DC0304 Collared Coil Warm Mole Measurement

TS-SSC 91-016
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I. Introduction

The harmonic coefficients of collared coil DC0304 were measured on January 16, 1991 with the 24" BNL B2 mole. The transfer function and harmonic coefficients derived from the mole measurement are described in this memo. Comparisons are made with similar data for the DC0302 and DC0303 collared coils. The earth's magnetic field along the axis of collared coil DC0304 is also examined, mainly as a cross-check on the mole's performance.

Three sets of measurements were performed on collared coil DC0304. The first set established the magnetic center of the collared coil along its axis. The second set, taken in pairs of +10 A and -10 A current with the mole positioned at axial positions at 3 inch increments, were used to extract the transfer function of the coil as a function of axial position. The earth's magnetic field at each position may also be inferred from these data. The third set, done with the current set to zero, measured directly the earth's magnetic field at each position along the coil.

II. Transfer Function

To obtain the transfer function of the coil at a given position, the following equations are used:

$$\mathbf{D}^+ = \mathbf{B}_e + \mathbf{T} * I^+ \quad (1)$$

$$\mathbf{D}^- = \mathbf{B}_e + \mathbf{T} * I^- \quad (2)$$

In these equations, the bold-faced quantities are meant to be two-component vectors, with horizontal and vertical components. The horizontal component is understood to be directed perpendicular to the coil axis. (In other words, field components along the axis of the magnet are ignored in this analysis.)

$\mathbf{D}^+$ and $\mathbf{D}^-$ are the dipole field vectors measured with +10 A and -10 A current respectively. The magnitudes of these vectors are taken from bucking coil #1 (DPBUCK1 in the event record; see Appendix.) The dipole field angles are obtained from the phase of the dipole signal from bucking coil #1[1].

The vector quantity $\mathbf{T}$ is the transfer function of the collared coil. Of course, only the magnitude of the transfer function "vector" is really of interest. Its angle is only an indication of which way the coil is oriented locally with respect to the vertical. This could come from a rotation of the entire collared coil assembly, or from "twist" along its length, which should be eliminated by the yoking process. The scalar quantities I^+ and I^- are the currents in the "+10 A" and "-10 A" settings.

$\mathbf{B}_e$ represents the earth's magnetic field.

To obtain the transfer function magnitude and orientation, it is only necessary to subtract the horizontal and vertical components of equations (1) and (2). This eliminates the contribution of the earth's field:

$$\mathbf{T} = (\mathbf{D}^+ - \mathbf{D}^-) / (I^+ - I^-) \quad (3)$$

The transfer function magnitude for DC0304 is shown in the second column of Table 1, as a function of axial position relative to the center of the magnet. The angle of the transfer function with respect to the vertical in degrees is shown in the third column. For the readings at 8.542 m, 7.933 m, and 7.917 m, a good portion of the mole sampling the coil turnaround field.

The fourth and fifth columns of Table 1 show the earth's magnetic field magnitude and angle with respect to the vertical, obtained by substituting the transfer function horizontal and vertical components back into equation (1).

The second and third columns of Table 2 show the earth's magnetic field magnitude and angle with respect to the vertical, obtained directly from the 0 A data. For these data, the current supply was not turned off; rather, the current demanded from the supply was set to 0 A. There may therefore be some slight systematic error in these data.

Figures 1a and 1b show the transfer function and the field angle as a function of position. Figure 1b looks fairly linear, as if the coil has a true twist along its length which will presumably be removed by the yoking process. For the purposes of these figures, the point at 8.542 meters has been dropped, since here the transfer function is complicated near the magnet end.

Figures 1c and 1d show the transfer functions of collared coils DC0302 and DC0303. These two functions were not flat as a function of axial position, but because of carelessness in the current measurements it was not possible to decide whether the "shape" was real or an artifact[2].

Figures 2a and 2b show the earth's magnetic field magnitude and angle from the vertical extracted from the ±10 A data and the 0 A data. In both figures the open squares are the from ±10 A data and the black diamonds are from the 0 A data. Other than a discrepancy near the center of the coil, the agreement seems quite good for these two data sets. The variations in the angle and magnitude of the earth's field along the length of the collared coil may be related to nearby iron in the industrial center building.

