**W.H. Campbell, *Introduction to Geomagnetic Fields* 2nd ed. published by Cambridge University Press, Cambridge, UK, 2003.**

# Chapter 1

### Ex. 1.1

Magnetic observatories report their field observations as either the $XYZ$ or $HDZ$ coordinate values depending on local historical or commercial demands. A researcher in geomagnetism should be able to readily convert between the two systems. The problem here is to transform the ABG station geographic direction field values of Xmean $=$ 3664 nT, Ymean $=$ 827 nT, and Zmean $=$ 2142 nT into values for $H$, $D$, $F$, and $I$.

Looking at Equation (1.4) we see that we can obtain $H$ and $D$ from $X$ and $Y$.

$$\begin{aligned}\mathrm{Hmean} &= \sqrt{(\mathrm{X}^2 + \mathrm{Y}^2)}\\ &= \sqrt{((3664)^2 + (827)^2)}\\ &= \sqrt{(14108825)}\\ &= 3756\ \mathrm{nT}\end{aligned}$$

Sketch the $X$ and $Y$ values in the horizontal plane and see that we are looking for an angle about equal to 10° eastward for $D$. Using Equation (1.4) to find $D$, we have

$$\begin{aligned}\mathrm{Xmean/Ymean} &= 827/3664\\ &= 0.2257,\end{aligned}$$

so

$$\begin{aligned}\mathrm{Dmean} &= \tan^{-1}\ (0.2257)\\ &= 12.72^\circ \text{ or 12deg 43min eastward.}\end{aligned}$$

Using Equation (1.2) we can write

$$\begin{aligned}\mathrm{Fmean} &= \sqrt{(\mathrm{Xmean}^2 + \mathrm{Ymean}^2 + \mathrm{Zmean}^2)}\\ &= \sqrt{(3664^2 + 827^2 + 2142^2)}\\ &= 4324\ \mathrm{nT}.\end{aligned}$$

For the dip (inclination) $I$, sketch the vertical angle using $H$ and $Z$ to indicate an estimate of 30°. Then $I$ is obtained from Equation (1.3) as

$$\begin{aligned}I &= \tan^{-1}(\mathrm{Zmean/Hmean})\\ &= \tan^{-1}(2132/3756)\\ &= \tan^{-1}(0.5676)\\ &= 29.58^\circ \text{ or 29deg 35min downward.}\end{aligned}$$

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**Ex. 1.2**
To find the geomagnetic coordinates of a location we use program C.1 in Appendix C. Download the file GMCORD.EXE onto your computer. While in the DOS mode, type the location where you have stored that file and enter "GMCORD". Follow directions to give the station name for your location, for the latitude in decimal degrees, and for the longitude in decimal degrees.

For my location in Boulder, Colorado, USA, whose geographic coordinates are $+40.0^\circ$ and $-105.0^\circ$, the program shows the coordinates of $+48.74^\circ$ geomagnetic latitude and $+321.2^\circ$ geomagnetic longitude. To compare with the map of Figure 1.16 we need to convert the east longitude location to $(360 - 321.2) = 38.8$ degrees west longitude. Then the map seems to verify the computed value. The Boulder location is a mid-latitude location.

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**Ex. 1.3**
At Boulder the geomagnetic latitude was found to be 48.74 degrees north (Exercise 1.2). From Figure 1.9, using the horizontal scale location for about 49 degrees we see that the computation curve corresponds to a field line of about 2.2 Earth radii distant from the Earth center. Assuming a mean Earth radius of 6,371 km, the radial distance of this field line would be at about 14,020 km from the Earth center.

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**Ex. 1.4**
At the Boulder geomagnetic latitude (above) of $+48.74$ degrees the approximate length, $l$, of the field line (Equation (1.30)) connecting Boulder with its conjugate location would be

$$\begin{aligned} l &= 0.38 \times 48.74 \\ &= 18.52 \text{ Earth radii.} \end{aligned}$$

Using a mean Earth radius of 6,371 km, that field line is about 118,000 km in length.

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**Ex. 1.5**
The map of Figure 1.10 shows that the location of Boulder (at geographic location 40 degrees north and 105 degrees west) would correspond to a value of about a 2.4 $L$-shell. Using Equation (1.31) to obtain the equivalent Invariant Latitude:

$$\begin{aligned} \cos(\text{Invarient Latitude}) &= 1/\sqrt{(2.4)} \\ &= 0.6455. \end{aligned}$$

Thus

$$\text{Invariant Latitude} = \cos^{-1}(0.6455)$$
$$= 49.8 \text{ degrees.}$$

This Invariant Latitude is, of course, quite close to the geomagnetic latitude of 48.74 degrees we found for Boulder using the GEOMAG program in Exercise 1.2.

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**Ex. 1.6**

Read the program description for the file SPH.EXE, at C.11 in Appendix C, then download the program on your computer. While in the DOS mode, enter the location where you have stored the file and type "SPH". In Figure 1.14 there is diagrammed the Legendre polynomials for $m = 3$ and $n = 6$, $m = 4$ and $n = 8$, $m = 4$ and $n = 4$, as well as $m = 0$ and $n = 5$. Use these four pairs of coefficients to call up the pictures of the Legendre surface. The $n$ is called the "degree" and the $m$ is called the "order" of the polynomial. To tilt the figure (degrees AWAY from vertical) toward you, start with 30. To rotate the figure (degrees ABOUT the vertical) on its axis, start with 0. Count the oscillations along a latitude line and compare it with the $m$ value. Count the oscillations around a longitude line and compare it with $n - m + 1$. Look again at Figure 1.4 and compare the explanations below each sphere.

