay (1965) pointed out the need for a complete set of standard curves of magnetic anomalies due to spheres but observed that ‘anomalies over spheres have not proven to be representable by a single family of curves, a characteristic reserved only for two-dimensional bodies’.

The Bureau of Mineral Resources, Geology & Geophysics has conducted extensive ground magnetic surveys using only the vertical component, and interest in improving the interpretation of such surveys led to the search for a family of curves to represent the vertical-component anomaly due to a sphere. It has been found that the vertical-intensity anomaly \( \Delta Z \) for all field inclinations and traverse directions can be represented by a single family of curves. The horizontal-intensity anomaly in the direction of the traverse (\( \Delta X' \)) can similarly be represented by a single family of curves. The horizontal-intensity anomaly in the north direction (\( \Delta H \)) cannot be represented by a single family but requires a separate curve for each value of field inclination and traverse direction. The standard curves derived for \( \Delta Z, \Delta X', \) and \( \Delta H \) are presented in Plates 2 to 15.

No attempt was made to derive the total-field anomaly due to a sphere.
Figure 1. Definition of axes

Figure 2. Distribution of field components
Consider a left-handed orthogonal co-ordinate system (Fig. 1) with its origin on the surface of the Earth directly above the centre of a small, uniformly magnetised sphere at unit depth, such that $X$ is positive in the traverse direction at an azimuth angle $\beta$ clockwise from magnetic north and $Z$ is positive vertically downwards. The magnetic moment $M$ induced in the sphere by the magnetic field $T$ of inclination $I$ may be resolved into components $M_x, M_y, M_z$ along the $X$, $Y$, and $Z$ axes respectively. At any point $P$ on the traverse, distant $x$ from the origin, these components may each be further resolved into radial and tangential components, which at $P$ give rise to the magnetic field components defined in Figure 2. Defining $Z_x$ as the field component at $P$ in the $Z$ direction due to the moment $M_x$, and similarly for other components, the net effect at $P$ may be written directly from the basic theory of the magnetic dipole (Jakosky, 1961, p. 79):

$$Z_x = \frac{-2 M_x r^3 \sin \delta}{R^5} - \frac{M_x t}{R^3} \cos \delta$$

$$X_x = \frac{2 M_x r^3 \cos \delta - M_x t}{R^5} \sin \delta$$

$$Y_x = 0$$

$$Z_y = 0$$

$$X_y = 0$$

$$Y_y = \frac{-M_y}{R^3} = \frac{-M \cos I \sin \beta}{R^3}$$

$$Z_z = \frac{2 M_z r^3 \sin \delta - M_z t}{R^3} \cos \delta$$

$$M \sin I (2 d^2 - x^2)$$
The net components of magnetic intensity in the X, Y, and Z directions are:

\[
\begin{align*}
\Delta X &= \frac{-3 M \sin I \cos \beta \sin E - 3 S \cos \beta}{d^3} \\
\Delta Y &= \frac{-M \cos I \sin \beta}{d^3} \\
\Delta Z &= \frac{M \sin I (2d^2 - x^2) - 3 M \cos I \cos \beta x d}{d^5}
\end{align*}
\]

and the net horizontal component is:

\[
\Delta H = \Delta X \cos \beta + \Delta Y \sin \beta
\]

Gay (1963) after Koulozmzine and Massé (1947) has defined the effective magnetic inclination in the direction of the traverse \(E\), and the same approach is followed in this derivation. A nomogram for the determination of effective inclination is shown in Plate 1. The traverse azimuth \(\beta\) may be eliminated from the above equations by use of the relation:

\[
\cos \beta = \frac{\tan I}{\tan E}
\]

and, defining \(d\) to be unit distance and \(S\) and \(Q\) such that:

\[
\begin{align*}
X &= S d \\
R &= Q d
\end{align*}
\]

we have:

\[
\begin{align*}
\Delta Z &= \frac{M \sin I (2 - S^2) \sin E - 3 S \cos E}{d^3} \\
&= \frac{K (2 - S^2) \sin E - 3 S \cos E}{Q^5} \\
&= K (f(S)) \\
\Delta X &= \frac{M \sin I (2 S^2 - 1) \cos E - 3 S \sin E}{d^3} \\
&= \frac{K (g(S))}{Q^5}
\end{align*}
\]
The functions for $\Delta Z$, $\Delta X$, and $\Delta H$ were computed and machine plotted using a ‘CDC 3600’ computer and ‘Calcomp’ graph plotter. Programme listings and flow charts are given in Appendix 1.