III. Harmonic Coefficients

Tables 3 and 4 give the normal and skew harmonic coefficients averaged between +5 m and -5 m for collared coils DC0302, DC0303, and DC0304. Two numbers are given for each harmonic coefficient. These are the average value of the coefficient, and the ratio of the average value and the standard deviation. Coefficients for which this ratio was less than 1.5 are not shown in the table.

All three coils have the same normal decapole harmonic. A relatively large normal 14-pole is present as well. The expected normal 22-pole is present in all three collared coils.

The only systematically outstanding skew moment seems to be the skew 22-pole, but this effect is not large.

Notes

[1] This angle is obtained from the dipole phase angle by adding $\pi/2$. This $\pi/2$ comes from the fact that the mole event record gives phases relative to the vertical (2π or 0 means up, and π means down.) So to translate these angles into a standard coordinate system in which 0 means positive x direction, $\pi/2$ must be added. For example,

$$D^+_x = \text{DPBUCK1} * \cos[\ \text{PHASE1} + \pi/2\ ]$$

$$D^+_y = \text{DPBUCK1} * \sin[\ \text{PHASE1} + \pi/2\ ], \text{ and so on.}$$

For the definitions of DPBUCK1 and PHASE1, see the Appendix describing the mole event record.

In principle, a small gravity sensor correction should be applied to the phase angles in the above equations. However, there is still some uncertainty in how to apply the gravity sensor corrections to these data. The two sensors do not give the same reading at each point, nor is there a simple systematic offset or factor relation between the two sensors. In the calculations done for this memo, no gravity sensor correction has been made. The largest potential gravity sensor correction for these data was about 1/20 of one degree.

[2] S. Delchamps, Warm Mole Measurements of DC0302 and DC0303 Collared Coils, TS-SSC 90-012, December 8, 1990.

Table 1. DC0304 Collared Coil Transfer Function and Derived Earth Magnetic Field

z (meters)	Transfer Function (Tesla/kA)	Transfer Function angle (degrees)	Bearth magnitude (Gauss)	Bearth angle (degrees)
8.542	0.519	1.8	.594	215.3
7.933	8.051	4.0	.635	219.0
7.323	8.009	3.7	.659	221.5
6.714	8.009	3.3	.664	224.0
6.104	8.009	3.5	.643	223.6
5.494	8.008	3.2	.569	218.2
4.885	8.007	2.8	.543	208.5
4.275	8.012	2.5	.480	201.2
3.666	8.008	2.6	.452	203.8
3.056	8.008	2.7	.439	207.2
2.446	8.006	2.7	.429	210.3
1.837	8.008	2.9	.425	214.9
1.227	8.008	2.4	.447	214.8
0.618	8.007	2.5	.449	217.1
0.008	8.008	2.5	.419	219.0
-0.602	8.008	2.0	.371	210.5
-1.211	8.007	1.8	.309	192.9
-1.821	8.009	1.9	.261	185.1
-2.430	8.007	1.9	.245	196.8
-3.040	8.009	1.8	.221	224.0
-3.650	8.006	1.9	.203	230.9
-4.259	8.007	1.8	.178	214.5
-4.869	8.005	1.5	.169	218.8
-5.478	8.004	1.3	.237	241.3
-6.088	8.009	0.9	.299	248.9
-6.698	8.007	0.5	.295	243.8
-7.307	8.006	-0.2	.315	244.8
-7.917	8.030	-0.8	.290	240.6

