THE ROSCOE MANUAL
Volume 15-Ambient Geomagnetic Field

Science Applications, Inc
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La Jolla, California 92037

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**THE ROSCOE MANUAL**

Volume 15 - Ambient Geomagnetic Field

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**ABSTRACT**
A preliminary model of the ambient geomagnetic field has been adopted for use in ROSCOE. The model fits a locally-best earth-centered dipole field in the battle space; this dipole field is then used for subsequent field evaluations and line tracings. Herein are presented derivations, flow diagrams, Fortran listings, and a test problem and evaluation. The model is found to be both fast and accurate.
EDITORS' NOTE

Volumes 13 to 17 were originally published by SAI to describe the atmospheric, geomagnetic, and high-altitude energy deposition and neutral heave models for ROSCOE. This whole section of code, when associated with an appropriate DRIVER subroutine, operated as a package that ran independently of the rest of the ROSCOE structure. Provision was also made, within this high-altitude package, for two completely independent descriptions of atmospheric heave, each with its own description of atmospheric chemistry.

When GRC incorporated this section of code within the ROSCOE framework, some modifications were necessary, which means that some of the descriptions in Volumes 13 to 17 are inappropriate to ROSCOE as it now exists. In particular, the NRL heave routines (deck NRLHYD) and associated chemistry (deck NRLCHM) are not presently used in ROSCOE. Three other subroutines are different: subroutines ATMOSU, EIF, and XTCOEF correspond to the ROSCOE subroutines ATMOS, EXPINT, and WDXP respectively. With these exceptions, the subroutines described in Volumes 13 to 17 correspond exactly to those currently in ROSCOE.
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1. INTRODUCTION

The geomagnetic field plays an important role in a number of high-altitude nuclear explosion phenomena, including debris-air coupling, the guiding of beta rays and energetic ions down into the atmosphere, and the formation of striations, to mention a few. For first bursts, and sufficiently late after any burst, this field will be the ambient geomagnetic field. Accordingly, a model of the ambient geomagnetic field is needed for the new radar and optical systems code.

The requirements of such a model, apart from the general ones of modularity and minimal demands on computer storage and running time, are that it provide reasonably accurate values of the vector field components, and that it permit the efficient tracing of field lines.

The RANC codes used an earth-centered dipole approximation to the ambient geomagnetic field. Such a model is certainly fast, and permits the easy tracing of field lines, but its predictions are of low accuracy. On the other hand, there are available highly-accurate multipole field models [SM-72e] that are fast-running except for their field-line tracing routines, which necessarily integrate numerically.

Because of the fact that the systems code will be concerned with only a limited battle space of the order of one thousand kilometers in linear dimension, a compromise solution incorporating the best features of both kinds of model becomes possible; it has been explored and is tentatively adopted. This model uses accurate field components obtained from the multipole model for some point in the middle of the battle space to fit a locally-best geocentric dipole field. This, of course, needs to be done only once, during problem setup. The dipole
model is then used for subsequent field evaluations, for line tracing, and so on. Thus both speed and good accuracy are obtained.

In the following sections there is a description of a set of computer subroutines that have been written to implement the model. Listings, cross-reference lists of variables, and input/output lists are included in an appendix, along with test problems that have been used in model evaluation.
2. SUBROUTINE ONEMG5 AND LINTRA

Personnel of the National Aeronautics and Space Administration have developed and thoroughly documented [SM-72e] a set of Fortran subroutines providing a multipole-expansion model of the geomagnetic field, including secular changes and provisions for tracing field lines to intersects at specified altitudes. One of these routines, called ONEMG5, * embodies the International Geomagnetic Reference Field (IGRF 1965.0), and it has been adopted here as the "good" magnetic field model. Another routine called LINTRA traces geomagnetic field lines to their intersections with prespecified altitudes; it has been used only for verification of the simplified dipole-field line-tracing routine.

A simplified flow diagram of ONEMG5 is shown in Fig. 1. Corresponding details for LINTRA have not been supplied here, for that routine does not form part of the present package, but was only used in evaluation. Moreover, these details are readily available in SM-72e.

One note of warning must be sounded concerning the description of secular changes that is provided in ONEMG5. This description is of first order only, and is based on a fairly small number of years of good data near the epoch 1965.0. Consequently, it is inadvisable to input a time more than a few years away from the data range of the model.

*Called ONEMAG in SM-72e.
Subroutine ONEMG5

First time thru?

No

Yes

Initialize

a) Calculate Schmidt coefficients for IGRF 1965.0
b) Convert to Gauss-normalized coefficients

Change in time?

No

Yes

Calculate new coefficients

Compute field components and magnitude

RETURN

Fig. 1. Subroutine ONEMG5 Flow Diagram.
3. SUBROUTINE MAGFIT

Given a point in space (normally near the earth's surface and centrally located in the battle space) for which accurate values of the geomagnetic field components are known, subroutine MAGFIT calculates the strength and orientation of an earth-centered magnetic dipole to reproduce those components. The routine is used only once, during problem setup, and the dipole properties are then stored and used later to provide field component values at other points within the limited battle space.

In Fig. 2, the point P at geocentric radial distance \( r \), north latitude \( \lambda \) (colatitude \( \theta \)), and east longitude \( \varphi \) is the reference point at which the field components \( B_r, B_\theta, \) and \( B_\varphi \) (in the same coordinate system \( (r, \theta, \varphi) \)) are known. The point Q at north latitude \( \lambda_o \) (colatitude \( \theta_o \)) and east longitude \( \varphi_o \) on the surface of an earth-centered sphere passing through P is the direction of the earth-centered dipole. The point N is the north geographic pole. The arc length (or central angle) between Q and P is denoted by \( \chi \).

From the equations for a magnetic dipole field we have the relations

\[
B_r = \frac{2M \cos \chi}{r^3},
\]

\[
B_2 = \frac{M \sin \chi}{r^3},
\]

where \( M \) measures the dipole strength and \( B_2 \) is the angular component in the direction of increasing \( \chi \). Consequently, from simple geometry there follows the relations
Fig. 2. Geometrical Relationships on an Earth-Centered Sphere through Point P.
\[ B_\theta = B_2 \cos \alpha , \]  
(3)

\[ B_\phi = B_2 \sin \alpha , \]  
(4)

and

\[ B_2^2 = B_\theta^2 + B_\phi^2 , \]  
(5)

where \( \alpha \) is the angle QPN.