The plotted curves were normalised to have unit amplitude. The true amplitude $a$ for each curve is listed in Table 1 or Table 2. The magnitude $A$ of the field anomaly in gammas is related to $K$ and $a$ by:

$$A = Ka$$

Now

$$M = \frac{4}{3} \pi r^3 k T$$

$$A = \frac{4 \pi r^3 k T a \sin I}{3 d^3 \sin E}$$

where $r$ is the radius of the sphere, $k$ is the susceptibility contrast, and $T$ is the total intensity of the Earth’s field.

$$r^3 k = \frac{(3 A \sin E) d^3}{4 \pi a T \sin I} = C d^3$$

The value of $(\sin E)/(T \sin I)$ will normally be constant within a given survey area. The value of the parameter $C$ may be calculated or may be obtained from the nomogram in Plate 14. If the value of $k$ is known or estimated, a value for the radius of the sphere may then be obtained from the nomogram in Plate 15.

For profiles of the horizontal-intensity anomaly the value of $C$ is as above except that the $(\sin E)/(\sin I)$ term is always 1.0.

The profiles as presented are for the northern hemisphere (north to the right) and may be converted to southern hemisphere profiles by transposing them from left to right. The profiles for $Z$ may also be inverted depending on the plotting convention adopted for the observed profiles. In the southern hemisphere it is customary to plot $-Z$ upwards in order to produce anomalies that ‘look’ right; in this case the theoretical profiles should not be inverted.
3. DISCUSSION

A discrete point method of interpreting magnetic anomalies due to spheres has been described by Daly (1957), who also described methods of calculating the theoretical curve for any given interpretation. However, this is quite tedious and would not normally be carried out in routine interpretation. The present method gives a rapid interpretation for the anomalies due to spheres, and also gives a measure of the reliability of the method from the degree of fit between the observed values and the theoretical curve.

The method of interpretation by curve superposition has been adequately described by Gay (1963, 1965), and the curves as presented here need little discussion.

As shown in the derivation, anomalies in $\Delta Z$ and $\Delta X$ are represented by separate families of curves (Plates 2 and 3), but the anomaly in $\Delta H$ requires a separate curve for each field inclination and traverse azimuth (Plates 4 to 13). It is obvious from the plates that in high magnetic latitudes, measurements of $\Delta H$ should not be taken on traverses that lie near an east-west direction; on such traverses, variations of only one or two degrees in azimuth cause large variations in the anomaly profile.

In planning a survey where horizontal magnetic measurements are to be made direct, consideration should be given to the desirability of measuring $\Delta X$ rather than $\Delta H$. Measurements of $\Delta X$ can be made with a Schmidt balance, torsion magnetometer, or horizontal fluxgate magnetometer; all these instruments measure the horizontal intensity in the azimuth to which they are constrained. Interpretation of the anomalies in $\Delta X$ can be simply carried out using the single family of curves shown in Plate 3. There is still a restriction on the allowable traverse azimuth, imposed by the errors that may be introduced by mis-orientation of the instrument. For example, in a horizontal field of 25,000 gammas, with a traverse azimuth of 30°, a mis-orientation of one tenth of a degree introduces an error of about 20 gammas in $\Delta X$; if the traverse azimuth is 60°, the error increases to about 37 gammas. Nevertheless, if a suitable sighting device were attached to the instrument, accurate orientation should not prove difficult.

Chapter 4 gives a summarised step-by-step procedure for using the standard curves in the interpretation of magnetic anomalies.