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**Ex. 1.7**

Read the program description for GEOMAG.EXE, at C.2 in Appendix C, and download the file onto your computer. While in the DOS mode, type the location where you have stored the file and type "GEOMAG". Enter "igrf" for the model and then answer the questions. For example, note that you are asked for the site elevation and if you want a decimal representation of the year (yes/no). For the Boulder location, elevation of 5280 ft at 40.0 degrees north and 105 degrees west, the program computed values for 1 June 2003 gives $X = 20694$ nT, $Y = 3710$ nT, $Z = 49580$ nT, $F = 53853$ nT, etc. for the other component representations.

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**Ex. 1.8**

Let us take 31 December in the year 2004 for our problem. The Table 1.2 shows us Gauss coefficients for 1 January of each year – that is 2000.0 in the format used by IGRF modelers (mid year in 2000 would be 2000.5). For our problem we need to add in the secular variation (*sv*) of 14.6 nT/year for five years to extend the 2000 model to just before start of 2005. So we have

$$a_1^0 = g_1^0 = -29615 + 5 \times 14.6 = -29542.$$

The geomagnetic colatitude of Boulder (see Ex. 1.2) is just $(90 - 48.74) = 41.26$ degrees. Thus, our three field components (computed from the axial dipole model only) are given as

$$X' = -(-)29542 \times \sin(41.26)$$
$$X' = 29542 \times 0.6595$$
$$X' = 19482 \text{ nT}$$

$Y' = 0$ (no axial tilt for axial model geomagnetic dipole)

$$Z' = -(-)2 \times 29615 \times \cos(41.26)$$
$$Z' = 59230 \times 0.7517$$
$$Z' = 44525 \text{ nT}.$$

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**Ex. 1.9**

First we must obtain the Gauss coefficients for our selected year 2005 (or 31 December 2004). In Exercise 1.8 we found $g_1^0$ to be $-29542$. Similarly, using Table 1.2 we calculate

$$\begin{aligned} g_1^1 &= -1728 + 5 \times 10.7 \\ &= -1728 + 53.5 \\ &= -1674.5 \end{aligned}$$

and

$$\begin{aligned} h_1^1 &= 5186 + 5 \times (-22.5) \\ &= 5186 - 112.5 \\ &= 5073.5. \end{aligned}$$

Thus we have for the colatitude Equation (1.80):

$$\sqrt{[(5073.5)^2 + (-1674.5)^2]} = 5342.7.$$

Then

$$[5342.7/(-29542)] = -0.1809.$$

The pole colatitude location is $\theta$, the negative of the angle whose tangent is $-0.1809$:

$$\theta = 10.25 \text{ degrees}.$$

Using the longitude Equation (1.81) we have

$$[5073.5/(-1674.5)] = -3.0299.$$

The pole longitude is $\varphi$, the angle whose tangent is $-3.0299$.

$$\varphi = -71.73 \text{ degrees.}$$

Therefore, we find that the centered dipole axial pole position (used for geomagnetic coordinates) derived for the end of year 2004 (begining of 2005), projected from the IGRF-2000 model, is located at $(90 - 10.25) = 79.75$ degrees north and 71.73 degrees west. Compare this result with the axial pole position for the geomagnetic coordinates plotted in Figure 1.16. As we shall see later in the text, the geomagnetic coordinate pole position is not the best representation of the magnetic field for the high latitude regions.

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**Ex. 1.10**

The magnetic dipole moment ($M$) is derived from the $g_1^0$, $g_1^1$, and $h_1^1$ Gauss coefficients which we have already found in the above exercises. Thus, with $R_e = 6371$ km, using Equation (1.82), we obtain

$$\begin{aligned} M &= [(4\pi \times 10^{-7}) \times (6.371 \times 10^6] \times \\ &\quad \sqrt{[(-29542)^2 + (-1674.5)^2 + (5073.5)^2]} \\ &= [8.006] \times [30,021] \\ &= 240,348 \\ &= 2.403 \times 10^5 \text{ Ampere-meters}^2. \end{aligned}$$

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**Ex. 1.11**

Follow instructions to the website; then view and print the field charts. The polar grid chart shows the location of the pole obtained from a full-field representation using ALL the Gauss coefficients. The geomagnetic coordinate system is obtained from the first three Gauss coefficients that represents just the centered dipole part of the full field display. The two pole locations differ considerably.

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**Ex. 1.12**

Taking YEAR2 = 1900, Table 1.2 gives

$$\begin{aligned} h_1^1/g_1^1 &= 5922/(-2298) \\ &= -2.577. \end{aligned}$$

and $\varphi$ is the angle whose tangent is $-2.577$; thus $\varphi = -68.79$ degrees. The centered dipole longitude in 1900 was at 68.79 degrees west.