From Eqs. (1) and (2) one finds the formulas

\[ M = \frac{r^3}{2} \left[ B_2^2 + 4B_2^2 \right] , \]  
(6)

\[ \chi = \tan^{-1} \left( \frac{2B_2}{B_\theta} \right) . \]  
(7)

From Eqs. (3) and (4) it follows that

\[ \alpha = \tan^{-1} \left( \frac{B_\phi}{B_\theta} \right) . \]  
(8)

By applying the cosine law of spherical trigonometry to the spherical triangle QPN, one obtains the relation

\[ \cos \theta_0 = \cos \chi \cos \theta + \sin \chi \sin \theta \cos \alpha . \]  
(9)

Application of the sine law leads to the further relation

\[ \sin (\phi - \phi_o) = \sin \chi \sin \alpha / \sin \theta_0 . \]  
(10)

One more use of the cosine law yields the equation

\[ \cos (\phi - \phi_o) = (\cos \chi - \cos \theta_0 \cos \theta) / (\sin \theta_0 \sin \theta) , \]  
(11)

useful in establishing the correct quadrant.
Equations (5)-(11) constitute the working equations of subroutine MAGFIT. A Fortran listing of the routine appears in the appendix. A simplified flow diagram is given in Fig. 3.

Fig. 3. Subroutine MAGFIT Flow Diagram.
4. SUBROUTINE BFIELD

For any point P at geocentric radial distance r, north latitude \( \lambda \) (colatitude \( \theta \)), and east longitude \( \varphi \), subroutine BFIELD calculates the geomagnetic field strength \( B \), the dip angle \( I \), and the declination angle \( D \), based on a locally-fitted geocentric magnetic dipole of strength \( M \) oriented in the direction of north latitude \( \lambda_0 \) (colatitude \( \theta_0 \)) and east longitude \( \varphi_0 \). These latter three quantities must have been found previously by the use of subroutines MAGFIT and ONEMG5 for a reference point within a thousand kilometers or so of point P, if good accuracy is to be assured. Figure 2 may be used to help visualize the geometrical relationships.

The equations of subroutine BFIELD are, for the most part, just those presented above in Section 3, but solved for different variables. Thus, the angle \( \chi \) between the dipole moment and the field point is obtained from the equation

\[
\cos \chi = \cos \theta \cos \theta_0 + \sin \theta \sin \theta_0 \cos (\varphi - \varphi_0),
\]

which follows from spherical trigonometry. The total field strength \( B \) is obtained by use of Eqs. (1) and (2) from the relation

\[
B = \left[ B_r^2 + B_2^2 \right]^{\frac{1}{2}} = \frac{M}{r^3} \left[ 3 \cos^2 \chi + 1 \right]^{\frac{1}{2}}.
\]

The dip angle \( I \) is obtained by use of Eqs. (1) and (2) and the definition

\[
\sin I = B_r/B
\]

\[
= 2 \cos \chi/\left[ 3 \cos^2 \chi + 1 \right]^{\frac{3}{2}}.
\]
The declination angle $D$ is obtained by use of the definition

$$D \equiv \pi - \alpha$$

(17)

and Eqs. (10) and (9) through the equations

$$\sin D = \sin \theta_o \sin (\phi - \phi_o)/\sin \chi,$$

(18)

$$\cos D = (\cos \theta_o - \cos \chi \cos \theta)/(\sin \chi \sin \theta),$$

(19)

both equations being necessary to resolve quadrant ambiguities.

Equations (14), (16), (18), and (19) are the working equations of subroutine BFIELD. A Fortran listing of the routine appears in the appendix. A simplified flow diagram is shown in Fig. 4.
Subroutine BFIELD

- Compute cosine of angle between magnetic dipole moment and field point, COSCHI
- Determine sign of COSCHI
- Compute magnetic dipole field strength and declination and dip angles from magnetic dipole moment and COSCHI
- RETURN

Fig. 4. Subroutine BFIELD Flow Diagram.
5. SUBROUTINE CONJUG

The main function of subroutine CONJUG is to locate the latitudes and longitudes of those points where a given geocentric magnetic dipole field line intersects a prespecified altitude. There are generally two such points; the routine will locate either, depending on the choice of an input quantity. CONJUG also computes (1) the dimensionless field-line distance (in units of the equatorial radius to the dipole field line) between two specified points \( P_1 \) and \( P_2 \) and (2) the ratio of the equatorial field to that at point \( P_1 \), for the same field line.

Suppose the orientation of the geocentric dipole is specified by the north latitude \( \lambda_o \) (colatitude \( \theta_o \)) and east longitude \( \varphi_o \). Let the field line be specified by the fact that it passes through a point \( P_1 \) in space at altitude \( h_1 \), north latitude \( \lambda_1 \) (colatitude \( \theta_1 \)), and east longitude \( \varphi_1 \). Then we seek the north latitude \( \lambda_2 \) (colatitude \( \theta_2 \)) and east longitude \( \varphi_2 \) of a point \( P_2 \) on the same dipole field line as \( P_1 \). The geometry of the situation is illustrated in Fig. 5.

From the cosine law of spherical trigonometry applied to the spherical triangle \( P_0 P_1 N \), we obtain the result

\[
\cos \chi_1 = \cos \theta_o \cos \theta_1 + \sin \theta_o \sin \theta_1 \cos (\phi_1 - \phi_o) .
\]

The sine law for the same triangle gives the result

\[
\sin \psi = \sin \theta_1 \sin (\phi_1 - \phi_o)/\sin \chi_1 ,
\]

and another application of the cosine law gives the formula

\[
\cos \psi = (\cos \theta_1 - \cos \chi_1 \cos \theta_o)/\sin \chi_1 \sin \theta_o ,
\]

so there is no ambiguity as to the quadrant of \( \psi \).
Fig. 5. Geometrical Relationships for the Field-Line Intersection Problem.
The equation of a dipole field line has the form

\[ r = r_0 \sin^2 \chi, \quad (23) \]

so the requirement that \( P_1 \) and \( P_2 \) lie on the same dipole field line leads to the result

\[ \sin \chi_2 = \sin \chi_1 \left[ \frac{(R_e + h_2)/(R_e + h_1)}{R_e} \right]^{\frac{3}{2}}, \quad (24) \]

where \( R_e \) is the radius of the earth and \( h_2 \) is the prespecified altitude of point \( P_2 \). Note that there are, generally, two solutions for \( \chi_2 \), since if \( \chi_2 \) is a solution, so is \( \pi - \chi_2 \).

Now, applying the sine and cosine laws to spherical triangle \( P_0 P_2 N \) leads to the results

\[ \cos \theta_2 = \cos \theta_0 \cos \chi_2 + \sin \theta_0 \sin \chi_2 \cos \psi \quad (25) \]

and

\[ \sin (\varphi_2 - \varphi_0) = \sin \chi_2 \sin \psi / \sin \theta_2, \quad (26) \]

whence \( \theta_2 \) (or \( \lambda_2 \)) and \( \varphi_2 \) can be obtained.