Two examples of the application of the curves for $\Delta Z$ are shown in Plate 16. Both are extracted from examples from the Tennant Creek area given by Daly (1957). In both cases the degree of fit of the observed points is only moderate, indicating that the sources of the anomalies are not actually spherical.

Example 1 is from Traverse 500W of the Eldorado anomaly. Daly's estimated depth to the centre of the body was 580 feet, which agrees well with the present determination (570 feet). However, Daly places the centre of the body below point 402N, whereas the present determination places it below 430N. The amplitude $A$ of the anomaly is 1600 gammas. Referring to Table 1, the true amplitude $a$ of the theoretical curve is 1.92. Taking $F = 50,000$ gammas, $(\sin E)/(T \sin I) = 2 \times 10^{-5}$. From the nomogram in Plate 14, $C = 4.0 \times 10^{-3}$. Daly has dis-
cussed the likely values for the susceptibility contrast of the ironstones at Tennant Creek, and he suggests that the most probable value is \( k = 0.1 \) c.g.s. units. Thus for a depth of 570 feet, the radius of the sphere is 200 feet (Plate 15).

In Example 2, Daly's estimated position for the centre of the sphere was at a depth of 410 feet below point 400S. The present determination places it at a depth of 500 feet below 410S. The amplitude of the anomaly is 3900 gammas, which gives values of \( C = 9.5 \times 10^{-3} \) and \( r = 250 \) feet.

It is interesting to note that the interpretations using the two methods give different results even though they are based on the same basic theory. This is attributed to the difference between the discrete point method and the complete curve fitting method.
4. INTERPRETATION PROCEDURE

To permit rapid interpretation of profiles using this method, it is recommended that the step-by-step procedure set out below be followed.

(1) Plot field results at a convenient scale.

(2) For profiles of $\Delta Z$ or $\Delta X$, determine the value of effective inclination $E$ from the field inclination $I$ and traverse azimuth $\beta$, using the nomogram in Plate 1, and select the theoretical curve appropriate to the value of $E$.

For profiles of $\Delta H$, select the theoretical curve appropriate to the values of $I$ and $\beta$.

(3) Change the vertical scale of the observed profile so that the amplitude (peak-to-peak) is the same as that of the theoretical profile.

(4) Vary the horizontal scale of the observed profile to obtain the best fit between it and the theoretical profile (it may be necessary to repeat steps 3 or 4 to obtain the best possible fit between the two sets of curves).

(5) The depth to the centre of the sphere is that distance on the horizontal scale of the observed profile which corresponds to one unit on the horizontal scale of the theoretical profile.

(6) Measure the gamma amplitude $A$ of the observed profile, and from Table 1 or Table 2 obtain the true amplitude $a$ of the theoretical profile.

(7) Compute $(\sin E)/(T \sin I)$.

(8) From the equation on page 7 or from the nomogram in Plate 14, obtain a value for $C$.

(9) From the value of $C$ obtained in step 8, and a selected value of susceptibility contrast $k$, determine the value of the radius $r$ from the nomogram in Plate 15.

5. REFERENCES


## TABLE 1. VALUES OF TRUE AMPLITUDE $a$

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## TABLE 2. VALUES OF TRUE AMPLITUDE $a$. PROFILES OF $\Delta H$. 

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NOMOGRAM FOR DETERMINATION
OF EFFECTIVE INCLINATION
MAGNETIC ANOMALIES OVER A SPHERE

RELATIVE ANOMALY

DISTANCE

Vertical Component Z

PLATE 2
MAGNETIC ANOMALIES OVER A SPHERE

Horizontal Component in the Traverse Direction (X)
MAGNETIC ANOMALIES OVER A SPHERE