Now YEAR1−YEAR2 is 2005−1900 or 105 years and $\phi$(YEAR1) − $\phi$(YEAR2)= 71.73 − 68.79 or 2.94 degrees. Therefore, the westward drift of the centered dipole over those years is about

0.028 degrees per year. To circle 360 degrees around the spin axis it would seem to take about $(360/0.028) = 12,857$ years at that rate.

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**Ex. 1.13**

The best baseline can be obtained from the values on extremely quiet days of the year. A Fourier analysis, run on those representative monthly mean values of the daily field, will extract four things: the annual variation, the semiannual variation, a base level, and the trend in the base level. That assumes that the quiet daily variation will average out for the day. For a more accurate representation of the best baseline, you can assume that a daily variation must first be removed from the quiet day data by a program such as FOURSQ1 given in C.8 of Appendix C before establishing representative monthly values for the year's Fourier analysis.

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## Chapter 2

**Ex. 2.1**

Read the description of file SQ1MODEL.EXE, at C.3 in Appendix C, and download the program file onto your computer. For Boulder (BDR) latitude of 40 deg north and 105 deg west, (on year 2003, month 6, day 21) I selected to have the hourly (60-min) values printed. The program reports the station declination to be 8.8 degrees east. The Sq hourly values, from this model for extremely quiet values, show a minimum $H$ of $-15.6$ gamma (nT) occurring at 10 am local meridian time (LT) with a maximum of 3.26 gamma at midnight. $D$ shows a maximum of 30.6 gamma at 8 am LT and a minimum of $-2.8$ gamma at 1 pm LT. $Z$ shows a minimum of $-11.9$ gamma at 11 am LT and maxima of 4.7 gamma at 6 am LT and 5.3 gamma at 6 pm LT.

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**Ex. 2.2**

Read the description of file SUN-MOON.EXE, at C.5 in Appendix C, and download the program file onto your computer. Boulder (BDR) has a latitude of 40 deg north and 105 deg west, (on year 2003, month 6, day 21). The program works in Universal Time (UT) so that the request for 12 hours Local Time (LT) must be changed. At the Boulder longitude of $-105$ degrees, with 15 degrees per hour around the Earth, we must add 7 hours to the LT and obtain 19 UT. Entering 19 UT for the requested hour, the program output for the Chapman Function (SQRTCOSCHI = Square Root of the Cosine of Chi) becomes 0.978 at local noon on the given day.

$\chi$, the solar zenith angle, is $90 - \text{ALTITUDE} = 90 - 73.204$ or 16.796 degrees. The given values of the Chapman function was computed in the program by just taking

$$\begin{aligned} \text{cosine } (\chi) &= \cos(16.796) \\ &= 0.9573 \end{aligned}$$

so

$$\sqrt{(\text{cosine})} = 0.9784.$$

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**Ex. 2.3**

The Larmor frequency becomes the gyrofrequency (Equation (2.7)) when we use the value of $(q/m) = (e/m)$ as $1.76 \times 10^{11}$. Thus, with the Exercise 1.7 value of $B_0 = F = 53853 \times 10^{-9}$ Tesla we obtain

$$\begin{aligned} \text{Larmor frequency} &= 1.76 \times 10^{11} \times 5.3853 \times 10^{-5} \\ &= 1.76 \times 5.38 \times 10^{6} \\ &= 9.47 \times 10^{6} \text{ cycles/second.} \end{aligned}$$

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**Ex. 2.4**

When the collision frequency is much smaller than the gyrofrequency we can use the two approximations for the Pederson ($\sigma_1$) and Hall ($\sigma_2$) conductivities given in the text at Equations (2.10) and (2.11). Thus we have the ratio

$$\begin{aligned} \sigma_2^2/\sigma_1 &= [\sigma_0 \times (\text{coll.freq.}/\text{gyrofreq})]^2/[\sigma_0 \times (\text{coll.freq.}/\text{gyrofreq})^2] \\ &= \sigma_0 \end{aligned}$$

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**Ex. 2.5**

In Figure 2.10, the maximum Hall conductivity $\sigma_2$ is about $1.0 \times 10^{-3}$ S/m. From Equation (2.11) we have

$$1.0 \times 10^{-3} = (\text{coll.freq.})/(\text{gyrofreq.})$$

but we found (in Ex. 2.3) that the gyrofrequency $= 9.47 \times 10^6$.
So

$$\begin{aligned} \text{Collision Frequency} &= (1.0 \times 10^{-3}) \times (9.47 \times 10^{6}) \\ &= 9.47 \times 10^{3} \text{ times/sec.} \end{aligned}$$

The collision frequency is about a thousand times greater than the gyrofrequency. The Figure 2.10 gives us only a rough estimate of the expected conductivity values because the figure applies to midlatitude noon; at other hours the conductivity is likely to be less. The values should be greater at lower latitudes and less at higher latitudes. No information is given about what month applies. Also, a seasonal variation is expected with the change in solar radiation (Figure 2.14).

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**Ex. 2.6**

The SQ1MODEL program was run and the $H$, $D$, and $Z$ variations for Boulder data of 21 June 2005 in Local Time were sketched from the listed values. The $H$ field component had a minimum of $-15.66$ nT at 10:00 and a maximum of 3.30 nT at 23:30. The $D$ showed a maximum of 31.23 nT at 7:30 and a minimum of $-28.17$ nT at 13:30. The $Z$ showed a minimum of $-11.94$ nT at 11:30 and maxima of 0.95 and 5.45 nT at 2:30 and 17:30 respectively. The peaks and valleys compared with the sketch of values expected from Figure 2.19.