Table 2. DC0304 Collared Coil Measurement:
Earth's Magnetic Field from 0 A Data

z (meters)	Bearth magnitude (Gauss)	Bearth angle (degrees)
8.542	.608	214.5
7.933	.590	224.8
7.323	.618	225.3
6.714	.666	223.9
6.104	.573	228.9
5.494	.563	219.0
4.885	.520	209.7
4.275	.495	201.8
3.666	.423	204.8
3.056	.425	208.6
2.446	.414	212.9
1.837	.431	213.2
1.227	.453	215.2
0.618	.402	221.5
0.008	.329	234.4
-0.602	.357	209.6
-1.211	.308	194.0
-1.821	.258	188.2
-2.430	.254	196.7
-3.040	.209	222.0
-3.650	.183	231.5
-4.259	.194	214.1
-4.869	.138	221.1
-5.478	.220	248.7
-6.088	.268	263.9
-6.698	.284	248.6

Table 3. Normal Harmonic Coefficients for Collared Coils
DC0302, DC0303, DC0304 (B2 Mole Measurement, ±10 A)

Coil	b1	**b2**	b3	**b4**	b5	**b6**	b7	**b8**	b9	**b10**
DC0302	---	---	---	-1.878 21	---	0.253 16	---	0.022 2.9	---	0.124 38
DC0303	---	1.298 1.8	---	-1.806 33	---	0.319 13	---	0.014 2.0	---	0.126 27
DC0304	---	---	---	-1.819 13	---	0.280 17	---	---	---	0.124 32

Table 4. Skew Harmonic Coefficients for Collared Coils
DC0302, DC0303, DC0304 (B2 Mole Measurement, ±10 A)

Coil	a1	a2	a3	a4	a5	a6	a7	a8	a9	**a10**
DC0302	---	---	---	---	---	---	---	---	---	.0127 3.2
DC0303	1.326 2.5	---	---	-.186 1.8	---	---	---	---	---	.0197 5.3
DC0304	---	---	-.283 1.7	---	-.086 1.9	---	---	---	---	0.183 6.3