The figure on the curve is the Traverse Azimuth

Horizontal Component $H$
Inclination $0^\circ$

DISTANCE

RELATIVE ANOMALY
MAGNETIC ANOMALIES OVER A SPHERE

The figure on the curve is the Traverse Azimuth

Horizontal Component $H$
Inclination $10^\circ$
MAGNETIC ANOMALIES OVER A SPHERE

The figure on the curve is the Traverse Azimuth

Horizontal Component $H$
Inclination 20°
MAGNETIC ANOMALIES OVER A SPHERE

The figure on the curve is the Traverse Azimuth

Horizontal Component $H$

Inclination 30°
MAGNETIC ANOMALIES OVER A SPHERE

The figure on the curve is the Traverse Azimuth

Horizontal Component $H$
Inclination $40^\circ$
MAGNETIC ANOMALIES OVER A SPHERE

The figure on the curve is the Traverse Azimuth

Horizontal Component $H$
Inclination 50°
MAGNETIC ANOMALIES OVER A SPHERE

The figure on the curve is the Traverse Azimuth

Horizontal Component $H$
Inclination $60^0$
MAGNETIC ANOMALIES OVER A SPHERE

The figure on the curve is the Traverse Azimuth

Horizontal Component \( H \)
Inclination \( 70^0 \)
MAGNETIC ANOMALIES OVER A SPHERE

The figure on the curve is the Traverse Azimuth

Horizontal Component $H$
Inclination 80°
MAGNETIC ANOMALIES OVER A SPHERE

The figure on the curve is the Traverse Azimuth

Horizontal Component $H$

Inclination $90^\circ$
NOMOGRAM FOR DETERMINATION OF PARAMETER C

(1) Join $\frac{\sin E}{T \sin I}$ to A
(2) Join intercept on R to a
NOMOGRAM FOR DETERMINATION OF RADIUS OF A MAGNETISED SPHERE

(1) Join C to D
(2) Join intercept on R to k
PLATE 16

CENTER OF SPHERE
(=450N)

1500N 1000 500 0 500S

1 DEPTH UNIT
(=570ft)

(1) "ELDORADO" TRAV 500W TENNANT CK AREA
(AFTER DALY 1957)

(2) "PEKO" TRAV 3400E TENNANT CK AREA
(AFTER DALY 1957)

EXAMPLES OF THE APPLICATION OF THE CURVES FOR ΔZ

(1) OBSERVED VERTICAL INTENSITY
THEORETICAL PROFILE FOR ΔZ, INCLINATION = 50°
APPENDIX 1
PROGRAMME LISTINGS AND FLOW CHARTS

Computer programme listings and flow charts used in the computations described in this Bulletin appear on the next four pages.

PROGRAM XZPLOT
DIMENSION FUNCT(500)
1 FORMAT(5X,12,8X,F6.3,2X,E12.5)
4 FORMAT(1H1, *INCLINATION INTERCEPT AMPLITUDE*/)
PRINT 4
5 CALL PLOT (.5,0.2,2)
DO 51, J=1,12
CALL PLOT (-7.,-1.0,1)
CALL PLOT (-5.,-1.,3)
CALL PLOT ( 5.,-1.,3)
CALL PLOT ( 5.,0.,4)
CALL PLOT (0.,-1.,3)
CALL PLOT (-5..1., 1.)*
CALL PLOT (-5.,1., 1.)*
CALL PLOT (-5.,0.,3)
CALL PLOT ( 5., 1., 1.)*
CALL PLOT (-5.,-1., 1.)*
CALL PLOT ( 5.,0., 1.)*
CALL PLOT ( 6.5,0.7,3)
DO 47, J=10,100,10
10 = J-10
RIO = 3.1416*10/180.
A = COS (RIO)
B = SIN(RIO)
FMAX=FM1N=0
DO 40, M=1,361
Y = (M-181)/40.
R = SQRT(Y*Y + 1.0) R3=R*R*R
R5=R3*R*R
1 IF(1.EQ.2)400,401
400 FUNCT(M) = (2.0*B - B*Y*Y - 3.0*A*Y)/R5
401 FUNCT(M) = (2.0*A*Y*Y - A - 3.0*B*Y)/R5
32 IF (FUNCT(M).GT.FMAX) 33, 34
33 FMAX = FUNCT(M)
GO TO 40
34 IF (FUNCT(M).LT.FMIN) 35, 36
35 FMIN = FUNCT(M)
GO TO 40
36 CONTINUE
CONST = (FMAX-FMIN)
ZEROPT = FUNCT(181)/CONST
PRINT 1,10,ZEROPT,CONST
M=1
Y=-4.50
X= FUNCT(M)/CONST
CALL PLOT (Y,X,3)
45 Y=Y+0.025
M=M+1
X= FUNCT(M)/CONST
CALL PLOT (Y,X,4)
48 IF (Y.LT.4.5) 45, 47
47 CONTINUE
51 CALL PLOT(-7.0,2.0,3)
98 END
PROGRAM XZ PLOT