The absolute value of the dimensionless field-line distance between points \( P_1 \) and \( P_2 \) is

\[ S_{12} = \frac{1}{r_0} \left| \int_{S_1}^{S_2} ds \right|, \quad (27) \]

where the element of arc length is given by

\[ \frac{ds}{d\chi} = r_0 \sin \chi (1 + 3 \cos^2 \chi)^{\frac{1}{2}}. \quad (28) \]
After substituting Eq. (28) into (27) and performing the integration, we obtain

\[
S_{12} = \frac{\sqrt{3}}{6} \left| I \left( \sqrt{1 + \eta_1^2} - \eta_2 \sqrt{1 + \eta_2^2} + \ln \left( \frac{\eta_1 + \sqrt{1 + \eta_1^2}}{\eta_2 + \sqrt{1 + \eta_2^2}} \right) \right) \right|, \quad (29)
\]

where

\[
\eta_1 = \sqrt{3} \cos x_1 \quad (30a)
\]
\[
\eta_2 = \sqrt{3} \cos x_2 . \quad (30b)
\]

Equation (29) is valid provided points \( P_1 \) and \( P_2 \) are in the same hemisphere. If points \( P_1 \) and \( P_2 \) are in opposite hemispheres, then we must perform the integration in two parts, with the equator being the intermediate point. The result may be expressed in the form

\[
S_{12} = \frac{\sqrt{3}}{6} \left| S_{1E} - \text{AJUG} \times S_{2E} \right|, \quad (31a)
\]

where

\[
S_{1E} = \left| \eta_1 \sqrt{1 + \eta_1^2} + \ln \left( \eta_1 + \sqrt{1 + \eta_1^2} \right) \right| \quad (31b)
\]
\[
S_{2E} = \left| \eta_2 \sqrt{1 + \eta_2^2} + \ln \left( \eta_2 + \sqrt{1 + \eta_2^2} \right) \right|, \quad (31c)
\]

and AJUG is a parameter equal to (+1) if Points \( P_1 \) and \( P_2 \) are in the same hemisphere and equal to (-1) if Points \( P_1 \) and \( P_2 \) are in opposite hemispheres.

The equatorial radius, \( r_o \), is given by

\[
r_o = (M/B_o)^{\frac{3}{4}}, \quad (32)
\]
where the equatorial value of the field, $B_0$, is related to the field $B(r, \chi)$ by the expression

$$B_0 = B(r_0', \chi=\pi/2) = \frac{\sin^6 \chi}{(1 + 3 \cos^2 \chi)^4} B(r, \chi).$$  \hspace{1cm} (33)

Equations (20)-(22), (24)-(26), and (31)-(33) are the working equations of subroutine CONJUG. A simplified flow diagram of the routine is presented in Fig. 6. A Fortran listing is given in the appendix.
Subroutine CONJUG

Calculate sine and cosine of angle between magnetic dipole moment and point 1

Calculate sine and cosine of angle between magnetic dipole moment and point 2

Calculate sine and cosine of angle between field line and line joining magnetic dipole moment and geographic north pole

Calculate latitude and longitude of point 2

Calculate dimensionless distance between point 1 and point 2

Calculate ratio of equatorial value of field and that at point 1

RETURN

Fig. 3. Subroutine CONJUG Flow Diagram.
6. SUBROUTINE MAGDRV AND VERIFICATION TESTS OF THE AMBIENT GEOMAGNETIC FIELD MODEL

To permit the exercise of the ambient geomagnetic field model for purposes of testing and validation, a special driver routine called MAGDRV has been written. The required input consists of latitude, longitude, and altitude coordinates of a set of reference locations, at each of which the vector field of a geocentric magnetic dipole is fitted to an accurate multipole field, for a specified year. Further input consists in a set of locations relative to each reference point, for which both the dipole field and the accurate multipole field are evaluated and compared for relative accuracy of the total field strength. Additional input consists in sets of altitudes for the calculation of field-line intersects for each of the test points, together with flags indicating whether the desired intersection is in the same or opposite magnetic hemisphere. Additional output consists in the inclination and declination angles for each test point, according to the fitted dipole model.

The principal testing carried out so far and described herein was for a set of reference points at 200-km altitude, distributed over -60°(30°)60° in north latitude and 0°(60°)300° in east longitude. For each of these, a set of test points at 200-km altitude was specified with offsets in latitude of +5°, 0°, -5° and in longitude of +10°, 0°, -10° (a total of nine test points for each reference point). A field-line intersection altitude of 60-km altitude was called out, in separate runs for both the near and far magnetic hemisphere. (One additional reference point with a set of test points near the south magnetic pole was also run.) A check on the field-line intersection locations was provided by separate runs of the LINTRA routine.
The results of the field-strength comparisons are illustrated in Fig. 7 in the form of a histogram of the distribution of errors. It will be seen that the standard deviation is of the order of 1-2 percent. However, some test locations were found where the error was considerably larger than this. The geomagnetic field has considerable deviations from a dipole in some parts of the world. Nevertheless, it is felt that the fitted dipole model is of acceptable accuracy.

The results for the tests of field line intersection locations can be summarized by stating that, for intersection locations in the near magnetic hemisphere, the average latitude error was 0.038° and that in longitude, 0.019°. However, the median errors in both latitude and longitude were about 0.01°, showing again that occasional errors much larger than the average occur.

As for the location of intersection points in the opposite magnetic hemisphere, the less said the better, in general. The present ambient geomagnetic field model is a local best fit, and that is not a procedure that gives a good fit in the large.
Fig. 7. Frequency Distribution of Errors in Total Field Strength.
7. REFERENCES

APPENDIX

In this appendix are included certain materials of interest only to those who wish to exercise this model on their own computer, and who presumably have a Fortran card deck or tape available.

Table A1 contains a definition of the variables used in the equations of the text, and a cross reference with the Fortran names of the variables used in the listing.

Tables A2 through A6 contain lists of the input/output quantities for subroutines ONEMG5, MAGFIT, BFIELD, CONJUG, and MAGDRV.

Table A7 contains a compile-and-run listing of the whole module, together with the input and output for the test problem described in the text of the report.