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**Ex. 2.7**

Entering the 30-min $H$ values obtained in Ex. 2.6, for the Boulder data of 21 June 2005 into program FOURSQ1, the Fourier analysis of the quiet horizontal field is obtained. Because we have used an Sq program to obtain the input field the daily mean value is 0 and the trend line (A and B values) about a midday axis is also 0. If we had analyzed some raw data we would have non-zero values for these.

The Fourier coefficients found for the Sq($H$) at Boulder on the given date are:

$$A1 = +4.377 \quad A2 = -2.199 \quad A3 = +0.349 \quad A4 = +0.762 \quad A5 = 0.000$$
$$B1 = -2.973 \quad B2 = +4.938 \quad B3 = -3.815 \quad B4 = +0.942 \quad B5 = 0.000.$$

The coefficients higher than 4 are all zero here because that was the limiting size provided by SQ1MODEL. If we had analyzed raw data there would be higher values, limited only by the resolution of the input scaling.

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**Ex. 2.8**

For the 24 hourly values of Sq($H$) at Boulder, the median was found to exist between 0.9 and 1.1; whereas 0.0 was the mean value. Recall that the Sq($H$) analysis values were obtained from a field modeling program that used Fourier components oscillating about a mean value of 0 – so, no wonder that our mean turned out to be 0. The median identifies the Sq($H$) value where there are as many values above as are below: this turns out to be not 0 but about 1.0 gamma. The mean value of 0 had a sample deviation of 5.4 gamma, so the median was well within one standard deviation size. This is an exercise in the use of the two programs.

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**Ex. 2.9**

The flare effect is a result of the increased ionization affecting the Sq currents in the ionosphere. Assuming that the December flare occurs near noon at our station latitude, we just estimate that the relative flare size between latitudes is comparable to that found in Figures 2.23 and 2.24 for the Sq.

The December flare effect on $H$ at the equator, shown in Figure 2.33, is about 20 gammas in amplitude. For our Boulder location (at 40 degrees north latitude), using Figure 2.23, we see that the December relative magnitudes of Sq($H$) at $0^\circ$ and $40^\circ$ are about 3 to 1. Therefore, at the 40 degrees latitude of Boulder we expect that flare to be about 7 gammas (1/3 of the size at Huancayo in Figure 2.33).

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**Ex. 2.10**

In the absence of detailed records, the program SQ1MODEL in Appendix C can provide preliminary values of the quiet field for the solstices and equinoxes. However, that model was derived from data taken during a year of extreme solar-quiet conditions. For more accurate values in today's conditions, the local Sq values should be scaled from your recent local observatory records on isolated quiet days, selected so there was also not any geomagnetic field disturbances on the full preceding day or beginning of the following day (to avoid associated storm effects). After scaling 12 or more days spread through the year, run the analysis to obtain the Fourier coefficient of those individual Sq days using FOURSQ1 program. Then do a linear extrapolation of the values you have found and determine the expected values of the coefficients at evenly spaced days through the 360 days of the year. Next, for each coefficient, run a second Fourier analysis on these values. (You can trick the FOURSQ1 program input to represent the daily values as annual, semiannual, etc. values.) The coefficients from this run will allow you to predict (Equation (1.46)) the Sq at any day of the year for the aeromagnetic survey people. Be sure to tell the user that on some disturbed days, the ionosphere may be modified so that the expected Sq contribution may be different. However, it is usual for areomagnetic flights to avoid making measurements on disturbed days.

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## Chapter 3

**Ex. 3.1**

Using Equation (3.7) we see that the Alfen Mach Number, $M_{\mathrm{aA}}$, is equal to the ratio of the Source Disturbance Velocity to the Alfven Velocity:

$$\begin{aligned} M_{\mathrm{aA}} &= 300/30 \\ &= 10 \end{aligned}$$

or

$$
\begin{aligned}
M_{\mathrm{aA}} &= 400/30 \\
&= 13.3 \text{ Alfven Mach Number.}
\end{aligned}
$$

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**Ex. 3.2**

From the equations in Figure 3.20, the magnetopause standoff position in Earth radii can be found for a satellite that identifies the magnetopause boundary at its passage at six Earth radii distance and an angle of 30 degrees from the ecliptic.