DIMENSION PRINT HEADING

SET PLOTTER SCALE

DO 51 I = 1, 2

SET PLOTTER ORIGIN ETC

DO 47 J = 10, 100, 10

10 RIO = RI
FMAX = FMIN = 0

D040 M = 1, 361, 1

Y = R = RS

I = 2 ?

YES

FUNCTION = (HORIZONTAL)

FMAX = FUNCTION(M)

FUNCTION(M) > FMAX

NO

FUNCTION = (VERTICAL)

FMIN = FUNCTION(M)

FUNCTION(M) < FMIN

FLOW DIAGRAM - PROGRAM XZ PLOT
PROGRAM SPHRPLOT
DIMENSION FUNCT(500)
1 FORMAT(5X,12,10X,12, 5X,E12.5,4X,F6.3)
4 FORMAT(IHH,*(INCLINATION STRIKE AMPLITUDE INTERCEPT*))
7 FORMAT(I12)
PRINT 4
5 CALL PLOT (.5,0.2,2)
DO 51, J=10,100,10
10 = J-10
RIO = 3.1416*10/180.
AD= COS (RIO)
B = SIN (RIO)
CALL PLOT (- 7.,-1.,0,1)
CALL PLOT (- 5.,-1.,4)
CALL PLOT ( 5.,,1,4)
CALL PLOT (- 5.,1.,1,4)
CALL PLOT ( 5.,1.,-1,4)
CALL PLOT (- 5.,0.,3)
CALL PLOT ( 5.,0.,4)
CALL PLOT (0.,-1.,3)
CALL PLOT (0.,1.,4)
CALL PLOT ( 6.5,0.7,3)
ENC0DE(3,7,CCC)10
CALL TEXT(CCC,3,3)
DO 51, NIT=10,100,10
NUT=NIT-10
ALPHA = NUT *3.1416/180.0
A=AD*COS(ALPHA)
COSAL=COS(ALPHA)
SINAL=SIN(ALPHA)
SINAL2=SINAL*SINAL
FMAX=FMIN=0
DO 40, M=1,361
Y = (M-180)/40.
R = SQRT(Y*Y + 1.0) R3=R*R*R R5=R3*R*R
XH=(2.0*Y*Y-1.0)*A*COSAL/R5
YH=-AD*SINAL2/R3
ZH=-3.0*B*Y*COSAL/R5
FUNCT(M)=XH+YH+ZH
30 IF (FUNCT(M).GE.FMAX) 33,34
33 FMAX = FUNCT(M)
GO TO 40
34 IF (FUNCT(M).LE.FMIN) 35,40
35 FMIN = FUNCT(M)
40 CONTINUE
CONST = (FMAX-FMIN)
ZEROPT = FUNCT(181)/CONST
PRINT 1,10,NUT,CONST,ZEROPT
M=1
Y=-4.50
X= FUNCT(M)/CONST
CALL PLOT (Y,X,3)
45 Y=Y+0.025
M=M+1
X= FUNCT(M)/CONST
CALL PLOT (Y,X,4)
48 IF (Y.LT.4.5) 45,47
47 CONTINUE
51 CALL PLOT(-7.0,2.0,3)
88 END
FLOW DIAGRAM - PROGRAM SPHRPLOT