Finally, Table A8 contains a summary of our experience of the running times of the various routines on a CDC 7600 computer.
Table A1. Symbols and Their Fortran Names.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Fortran</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sin(\lambda_o))</td>
<td>SINLT0</td>
<td>Sine and cosine of north latitude of magnetic dipole moment</td>
</tr>
<tr>
<td>(\cos(\lambda_o))</td>
<td>COSLT0</td>
<td></td>
</tr>
<tr>
<td>(\varphi_0)</td>
<td>PHI0</td>
<td>East longitude of magnetic dipole moment</td>
</tr>
<tr>
<td>(M)</td>
<td>MU0</td>
<td>Magnetic dipole moment</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>ANGS</td>
<td>North latitude of field point</td>
</tr>
<tr>
<td>(\phi)</td>
<td>ANGE</td>
<td>East longitude of field point</td>
</tr>
<tr>
<td>(r)</td>
<td>RCUBE</td>
<td>Geocentric radius of field point</td>
</tr>
<tr>
<td>(B_r)</td>
<td>BR</td>
<td>Geocentric spherical field vector components ((B_r, \text{ positive outward}; B_\theta, \text{ positive southward}; \text{ and } B_\phi, \text{ positive eastward})) of IGRF 1965.0 field.</td>
</tr>
<tr>
<td>(B_\theta)</td>
<td>BTHETA</td>
<td></td>
</tr>
<tr>
<td>(B_\phi)</td>
<td>BPHI</td>
<td></td>
</tr>
<tr>
<td>(\chi)</td>
<td>CHI</td>
<td>Angle between the magnetic dipole moment vector and field point</td>
</tr>
<tr>
<td>(\cos(\chi))</td>
<td>COSCHI</td>
<td>Cosine of angle between the magnetic dipole moment vector and field point</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>ALPHA</td>
<td>Angle between the magnetic dipole moment and geographic north pole</td>
</tr>
<tr>
<td>(B^2)</td>
<td>B2SQ</td>
<td>Square of the angular component of the magnetic field</td>
</tr>
<tr>
<td>(I)</td>
<td>DIPANG</td>
<td>Magnetic dip angle at field point</td>
</tr>
<tr>
<td>(D)</td>
<td>DECANG</td>
<td>Magnetic declination angle at field point</td>
</tr>
<tr>
<td>(B)</td>
<td>BVAL</td>
<td>Magnetic field strength at field point</td>
</tr>
<tr>
<td>(R_e)</td>
<td>RE</td>
<td>Radius of earth</td>
</tr>
<tr>
<td>(\lambda_1)</td>
<td>A1LAT1</td>
<td>North latitude of point 1</td>
</tr>
<tr>
<td>Symbol</td>
<td>Fortran</td>
<td>Definition</td>
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<td>--------</td>
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</tr>
<tr>
<td>$\varphi_1$</td>
<td>ALON1</td>
<td>East longitude of point 1</td>
</tr>
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<td>$h_1$</td>
<td>ALT1</td>
<td>Altitude of point 1</td>
</tr>
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<td>$h_2$</td>
<td>ALT2</td>
<td>Altitude of point 2</td>
</tr>
<tr>
<td>$\lambda_2$</td>
<td>ALAT2</td>
<td>North latitude of point 2</td>
</tr>
<tr>
<td>$\varphi_2$</td>
<td>ALON2</td>
<td>East longitude of point 2</td>
</tr>
<tr>
<td>AJUG</td>
<td></td>
<td>Flag controlling which magnetic hemisphere the location of the intersection point is calculated</td>
</tr>
<tr>
<td>$\sin(\chi_1)$</td>
<td>SINZ1</td>
<td>Sine of angle between the magnetic dipole moment vector and point 1</td>
</tr>
<tr>
<td>$\cos(\chi_1)$</td>
<td>COSZ1</td>
<td>Cosine of $\chi_1$</td>
</tr>
<tr>
<td>$\sin(\chi_2)$</td>
<td>SINZ2</td>
<td>Sine and cosine of angle between the magnetic dipole moment vector and point 2</td>
</tr>
<tr>
<td>$\cos(\chi_2)$</td>
<td>COSZ2</td>
<td></td>
</tr>
<tr>
<td>$\sin(\psi_1)$</td>
<td>SINPSI</td>
<td>Sine and cosine of angle between the field line and line joining the magnetic dipole moment with the north geographic pole</td>
</tr>
<tr>
<td>$\cos(\psi_1)$</td>
<td>COSPSI</td>
<td></td>
</tr>
</tbody>
</table>
Table A2. ONEMG5 Subroutine Input/Output.

**INPUT VARIABLES**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM</td>
<td>Time in years for desired field</td>
</tr>
<tr>
<td>RKM</td>
<td>Geocentric distance of point (km)</td>
</tr>
<tr>
<td>ST</td>
<td>Sine of (geocentric) colatitude of point</td>
</tr>
<tr>
<td>CT</td>
<td>Cosine of (geocentric) colatitude of point</td>
</tr>
<tr>
<td>SPH</td>
<td>Sine of (geocentric) east longitude of point</td>
</tr>
<tr>
<td>CPH</td>
<td>Cosine of (geocentric) east longitude of point</td>
</tr>
</tbody>
</table>

**OUTPUT VARIABLES**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR</td>
<td>Radial field component (gauss)</td>
</tr>
<tr>
<td>BTHETA</td>
<td>Positive-south field component (gauss)</td>
</tr>
<tr>
<td>BPHI</td>
<td>Positive-east field component (gauss)</td>
</tr>
<tr>
<td>B</td>
<td>Total field magnitude (gauss)</td>
</tr>
</tbody>
</table>
Table A3. MAGFIT Subroutine Input/Output

INPUT VARIABLES

Argument List

ALATF North latitude of specified point P (radians)
ALONF East longitude of specified point P (radians)
ALTTF Altitude of specified point P (km)
TM Time for desired field (years)

OUTPUT VARIABLES

MAGLNK Common

MU0 Magnetic dipole moment (gauss km^3)
COSLT0 Cosine of north latitude of magnetic dipole moment
SINLT0 Sine of north latitude of magnetic dipole moment
PHI0 East longitude of magnetic dipole moment (radians)
Table A4. BFIELD Subroutine Input/Output

### INPUT VARIABLES

**Argument List**

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANGS</td>
<td>North latitude of field point (radians)</td>
</tr>
<tr>
<td>ANGE</td>
<td>East longitude of field point (radians)</td>
</tr>
<tr>
<td>ALT</td>
<td>Altitude of field point (km)</td>
</tr>
<tr>
<td>MAGLNK</td>
<td>Common</td>
</tr>
<tr>
<td>MU0</td>
<td>Magnetic dipole moment (gauss km³)</td>
</tr>
<tr>
<td>COSLT0</td>
<td>Cosine of north latitude of magnetic dipole moment</td>
</tr>
<tr>
<td>SINLT0</td>
<td>Sine of north latitude of magnetic dipole moment</td>
</tr>
<tr>
<td>PHI0</td>
<td>East longitude of magnetic dipole moment (radians)</td>
</tr>
</tbody>
</table>

### OUTPUT VARIABLES

**Argument List**

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BVAL</td>
<td>Magnetic dipole field strength at point (gauss)</td>
</tr>
<tr>
<td>DIPANG</td>
<td>Dip angle of the magnetic dipole field at point (radians)</td>
</tr>
<tr>
<td>DECANG</td>
<td>Declination angle of the magnetic dipole field at point (radians)</td>
</tr>
<tr>
<td>COSCHI</td>
<td>Cosine of angle between the magnetic dipole moment vector and field point</td>
</tr>
</tbody>
</table>
Table A5. CONJUG Subroutine Input/Output

INPUT VARIABLES

Argument List

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALAT1</td>
<td>North latitude of point 1 (radians)</td>
</tr>
<tr>
<td>ALON1</td>
<td>East longitude of point 1 (radians)</td>
</tr>
<tr>
<td>ALT1</td>
<td>Altitude of point 1 (km)</td>
</tr>
<tr>
<td>ALT2</td>
<td>Altitude of point 2 (km)</td>
</tr>
<tr>
<td>AJUG</td>
<td>1. - Calculates latitude and longitude of point 2 in same magnetic hemisphere</td>
</tr>
<tr>
<td></td>
<td>-1. - Calculates latitude and longitude of point 2 in opposite magnetic hemisphere</td>
</tr>
</tbody>
</table>