With $\alpha = 1.5$ we have $\theta_1 = (30 - \alpha)$ equal to 28.5 so that $(\sin\theta_1)^4$ becomes $(0.47715)^4 = 0.051838$ and

$$
\begin{aligned}
R_{\mathrm{MSO}} &= (r_{\mathrm{M}^2}/2)\left[1 \pm \sqrt{(1 - \sin^4\theta_1)}\right] \\
&= 3 \times [1 + \sqrt{(1 - 0.051838)}] \\
&= 3 \times [1 + \sqrt{(0.9482)}] \\
&= 3 \times [1 + 0.97376] \\
&= 3 \times 1.97376 \\
&= 5.92 \text{ Earth radii at magnetospheric standoff.}
\end{aligned}
$$

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**Ex. 3.3**

Equation (3.9) gives $H_{\mathrm{b}}$, the increment of the $H$ component resulting from a compression of the Earth's field by the arrival of the solar wind. It is given in terms of the geomagnetic colatitude of the station (for Boulder at $90 - 48.74 = 41.26$ degrees) and the magnetospheric standoff position, $R_{\mathrm{ms}}$, equal to the $R_{\mathrm{MSO}}$ found in Exercise 3.2.

$$
\begin{aligned}
H_{\mathrm{b}} &= [250 \times \sin(\theta)]/R_{\mathrm{MSO}} \\
&= (250 \times 0.65950)/5.92 \\
&= 164.87/5.92 \\
&= 27.8 \text{ gamma compression effect on } H \text{ component.}
\end{aligned}
$$

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**Ex. 3.4**

Equation (3.10) tells us the energy, $E$, required to confine the magnetic dipole field at the Equator. First we must find the value of $H_{\mathrm{b}}$ at the Equator using Equation (3.9):

$$
\begin{aligned}
H_{\mathrm{b}} &= [250 \times \sin(90)]/5.92 \\
&= (250 \times 1)/5.92 \\
&= 42.3 \text{ gamma.}
\end{aligned}
$$

So Equation (3.10) becomes

$$\begin{aligned} E &= 4.1 \times 10^{13} H_b \\ &= (4.1 \times 10^{13}) \times 42.3 \\ &= 173.43 \times 10^{13} \\ &= 1.73 \times 10^{11} \text{ Joules.} \end{aligned}$$

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**Ex. 3.5**

At website www.ptialaska.net/~hutch/aurora.html scroll down to the third auroral photo on the main page. It is the picture with an SUV vehicle in the lower right corner. The auroral display resembles great light-greenish window curtains, seen from below and spreading almost from horizon to horizon as "drapery" form auroras. The bottom of these draperies seems well defined and at a constant altitude above the Earth (that turns out to be about 100 km). Some of the draperies are so faint that only the lower borders are visible. The auroral draperies themselves show many vertical dark lines (that follow the magnetic main field directions) perpendicular to the lower borders. All the draperies seem to be "hung" in the same general (magnetic east – west) direction and some seem to be almost parallel to others in their folds.

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**Ex. 3.6**

We use Table 3.4 for estimates of the yearly occurrence of the Ap index. If we select Ap = 70 and Ap = 5 as the high and low values for this exercise, then

$$\begin{aligned} N \text{ Number days/year for Ap} \geq 70 \text{ is } 4.14 \times 10^4 \times \text{Ap}^{-2.25} \\ N = 4.14 \times 10^4 \times (70)^{-2.25} \end{aligned}$$

so

$$\begin{aligned} \log(N) &= \log(4.14) + 4 - 2.25 \times \log(70) \\ &= 0.617 + 4 - 2.25 \times 1.845 \\ &= 0.617 + 4 - 4.151 \\ &= 0.466. \end{aligned}$$

Thus $N = 2.9\ (\pm 0.2)$ times per year for Ap $\geq$ 70.

$$\begin{aligned} N \text{ Number days/year for Ap} \leq 5 \text{ is } &-52.3 + 267.4 \times \log(\text{Ap}) \\ N &= -52.3 + [267.4 \times \log(5)] \\ &= -52.3 + (267.4 \times 0.69897) \\ &= -52.3 + 186.9 \\ &= 134.6. \end{aligned}$$

Thus $N = 134.6(\pm 5.4)$ times per year for Ap $\leq 5$.

Note the > and < signs and that these values are simply a guide to average expectations. The approximations for Ap were obtained as an average behavior over a full solar activity cycle. In quiet solar years the number of low Ap values will be larger; in active solar years the number of high Ap values will be larger.

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**Ex. 3.7**

Using Equation (3.16) we can estimate the values of AE for various Ap indices:

$$\text{AE} = 1.94 + 11.2 \times \text{ Ap}.$$

With Ap = 70 we have

$$\begin{aligned} \text{AE} &= 1.94 + 11.2 \times 70 \\ &= 1.94 + 784 \\ &= 786 \text{ nT (AE value for a large storm).} \end{aligned}$$

With Ap = 5 we have

$$\begin{aligned} \text{AE} &= 1.84 + 11.2 \times 5 \\ &= 57.8 \text{ nT (value for a quiet period).} \end{aligned}$$

Next, enter website http://www.ngdc.noaa.gov following the directions in the exercise. It is shown that on 20 April 2002 (020420) the Ap value was 70.

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**Ex. 3.8**

Note that the date 22 January 2000 is shown at the beginning of the data line as DST0001P22. The 24 hourly values of Dst on the given date are displayed as groups of four spaces following the 000. Be sure to ignore the values in the last four spaces of each data line. The sample was selected to show the main phase and the recovery phase of a storm.

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**Ex. 3.9**

Using the DSTDEMO program, enter the values starting with UT hour 15 (which will be called hour 1 in storm time). When editing the data for mis-keyed values be sure to note that the negative of all values is what is listed and plotted. This storm shows a typical rise to main phase peak, but the slow recovery is interrupted by a second burst of activity near hour 20 (storm time) and another burst near hour 45.