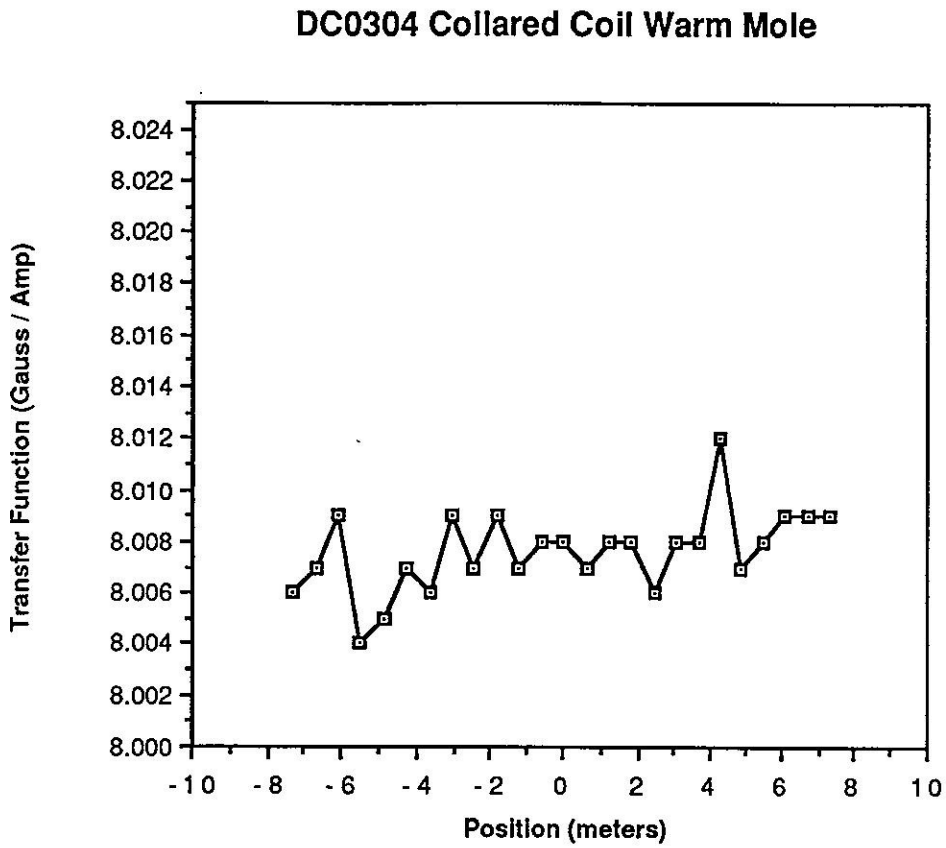

Figure 1a. DC0304 Transfer Function

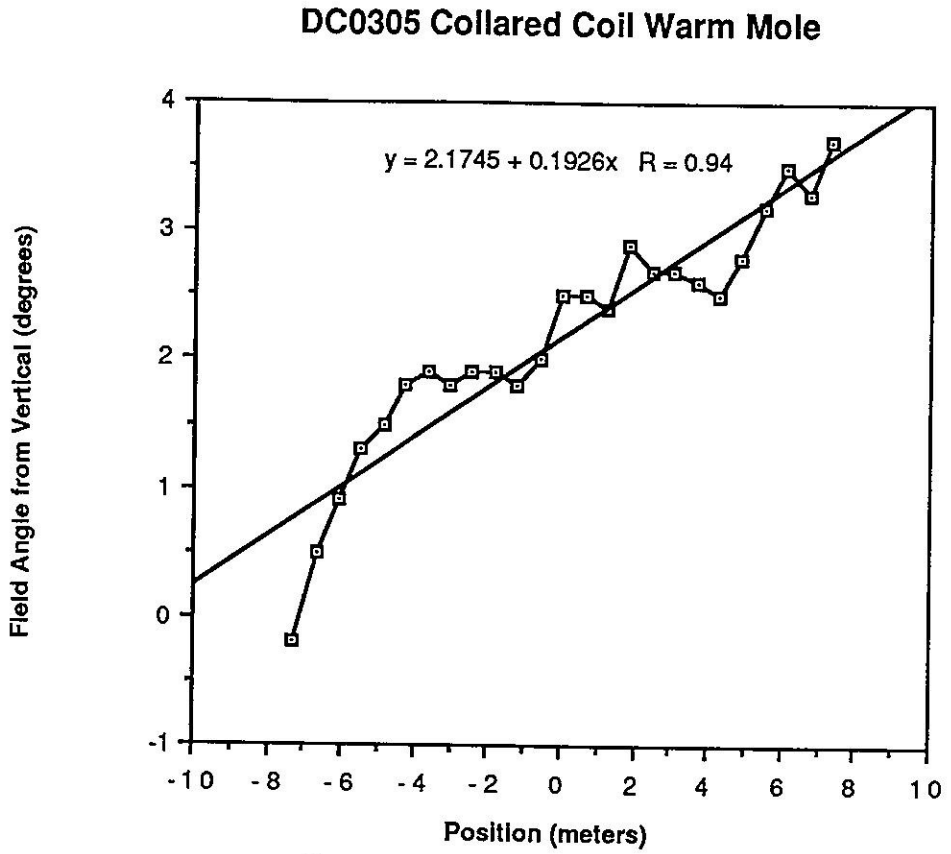

Figure 1b. DC0304 Transfer Function Angle

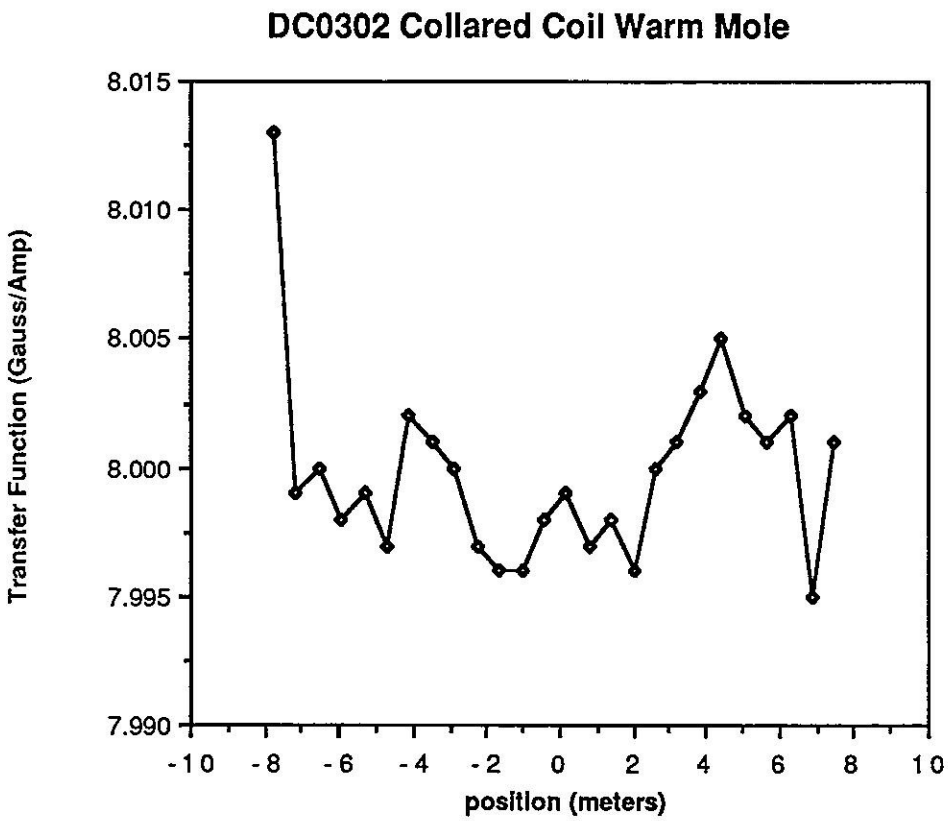

Figure 1c. DC0302 Transfer Function

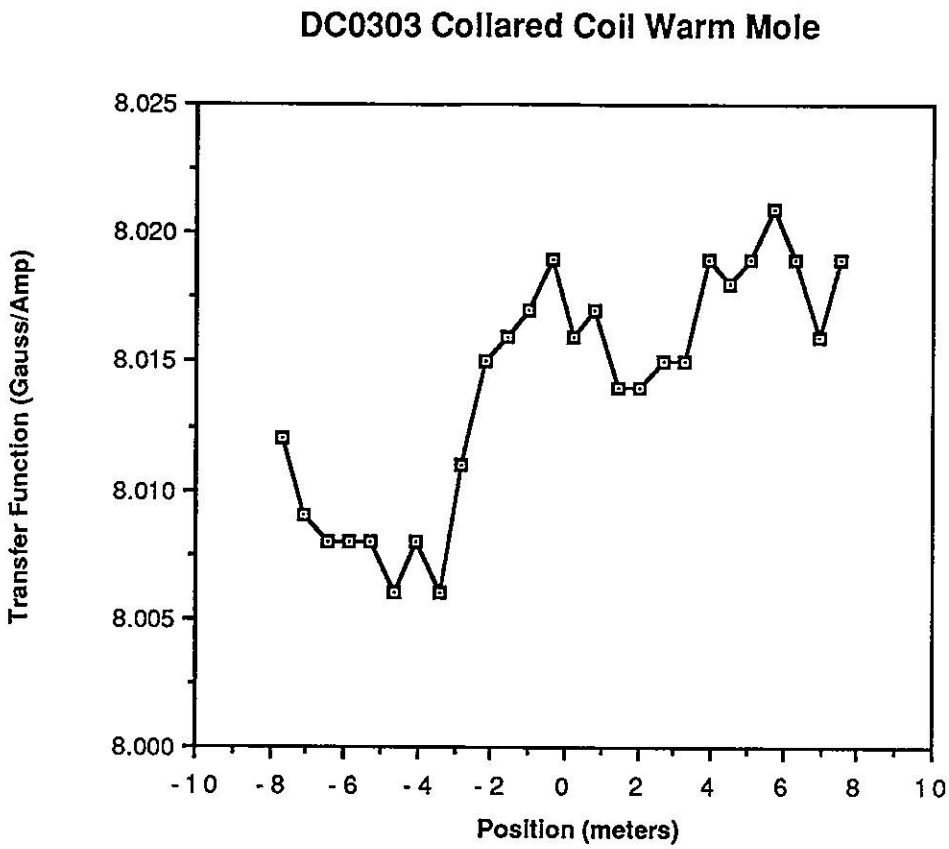

Figure 1d. DC0303 Transfer Function

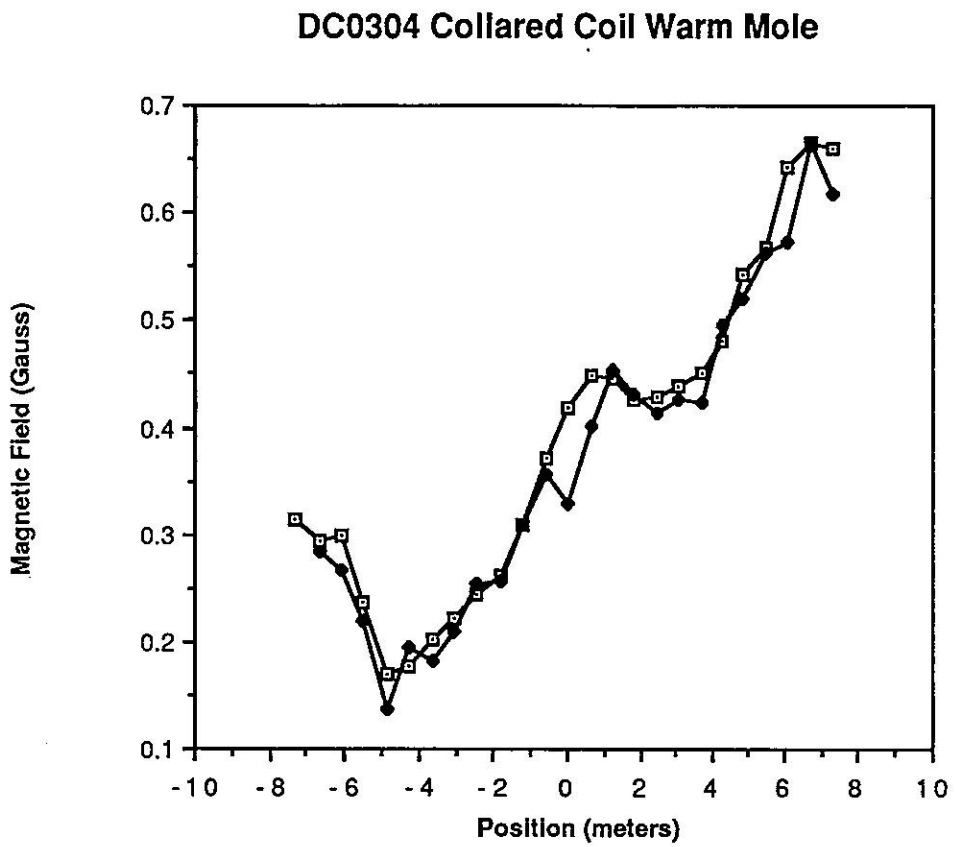

Figure 2a. Earth's Magnetic Field

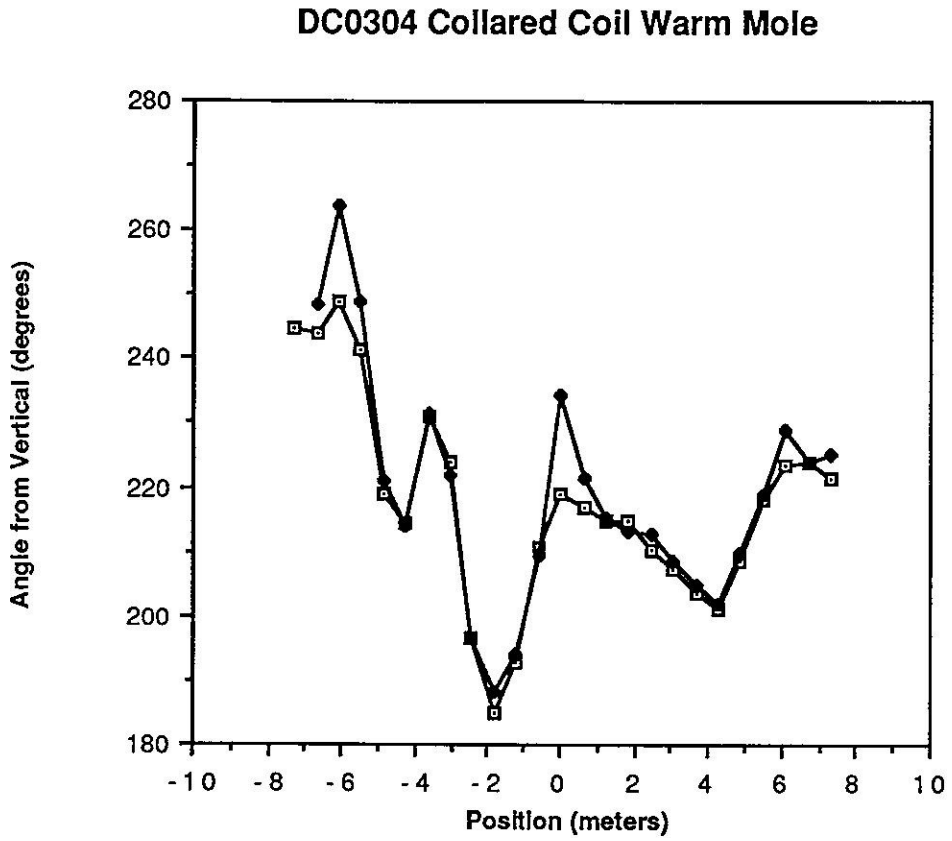

Figure 2b. Earth's Magnetic Field Angle

Appendix. Mole Event Record

The "raw data files" on the vax from the mole processing are actually already reduced from