MAGLNK Common

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MU0</td>
<td>Magnetic dipole moment (gauss km$^3$)</td>
</tr>
<tr>
<td>COSLT0</td>
<td>Cosine of north latitude of magnetic dipole moment</td>
</tr>
<tr>
<td>SINLT0</td>
<td>Sine of north latitude of magnetic dipole moment</td>
</tr>
<tr>
<td>PHI0</td>
<td>East longitude of magnetic dipole moment (radians)</td>
</tr>
</tbody>
</table>

OUTPUT VARIABLES

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALAT2</td>
<td>North latitude of point 2 (radians)</td>
</tr>
<tr>
<td>ALON2</td>
<td>East longitude of point 2 (radians)</td>
</tr>
<tr>
<td>S12</td>
<td>Path length along the field line from point 1 to point 2 (in units of the equatorial radius of the traced field line)</td>
</tr>
<tr>
<td>BEB1</td>
<td>Ratio of the equatorial value of the field to that at point 1 for the traced field line</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>ALATFI</td>
<td>Array of north latitudes of fit points (deg)</td>
</tr>
<tr>
<td>ALONFI</td>
<td>Array of east longitudes of fit points (deg)</td>
</tr>
<tr>
<td>ALTIFI</td>
<td>Array of altitudes of fit points (km)</td>
</tr>
<tr>
<td>NFIT</td>
<td>Number of fit points</td>
</tr>
<tr>
<td>TM</td>
<td>Time at which to evaluate exact field (years)</td>
</tr>
<tr>
<td>RLATS*</td>
<td>Array of north-latitude deltas of test points (deg)</td>
</tr>
<tr>
<td>RLONS*</td>
<td>Array of east-longitude deltas of test points (deg)</td>
</tr>
<tr>
<td>RALTS*</td>
<td>Array of altitude deltas of test points (km)</td>
</tr>
<tr>
<td>NRS</td>
<td>Number of test points relative to a fit point</td>
</tr>
<tr>
<td>RCONS</td>
<td>Array of test altitudes for intersection calculations (km)</td>
</tr>
<tr>
<td>AJUGS</td>
<td>Array of calculation options for conjugate-region intersection calculations:</td>
</tr>
<tr>
<td></td>
<td>1. - Calculate intersection point in same magnetic hemisphere.</td>
</tr>
<tr>
<td></td>
<td>-1. - Calculate intersection point in opposite magnetic hemisphere.</td>
</tr>
<tr>
<td>IOPT</td>
<td>MAGDRV calculation options:</td>
</tr>
<tr>
<td></td>
<td>1. - Calculate only magnetic dipole field at test points.</td>
</tr>
<tr>
<td></td>
<td>2. - Also calculate location of intersection points.</td>
</tr>
<tr>
<td></td>
<td>3. - Also calculate magnetic multipole field at test points.</td>
</tr>
</tbody>
</table>

*The (input) locations of the test points are relative to the fit point.*
Table A7. Compile-and-Run Listing of the Ambient Magnetic-Field Module, with Input and Output of Test Problems.

MAGDRV

PROGRAM MAGDRV(PARLPUT, OUTPUT, TAPE, IINPUT, IAPF, UINPUT)
C
C THIS PROGRAM EXECUTES THE AMBIENT MAGNETIC FIELD MODEL. THE
C MODEL CONSISTS OF FOUR ROUTINES. MAGFIT FITS A DIPOLLE FIELD TO
C THE MAGNETIC FIELD AT A GIVEN POINT, WHICH SHOULD BE NEAR
C THE CENTER OF THE REGION OF INTEREST. THE EXACT FIELD AT THE
C POINT IS CALCULATED FROM ONE MAGS, A MODEL OF THE INTERNATIONAL
C GEOMAGNETIC REFERENCE FIELD, EPJCL 1963.0,
C (SEE I) E. G. STASSINOPOLUS AND G. D. HEAD; NASA REPORT
C NSSCN 72-12, ALL MAGS PROGRAMS FOR
C GEOMAGNETIC FIELD AND FIELD-LINE CALCULATIONS, FEBRUARY 1972
C AND (2) J. C. CAIN AND S. J. CAIN; NASA TM D-6237, DERIVATION
C OF THE INTERNATIONAL GEOMAGNETIC REFERENCE FIELD (IGRF(10/68)),
C AUGUST 1971.
C
C A THIRD ROUTINE, RAFIELD, CALCULATES THE MAGNETIC FIELD STRENGTH
C FOR ANY GIVEN POINT FOR THE FITTED DIPOLLE. THE FOURTH ROUTINE
C CALCULATES THE LOCATION OF A POINT WITH A GIVEN ALTITUDE WHICH
C IS ON THE SAME FIELD LINE AS SOME SPECIFIED POINT FOR THE FITTED
C DIPOLLE FIELD.
C
C
C INPUT PARAMETERS (NAMELIST START)
C ALATI = ARRAY OF NORTH LATITUDES OF FIT POINTS (DEG)
C ALONF = ARRAY OF EAST LONGITUDES OF FIT POINTS (DEG)
C ALAT1 = ARRAY OF ALTITUDES OF FIT POINTS (KM)
C NFIT = NUMBER OF FIT POINTS
C EM = TIME AT WHICH TO EVALUATE EXACT FIELD (YEARS)
C MLATS = ARRAY OF NORTH LATITUDES OF TEST POINTS (DEG)
C MLONS = ARRAY OF EAST LONGITUDES OF TEST POINTS (DEG)
C MLATS = ARRAY OF ALTITUDES OF TEST POINTS (KM)
C NRS = NUMBER OF TEST POINTS
C RELATS = ARRAY OF TEST FIELD LINE ALTITUDES (KM)
C 1XLS = ARRAY OF TEST FIELD LINE CALCULATION OPTIONS
C 1. CALCULATES INTERSECTION POINT IN SAME
C MAGNETIC HEMISPHERE
C 2. CALCULATES INTERSECTION IN OPPOSITE
C MAGNETIC HEMISPHERE
C
C CAUTION: LOCATION OF OPPOSITE HEMISPHERE
C INTERSECTIONS MAY NOT BE ACCURATE
C
C INPT: CALCULATION OPTIONS
C 1 = CALCULATE ONLY DIPOLLE FIELD AT TEST POINTS
C 2 = ALSO CALCULATE LOCATION OF INTERSECTION POINTS
C 3 = ALSO CALCULATE MULTIPOLLE FIELD AT TEST POINTS
C
C FIT DIPOLLE TO POINT
C REAL M 1
C
C COMMON /MAGLINKS, MUN, CNSLT0, SINTO, PHIO