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**Ex. 3.10**

This is an excellent website to explore and learn about the space environment. The instructor can add to the exploration by discussing the displays and following the activity predictions through the class semester.

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**Ex. 3.11**

We would find that impulsive SEP events are quite common, lasting for hours. The events are accompanied by helium 3 and 4 isotopes in about similar amounts, iron and oxygen atoms in about equal amounts, and about ten times as many hydrogen atoms as helium atoms.

The Sun is about $1.496 \times 10^8$ km from the Earth. Light waves and X-rays travel at about $3 \times 10^5$ km per second. Thus, the X-rays will arrive at the same time as the event is seen, having taken $(1.496/3) \times 10^3 = 498.7$ seconds (or 8.3 minutes) for the trip from the Sun.

Assuming a particle flow of about 500 km/sec, the onset of the disturbance at the Earth could occur at

$$\begin{aligned}\text{Arrival} &= 1.496 \times 10^8/(5 \times 10^2) \text{ seconds}\\ &= 2.992 \times 10^5 \text{ seconds}\\ &= 99.7 \text{ hours}\\ &= 4 \text{ days and } 1.7 \text{ hours.}\end{aligned}$$

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**Ex. 3.12**

Geostationary orbits of Earth satellites are located at about six Earth radii distant near the equatorial plane. During large magnetic storms, the magnetospheric standoff position can be pushed inward past the geostationary satellite route. When on the dayside of the Earth during solar–terrestrial disturbances, onboard magnetometers can record the field interactions between the IMF and the Earth's main field. Scientists study these interactions in an effort to determine why some arriving solar particles have a major or minor effect on the Earth's space environment.

While on the nightside of the Earth, the geostationary satellite can, once a day, sense the magnetospheric tail current sheet changes following a storm and trace its seasonal variability. The tail current can be the reservoir of some auroral particles.

With an on-board magnetometer, an occasional erratic behavior of the satellite electronics can be evaluated for possible local field and particle source of damage.

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## Chapter 4

### Ex. 4.1

You may find that the instructions from GSFC/NASA need to be modified slightly to accommodate my available materials. The purpose of this exercise is to familiarize the student with the simplicity of magnetic measurements. If an observatory variometer is available for demonstration, that would be a better substitute for this exercise.

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### Ex. 4.2

For a 10 nT field, using $B = 4\pi \times 10^{-7} \times$ H, we have

$$\begin{aligned} H_y &= B_y/(4\pi \times 10^{-7}) \\ &= (10 \times 10^{-9})/(4\pi \times 10^{-7}) \text{ Tesla} \end{aligned}$$

at a frequency $f = 1/30$ cycles/second.

Equation (4.5), for ocean water conductivity $\sigma_w = 10$ Siemens/meter, the electric field would be:

$$E_x = H_y \times \sqrt{[(4\pi \times 10^{-7} \times 2\pi)/(30 \times \sigma_w)]}$$

$$\begin{aligned} E_x &= [B_y/(4\pi \times 10^{-7})] \times \sqrt{[(4\pi \times 10^{-7} \times 2\pi)/(30 \times 10)]} \\ &= [10 \times 10^{-9}/(4\pi \times 10^{-7})] \times \sqrt{[(8\pi^2 \times 10^{-7})/(3 \times 10^2)]} \\ &= [(10^{-8})/(4\pi \times 10^{-7})] \times \sqrt{[\pi^2 \times 2.667 \times 10 \times 10^{-10}]} \\ &= (10^{-1}/4\pi) \times (\pi \times 5.164 \times 10^{-5}) \\ &= (5.164/4) \times 10^{-6} \\ &= 1.291 \times 10^{-6} \text{ volts per meter.} \end{aligned}$$

At a probe separation of 10 meters, the electric field in millivolts would be

$$\begin{aligned} E\,(\text{water}) &= 10 \times 1.291 \times 10^{-6} \times 10^3 \text{ millivolts/meter} \\ &= 1.29 \times 10^{-2} \text{ millivolts.} \end{aligned}$$

Using Equation (4.5) we see that for similar conditions except a change to the conductivity of dry earth, $\sigma_e$=$10^{-5}$ Siemens/meter, the two electric field values will change as the square root of the inverse ratio of the conductivities.

$$E_x(\text{earth})/E_x(\text{water}) = \sqrt{(\sigma_w/\sigma_e)}$$

or

$$\begin{aligned} E_x(\text{earth}) &= E_x(\text{water}) \times [\sqrt{(\sigma_w/\sigma_e)}\,] \\ &= 1.291 \times 10^{-6} \times [\sqrt{(10/10^{-5})}\,] \end{aligned}$$

$$
\begin{aligned}
&= 1.291 \times 10^{-6} \times 10^{3} \\
&= 1.291 \times 10^{-3} \text{ volts per meter.}
\end{aligned}
$$

At a probe separation of 10 meters, the electric field in millivolts would be

$$
\begin{aligned}
E(\text{earth}) &= 10 \times 1.291 \times 10^{-3} \times 10^{3} \\
&= 12.91 \text{ millivolts.}
\end{aligned}
$$