the data taken on the Hewlett Packard system. A single event record is shown below. The two numbers following "CMAIN:" are the currents in amperes measured before and after the three mole rotations used to obtain harmonic data. The Z - mole position is given in feet. This number must be converted into a position relative to the center of the coil using the center position determined from the first set of mole data. The two numbers following "Gravity sensors:" are the readouts in degrees from the two gravity sensors. The two numbers following "DPBUCK1:" are the dipole field magnitude in gauss and phase angle in radians, respectively.

So in this case, the current is 10.008 A, DPBUCK1 is .4738077 Gauss, and the phase angle of DPBUCK1, refererred to in the text above ase PHASE1, is 6.175756 radians.

```
Record number:   1
Winding:      4
Message #4 reply: Buck: 1 & 2 Amplitude Differ - Check: Data/Plots
Time: 11:03:16
CMAIN:    10.008   10.008
CTRIM:     0.271    0.284    0.254    0.000
Z - Mole Position:   0.5663000E+02
Gravity sensors:   0.1193469E-01 -0.4733498E-01
FACT:  -0.3651990E+00 -0.5578408E+00  0.0000000E+00
DPBUCK1:   0.4738077E-03  0.6175756E+01
DPBUCK2:   0.4844910E-03  0.6243731E+01
    1  0.4738077E-03  0.6175756E+01
    2  0.2000933E-05  0.2587999E+01
    3  0.7427691E-05  0.9584613E+00
    4  0.1949770E-06  0.1133016E+01
    5  0.2540298E-06  0.4515848E+00
    6  0.7685996E-07  0.8572701E+00
    7  0.7909537E-07  0.3612185E+00
    8  0.4002348E-07  0.5510721E+00
    9  0.5272890E-08  0.2987416E+00
   10  0.1098126E-07  0.4523352E+00
   11  0.6094208E-08  0.2831575E+00
   12  0.3766080E-09  0.1672900E+00
   13  0.2527341E-08  0.3728159E+00
   14  0.3188675E-08  0.3343918E+00
   15  0.1819768E-08  0.7769477E-01
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