35
MAGDRV (Cont'd)

C COMM/CONSINT READ PI,MALPIN,FOURI,GRADV(?) NEWMAG,58
C
C DIMENSION RATS(50),RLUNS(50),CCONS(50),AJUGS(50) NEWMAG,59
C DIMENSION RATS(50) NEWMAG,60
C DIMENSION ALTFT(50),ALONFT(50),ALIFT(50) NEWMAG,61
C
C NAMFL /START/ALATFT,ALONFT,ALTFT,TM,RATS,RLUNS,RATS,NRS NEWMAG,62
C RCONS,AJUGS,IOPT NEWMAG,63
C
C KE = 1.0*E05*HECM NEWMAG,64
C RADS = MALPIN/90. NEWMAG,65
C
C READ IN DATA NEWMAG,66
C
C READ(S,START) NEWMAG,67
C WRITE(6,START) NEWMAG,68
C
C LUMP OVER FIT POINTS NEWMAG,69
C
C ON 900 JJ1,NFIT NEWMAG,70
C ALATF = ALATF(JJ) NEWMAG,71
C ALONF = ALONF(JJ) NEWMAG,72
C ALIFT = ALIFT(JJ) NEWMAG,73
C WRITE(n,1000)ALATF,ALONF,ALIFT,TM NEWMAG,74
C
C IF(IUPT *LT.,2) GO TO 50 NEWMAG,75
C
C CALL MAGFIT(ALATF,ALONF,ALIFT,TM) NEWMAG,76
C WRITE(6,1001)NEWMAG,77
C
C 10 WRITE(6,1002) NEWMAG,78
C 10 PRINTFH 1/10 MIN, COSLT,SINLT,PH10 NEWMAG,79
C 10 WRITE(6,1003) NEWMAG,80
C IF(IUPT *LT.,3) GO TO 50 NEWMAG,81
C 10 CONTINUE NEWMAG,82
C
C LUMP OVER TEST POINTS NEWMAG,83
C
C ON 400 JS1,NRS NEWMAG,84
C
C CALCULATE NIPUE FIELD VALUE AT TEST POINT NEWMAG,85
C
C ANGS = ALATF * RATS(1)*RADS NEWMAG,86
C
C 36
MAGDRV (Cont’d)

110  ANGF = ALONF + RLTNS(J) * RADN
113  ALT = ALTF + RLTNS(J)
115  CALL RFIELD(ANGS, ANGE, ALT, R, DIPANG, DECANG, COSCH)
120  ANGSD = ANGS / RADN
126  ANGED = ANGF / RADN
127  DIPANG = DIPANG / RADN
131  DECANG = DECANG / RADN
132  WRITE(*,1005) ANGS, ANGE, ALT, R, DIPANG, DECANG
152  IF(IOPT .LE. 1) GO TO 400

C CALCULATE LOCATION OF POINTS AT ALTITUDE CONS which are on the same FIELD LINE as the TEST POINT

154  AJUG = AJUGS(J)
157  ALT2 = RNDN(J)
161  CALL CONJUG(ANGS, ANGE, ALT, ALT2, AJUG, ALA2, ALD2, S12, R12B1)
171  ALA2 = ALA2/RADN
173  ALD2 = ALD2/RADN
174  WRITE(*,1006) ALT2, AJUG, ALA2, ALD2
207  IF(IOPT .LE. 2) GO TO 400

C CALCULATE EXACT FIELD FROM IGRF(1965) AT TEST POINT

212  RKM = RF + ALT
213  COLAT = MFPD*ANGS
214  ST = SIN(COLAT)
217  CT = COS(COLAT)
221  SPH = SIN(ANGF)
223  CMH = COS(ANGE)
224  CALL OMEGSS(TH, RM, ST, CT, SPH, CMH, RW, BT, P, RXACT)
237  DELT = (R - RXACT) / RXACT * 100
241  WRITE(*,1007) RXACT, DELT
252  400 CONTINUE
255  900 CONTINUE
257  WRITE(*,1009)
1009 FORMAT(///, 20H END OF TEST PROBLEM)
263  STOP
265  END
THIS ROUTINE CALCULATES THE AMBIENT MAGNETIC FIELD AT A POINT FROM THE MAGNITUDE AND DIRECTION OF THE MAGNETIC DIPOLE MOMENT, AND THE LOCATION OF THE POINT.

INPUT PARAMETERS
ARGUMENT LIST =
ANGF = NORTH LATITUDE OF FIELD POINT (RADIANS)
ANGE = EAST LONGITUDE OF FIELD POINT (RADIANS)
ALT = ALTITUDE OF FIELD POINT (KM)
MAGLNK COMMON
MUD = MAGNETIC DIPOLE MOMENT (GAUSS-KM)
COSLID = COSINE OF NORTH LATITUDE OF MAGNETIC DIPOLE MOMENT
SINLT = SINE OF NORTH LATITUDE OF MAGNETIC DIPOLE MOMENT
PHIO = EAST LONGITUDE OF MAGNETIC DIPOLE MOMENT (RADIANS)
CNSTINT COMMON
PI = 3.141592653589A
RFCON = EARTH RADIUS (CM)

OUTPUT PARAMETERS
ARGUMENT LIST =
BVAL = MAGNETIC FIELD STRENGTH AT FIELD POINT (GAUSS)
DIPANG = DIP ANGLE OF MAGNETIC FIELD AT FIELD POINT (RAD)
DIP (OR INCLINATION) IS THE VERTICAL ANGLE MEASURED FROM THE HORIZONTAL AT ANY POINT TO THE (VECTOR) LINE OF FORCE THROUGH THAT POINT. IT IS POSITIVE IN THE NORTHERN MAGNETIC HEMISPHERE AND NEGATIVE IN THE SOUTHERN MAGNETIC HEMISPHERE.
DECANG = DECLINATION OF MAGNETIC FIELD AT FIELD POINT (RAD)
DECLINATION (OR VARIATION), THE ANGLE BETWEEN THE GEOGRAPHIC AND MAGNETIC MERIDIANS AT A POINT, IS POSITIVE IF THE COMPASS NORTH POLE POINTS EAST OF GEOGRAPHIC NORTH.
COSCHI = COSINE OF MAGNETIC DIPOLE CULATITUDE
COSCHI IS NEGATIVE IN THE NORTHERN MAGNETIC HEMISPHERE AND POSITIVE IN THE SOUTHERN MAGNETIC HEMISPHERE.
REAL MUO
COMMON/MAGLNK/MUD,COSLID,SINLT,PHIO
COMMON/CNSTINT/RECHI,PI,HALFPI,FOURPI,GRAZ,BOLTZ,GAM1,GMII
1,PHNIT,PHXY
RFRECHI,4=5
CALCULATE SINE AND COSINE OF NORTH LATITUDE OF FIELD POINT
12 COSLAP = COS(LATITUDE)
13 SINLAP = SIN(LATITUDE)
DELFUN = ANGE = PHIO
CALCULATE SINE AND COSINE OF ANGLE BETWEEN MAGNETIC DIPOLE MOMENT AND FIELD POINT
COSCH = COSLAP\times COS(LAP\times COS(ANGE = PHIO)) \times SINLAP\times SINLAP
SINCH = SQRT(1 - COSCH\times COSCH)
CALCULATE CURE OF GEOCENTRIC RADIUS OF POINT
RCUR = RE + ALT
RCUR = RCUR\times RCUR\times RCUR
TOTAL FIELD STRENGTH
BTEN = SQRT(3\times COSCH\times COSCH + 1.)
BVAP = MU\times RCUR\times BTEN
MAGNETIC DIP ANGLE AT POINT
SINDP = 2\times SINDP / BTEN
DIPANG = -ASIN(SINDP)
MAGNETIC DECLINATION ANGLE AT POINT
SINPSI = COSLAP \times SIN(DELLOM / SINCH)
DECANG = ASIN(SINPSI)
COSPSI = -SINLAP \times COSCH \times SINLAP
IF(COSPSI,LT,0.) DECANG = SIGN(PI,SINPSI) = DECANG
RETURN
END
BLOCKH