---

**Ex. 4.3**

For Equation (4.7) we have

$$
\begin{aligned}
V &= 2\pi \text{ fNAB} \\
&= 2\pi(1/30) \times (10^{4}) \times 2 \times (10 \times 10^{-9}) \\
&= (4/30)\pi \times 10^{-4} \\
&= 4.189 \times 10^{-5} \text{ volts} \\
&= 0.04189 \text{ millivolts.}
\end{aligned}
$$

---

**Ex. 4.4**

In Exercise 1.7 we already used program GEOMAG and found the total field to be $F = 53853$ nT at the local location (here it is Boulder). The equation for this problem is Equation (4.10). In the fourth paragraph following that equation the gyromagnetic ratio is given as 0.2675 $(\text{nT}\times\text{sec})^{-1}$. Therefore our working equation becomes

$$
\begin{aligned}
\text{Larmor frequency} &= 0.2675 \times 5.3853 \times 10^{4} \\
&= 1.44 \times 10^{4} \text{ cycles per second.}
\end{aligned}
$$

The Larmor period is just $1/(1.44\times10^{4}) = 6.94 \times 10^{-5}$ seconds.

---

**Ex. 4.5**

The purpose of this exercise is to familiarize the student with the nearest INTERMAGNET observatory, the type of records found there and where more information can be obtained. For example, I have found that the Boulder observatory uses Fluxgate and proton precession magnetometers. The colatitude, east longitude and altitude are given. The station reports field as *HDZ* and total field. The local Geomagnetic Information Node (GIN) for details is located at Golden whose address and contact is given elsewhere in this website.

---

**Ex. 4.6**

For Boulder at 40 degrees latitude, $\theta = (90 - 40) = 50$ degrees. Also, $r = 6.37 \times 10^6$ and $dr = 1$. Using Equation (4.14) we have

$$\begin{aligned} db &= [-18.6 \times 10^4 \times \cos(50^\circ)] \times [1/(6.37 \times 10^6)] \\ &= (-1.86 \times 0.6428 \times 10^5)/(6.37 \times 10^6) \\ &= -0.1877 \times 10^{-1} \\ &= -0.0187 \text{ nT through one meter outward.} \end{aligned}$$

---

**Ex. 4.7**

Our bar magnet of $10^7$ gamma causes an oscillation period, $T$, of one-tenth second. Equation (4.4) tells us that $B$ varies as the inverse square of the period (or the period varies as the inverse square root of the field). Thus, calling the magnet field $B_m$ and the Earth's field $B_e$, and working in nT for the field, we have the ratio

$$T_e/T_m = \sqrt{(B_m/B_e)}.$$

Working with my Boulder field value of $5.3853 \times 10^4$ gamma.

$$\begin{aligned} T_e &= T_m\sqrt{(B_m/B_e)} \\ &= 10^{-1}\sqrt{[10^7/(5.3853 \times 10^4)]} \\ &= 10^{-1}\sqrt{(1.857 \times 10^4)} \\ &= 1.363 \times 10^1 \\ &= 13.6 \text{ seconds oscillation of the compass needle.} \end{aligned}$$

---

**Ex. 4.8**

The purpose of this exercise in reading about the Danish Oersted satellite is to have the student appreciate the wealth of information about magnetism on the websites and to realize the valuable contributions of many nations to the global magnetic field modeling.

---

**Ex. 4.9**

One should locate a site that is far from electrical noises, such as radiowave transmitters, industrial development, electric railways, and power lines. The site will have lower power transmission line noise to filter out if located at the end of a long feeder line for a commercial power source. A possible site needs to be excluded if major magnetic field gradients (due to surface anomalies) are found in a magnetic survey with a field proton magnetometer. Attention should be paid to measurement errors that can arise from the common objects listed in Table 4.4.

The exact direction for geographic north needs to be determined using a GPS system or a gyro-theodolite. The observatory needs to be constructed of non-magnetic materials and even the construction concrete must be examined to assure that the selected gravel to be used will not deflect the measured field. There should be concern for even large sheets of roofing metal that can move in the wind and generate dynamo currents to disturb the natural field readings.

For instrumentation, a proton magnetometer is best for establishing the baseline main field. Presently, commercial fluxgate magnetometers provide the rapid response to field variations about the baseline. Our book provides references for publications with information on observatory construction and calibration. Discussions with leaders of the INTERMAGNET program are advisable to determine if the observatory can meet the exacting standards of that program (Table 4.5). Note that observatories which contribute copies of their magnetic data to the World Data Center system are allowed to draw data from the WDC archives without charge.

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## Chapter 5

### Ex. 5.1

Communication satellite topics are: damage to the satellite and its orbit as well as temporary disruption in transmission of signals to and from the Earth's stations.

Too much increased weight is required to shield satellite electronics from space particles, so all satellites are exposed. Storm particles can initiate single-particle upsets in which satellite computer chips are hit by individual energetic, charged solar-terrestrial particles. Difficulties can also arise from the charged particle bombardment of the satellite itself, causing an electric charge build-up that discharges to damage operational components. Some of the storm particles flood the magnetosphere only during a magnetic storm; others linger and congregate at the South Atlantic/South American Anomaly (Figure 5.1) position (which can not always be avoided by judicial satellite placement). At geostationary distances, on occasions, the magnetospheric boundary is compressed sufficiently to cause the satellite to be exposed to the solar wind itself.

Because of the potential for a multitude of problems, satellite position-change commands should be avoided. The heating accompanying a geomagnetic storm changes the satellite drag within the magnetosphere so that the satellite position may later need thruster adjustments to avoid loss of its geostationary location.

Communication to and from satellites must traverse the Earth's ionosphere, which can become unstable during geomagnetic storms (Figure 5.7). At the ground communications center for the satellite, radiowave and telephone signals to other ground locations can be disrupted (Figure 5.6).

The communication satellite command site should be in constant contact with the global space disturbance forecasting centers and have skilled personnel to interpret the wealth of information about space weather that is provided by such centers.

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**Ex. 5.2**

The signal at 30 seconds period in Exercise 4.2 considered the dry earth and ocean water conductivities of $\sigma_e = 10^{-5}$ and $\sigma_w = 10$ Siemens per meter. With Equation (5.2), the approximate penetration depth for the dry earth is

$$
\begin{aligned}
Z_e &= (1/2\pi) \times \sqrt{[(5 \times T)/\sigma]} \\
&= (1/2\pi) \times \sqrt{[(5 \times 30)/(10^{-5})]} \\
&= (1/2\pi) \times \sqrt{[(15 \times 10) \times 10^5]} \\
&= (3.873 \times 10^3)/2\pi \\
&= 6.16 \times 10^2 \text{ kilometers} \\
&= 616 \text{ kilometers into the dry earth;}
\end{aligned}
$$

and for ocean water the depth becomes

$$
\begin{aligned}
Z_w &= (1/2\pi) \times \sqrt{[(5 \times 30)/10]} \\
&= (1/2\pi) \times \sqrt{(15)} \\
&= 3.873/2\pi \\
&= 0.616 \text{ kilometers} \\
&= 616 \text{ meters into the ocean water.}
\end{aligned}
$$

Another way is to realize that the penetration depth varies as the inverse square root of the conductivities. Thus, once we have the dry-earth depth, we can see that the ocean water has a coductivity of $10^6$ larger. Therefore the depth should be $10^3$ smaller.

---

**Ex. 5.3**

The purpose of this exercise is to familiarize the student with the available journal literature regarding pipeline corrosion. Whether the student reads Campbell (1986), Shapka (1993), or Trichtchenko and Boteler (2001), the references therein will provide some understanding of the importance of geomagnetic storms to the oil and gas industry.

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**Ex. 5.4**

The spectacular electric power grid failures are more newsworthy than other geomagnetic storm effects because of the immediate and widespread public inconveniences. However, public complacency concerning this subject exists because the occasions of major power failures are so widely spread in time. The student is asked to read the articles listed in Section 5.5 so that the relationship of magnetic storms to the public power-outages can be better appreciated.

---

**Ex. 5.5**

Aeromagnetic surveys are used for preliminary investigation of the geological formations within the Earth's outer crust. Oil/gas exploration companies principally fund such operations. A telephone call to the local geological exploration organizations (government or private) can provide the flight track information. However, realize that private organizations typically restrict their release of detailed mapping results.

---

**Ex. 5.6**

*Introduction to Geomagnetic Fields* has simply given the basic ideas for each magnetic topic; full textbooks have been written on each of the subjects. The student's reading of these two scientific papers on induction measurements should lead to an appreciation of geomagnetic studies to the application in geological surveys.

---

**Ex. 5.7**

The understanding of seafloor spreading, plate tectonics, and earthquake dynamics all had their start with geomagnetic field measurements. The USGS websites provide the student with excellent reviews of the scientific work on these subjects.

---

**Ex. 5.8**

Pseudo-science advocates often assign magnetism with mysterious properties. These two examples, the loss of ships in the mysterious Bermuda Triangle and magnet therapy (that is so popular just now), are exposed in detail by the Skepdic website.

---

**Ex. 5.9**

Looking at Table 5.3 for $Kp = 7$ we see that both power systems and pipeline problems can arise. Spacecraft can expect surface charging and orbit problems due to atmospheric drag changes. Navigation information from satellites and from ground transmitters can occur. Propagation of high frequency radiowave signals is affected.

The table indicates that Kp $= 7$ has an occurrence of about 200 times per 11 years. Taking 365 days/year and eight values of Kp index reported per day, that rate transforms to

$$\begin{aligned} \text{Rate} &= (200 \text{ times}/11\text{yr})/[(365\text{day/yr}) \times (8\text{ind/day})] \\ &= 0.0685 \text{ times/index} \\ &= 6.8 \text{ percent of the indices.} \end{aligned}$$

Using Figure 3.54, which gives the occurrence percent of all Kp indices, we see that a value of about 0.4 to 0.5 percent is indicated. There is more than a factor of ten difference! Is it that the Forecasting Center is overstating the danger or that one or the other of the sample sets was an inadequate representation? A new study should be made with the data available on the website given in Exercise 3.8. The logarithmic form of the Figure 3.54 is not in dispute.

Figure 3.54, using four levels, calls the Kp $= 7$ value a "Large Storm"; whereas the Forecasting Center Table 5.3, identifying five levels, calls it a "Strong Storm". Both names are in public use.

From Table 3.3 at Kp $= 7$ we have an eqivalent level of ap $= 132$. By convention, the midlatitude $H$ component of field would be about equal to that level, 132 nT.