BLOCK DATA BLOCKH
C INITIALIZE NAMED COMMON CONSTANTS AND DEFAULT VALUES
C SET OF CHEM QUANTITIES APPEARING UNDER VARIOUS CHEM OPTIONS
C DEPOSITION COEFFICIENTS FOR PROPG
COMMON/DEPDPAT/SGU(5,6),PREFF(5,6),ERGU(5),THRESH(4),SPINTH,
1 SPINT,XXM1
C MATHEMATICAL AND GEOPHYSICAL CONSTANTS
COMMON/CNSTNT/RE,PI,HALFP,FOURPI,GRAVZ,GIRE2,BOLTZK,GAM1,GM11
1,PHNIT,PHOXY
C
C CNSTNT
DATA RE ./1.357650E+08}/
1 PI ./3.145926535895}/
3 HALFP/1.15707963267399}/
5 FOURPI/12.5663706143592}/
7 GRAVZ/980.665}/
5 BOLTZK/1.38054E=16}/
2 PHNIT/2.324743E=23}/
3 PHOXY/2.6585E=23}/
6 GAM1/0.5}/
C
C DEPDPAT
DATA SGU/0.0,1.8,0E=18,2.0E=17,2.5E=17,2.0E=17,
1 2.0E=17,2.5E=17,2.0E=17,2.0E=17,
2 0.0,1.0E=17,1.0E=17,1.0E=17,1.0E=17,
3 0.0,3.2E=18,3.2E=18,9.0E=18,9.0E=18,
4 ERGU/1.762E=11,2.31E=11,2.50E=11,3.525E=11,5.767E=11,
5 THRES/1.564E=11,2.20E=12,2.331E=11,2.102E=11,
6 SPINTH/1.00E=17,SPINTH/2.77E=17
END

40
SUBROUTINE CONJUG(ALAT1,ALON1,AL11,ALT2,AJUG,ALAT2,ALON2,ST2,REB)  NEWMAG,274
C * * * * * * * *
C THE ROUTINE CONJUG CALCULATES, FOR A GIVEN ALTITUDE, THE LOCATION
C (LAT, Lon) OF THE POINT(2), WHICH IS ON THE SAME MAGNETIC DIPOLE
C FIELD LINE AS SOME OTHER GIVEN POINT(1). IT ALSO CALCULATES THE
C FIELD LINE DISTANCE BETWEEN POINT(1) AND POINT(2), IN UNITS OF
C EQUATORIAL VALUE OF THE FIELD TO THAT AT POINT(1) FOR THE TRACED
C LINE.
C * * * * * * * *
C INPUT PARAMETERS
C ARGUMENT LIST =
C      ALAT1 = NORTH LATITUDE OF POINT 1 (RADIANS)  NEWMAG,284
C      ALON1 = EAST LONGITUDE OF POINT 1 (RADIANS)  NEWMAG,285
C      AL11  = ALTITUDE OF POINT 1 (KM)             NEWMAG,286
C      ALT2  = ALTITUDE OF POINT 2 (KM)             NEWMAG,287
C      AJUG  =
C             1. CALCULATES LOCATION (LAT, Lon) OF POINT 2
C             IN SAME MAGNETIC HEMISPHERE
C             1. CALCULATES LOCATION (LAT, Lon) OF POINT 2
C             IN OPPOSITE MAGNETIC HEMISPHERE
C ***************
C CAUTION = LOCATION OF OPPOSITE HEMISPHERE
C INTERSECTIONS MAY NOT BE ACCURATE
C ***************
C MAGLNK COMMON
C MDO = MAGNETIC DIPOLE MOMENT (GAUSS·KM)          NEWMAG,307
C COSL0 = COSINE OF NORTH LATITUDE OF MAGNETIC DIPOLE MOMENT
C SINL0 = SINE OF NORTH LATITUDE OF MAGNETIC DIPOLE MOMENT
C PHIO = EAST LONGITUDE OF MAGNETIC DIPOLE MOMENT (RADIANS)
C CNSTNT COMMON
C RECH = EARTH RADIUS (CM)                           NEWMAG,312
C PI = 3.1415926535898                                NEWMAG,313
C OUTPUT PARAMETERS
C      ALAT2 = NORTH LATITUDE OF POINT 2 (RADIANS)   NEWMAG,314
C      ALON2 = EAST LONGITUDE OF POINT 2 (RADIANS)  NEWMAG,315
C      SI2  = DISTANCE ALONG FIELD BETWEEN POINT 1 AND POINT 2 (IN
C               UNITS OF THE EQUATORIAL VALUE OF THE TRACED LINE) NEWMAG,316
C      RF01 = RATIO OF THE EQUATORIAL VALUE OF THE FIELD TO THAT AT
C               POINT 1 FOR THE TRACED LINE
C COMMON /MAGLNK/ MDO,COSL0,SINL0,PHIO
C COMMON/CNSTNT/ RECH,PI,HALFP1,FIVRP1,GRAVZ(7)
C REAL MDO
C R = 1.2E05*RECH
TWOPI = 2.*PI
C CALCULATE SINE AND COSINE OF ANGLE BETWEEN MAGNETIC DIPOLE MOMENT
C AND POINT 1
C
CONJUG (Cont'd)

1. \( \cos^2 + \cos(\alpha + \beta) \)
2. \( \sin^2 + \sin(\alpha + \beta) \)
3. \( \sin(z + \lambda) \)
4. \( \cos(z + \lambda) \)

C. Calculate sine and cosine of angle between magnetic dipole moment and point 2.

48. \( \sin^2 = \sin(z + \lambda) \)
55. \( \cos^2 = \cos(z + \lambda) \)

C. Determine sign of \( \cos(z + \lambda) \) if point 2 is in the same hemisphere, then sign of \( \cos(z + \lambda) \) is the same as that of \( \sin(z + \lambda) \).

C. If in opposite magnetic hemisphere, then sign of \( \cos(z + \lambda) \) is opposite to \( \sin(z + \lambda) \).

C. Sign of \( \cos(z + \lambda) \)

C. Calculate sine and cosine of angle between field line and line joining magnetic dipole moment with geographic north pole.

72. \( \sin(\psi) = \cos(\lambda) \times \sin(\Delta z + \lambda) / \sin(\lambda) \)
106. \( \cos(\psi) = \sin(\lambda) \times \cos(\lambda) \times \sin(\Delta z + \lambda) / \sin(\lambda) \)

C. Calculate north latitude of point 2.

107. \( \lambda = \sin(\psi) + \sin(\lambda) \times \cos(\lambda) \times \sin(\Delta z + \lambda) / \sin(\lambda) \)

C. Calculate east longitude of point 2.

117. \( \sin(\Delta z + \lambda) = \sin(\lambda) \times \cos(\lambda) \times \sin(\Delta z + \lambda) / \sin(\lambda) \)
122. \( \cos(\Delta z + \lambda) = \cos(\lambda) \times \sin(\lambda) \times \sin(\Delta z + \lambda) / \sin(\lambda) \)
127. \( \text{IF} (\cos(\Delta z + \lambda) \times 0.1) \times \sin(\Delta z + \lambda) / \sin(\lambda) \times \cos(\lambda) \times \sin(\Delta z + \lambda) / \sin(\lambda) \)
141. \( \lambda = \lambda + \cos(\lambda) \times \Delta z + \lambda \)
143. \( \lambda = \lambda + \cos(\lambda) \times \Delta z + \lambda \)
147. \( \lambda = \lambda + \cos(\lambda) \times \Delta z + \lambda \)

C. Calculate dipole-field path length between point 1 and point 2 (in units of the equatorial radius of the traced field line).

153. \( R = \text{sort}(R) \)
155. \( R = \text{sort}(R) \)
156. \( R = \text{sort}(R) \)
160. \( R = \text{sort}(R) \)
164. \( R = \text{sort}(R) \)
171. \( S = \text{abs}(R) \)
200. \( S = \text{abs}(R) \)
215. \( S = \text{abs}(R) \)

C. Calculate ratio of equatorial value of the field to that at point 1.

C. For the traced field line.

223. \( \text{RETURN} \)
MAGFIT

SUBROUTINE MAGFIT(ALATF, ALONF, ALT, TM)

* * * *
THIS ROUTINE FITS A DIPOLE FIELD TO THE LOCAL MAGNETIC
FIELD AT A SPECIFIED POINT P, P IS GIVEN BY ALATF, ALONF, ALT.
THE MAGNETIC FIELD AT P IS FOUND FROM MODEL 5 OF STASSINOPULOS
MODELS, MODEL 5 IS IGRF 10/66, REFERENCE = STASSINOPULOS, E.G.
AND G.D. MEAD, ALL MAG, FIELD-LINE CALCULATION, NASA-GODDARD SPACE
FLIGHT CENTER, NSDC 72-12, FEBRUARY 1972.

* * * *

INPUT PARAMETERS
ALATF = GEOCENTRIC NORTH LATITUDE
OF SPECIFIED POINT P (RADIANS)
ALONF = GEOCENTRIC EAST LONGITUDE
OF SPECIFIED POINT P (RADIANS)
ALT = ALTITUDE OF SPECIFIED POINT P (KM)
TM = TIME FOR DESIRED FIELD (YEARS)

CONST NT COMMON
HALFPI = PI/2
PI = 3.1415926535898
RFEM = EARTH RADIUS (CM)

OUTPUT PARAMETERS (TO MAGLNK COMMON)
MUO = MAGNETIC DIPOLE MOMENT (GAUSS*CM)
COSLTO = COSINE OF NORTH LATITUDE OF MAGNETIC DIPOLE MOMENT
SINLTO = SINE OF NORTH LATITUDE OF MAGNETIC DIPOLE MOMENT
PHIO = EAST LONGITUDE OF MAGNETIC DIPOLE MOMENT (RADIANS)

REAL LAMDA, LAMARG
REAL MUO
COMON /MAGLNK/ MUO, COSLTO, SINLTO, PHIO
COMMON/CNSTNT/RFEM, PI, HALFPI, FOURPI, GRAVZ, GZHE2, BOLTZK, GAM1, GMII
1
, PNR, PHI

SET UP INPUT FOR CALL TO EXACT AMBIENT MAGNETIC FIELD MODEL

CALCULATE MAGNETIC FIELD COMPONENTS AT POINT P
FROM STASSINOPULOS MODEL, MODEL 5 (IGRF 10/66).

43
CALL NEMGS(TM,RKM,ST,CT,SPH,CPH,AR,BTHETA,BPHI,B)

CALCULATE MAGNETIC DIPOLE MOMENT (GAUSS=KM3) FROM THE FIELD COMPONENTS

AR (RADIAL), BTHETA (POSITIVE SOUTH), AND BPHI (POSITIVE EAST).

R280 = BTHETA*BTHETA + BPHI*BPHI

M00 = RKM*1.05*SQRT(R280 + 4.0*R280)

CALCULATE THE SINE AND COSINE OF THE ANGLE ALPHA AT P WHICH IS THE

ANGLE BETWEEN THE MAGNETIC DIPOLE MOMENT AND GEOGRAPHIC NORTH POLE

AND DETERMINE THE PROPER SIGNS

ALPARG = ALPHA/BTHETA

ALPHA = ATAN(ALPARG)

COSALP = ABS(COS(ALPHA))

SINALP = ABS(SIN(ALPHA))

IF(BTHETA .LT. 0.)

COSALP = -COSALP

IF(BPHI .LT. 0.)

SINALP = -SINALP

CALCULATE THE ANGLE CHI MEASURED AT EARTH CENTER WHICH

IS THE ANGLE BETWEEN THE MAGNETIC DIPOLE MOMENT AND THE SPECIFIED

POINT P

CHIARG = 2.0*SQR(R280)/BR

CHI = ATAN(CHIARG)

IF(CHI .LT. 0.)

CHI = CHI + PI

COSCHI = COS(CHI)

SINCHI = SIN(CHI)

CALCULATE SINE AND COSINE OF THE

NORTH LATITUDE OF THE MAGNETIC DIPOLE MOMENT

SINLTO = COSCHI*CT + SINCHI*ST*COSALP

COSLTO = SQRT(1.0 - SINLTO*SINLTO)

CALCULATE THE EAST LONGITUDE OF THE MAGNETIC DIPOLE MOMENT

SINDEL = SINCHI*SINALP*COSLTO

DEL = ASIN(SINDEL)

COSDEL = COSCHI - SINLTO*CT

IF(COSDEL .LT. 0.)

DEL = SIGN(PI,SINDEL) - DEL

PHIO = ALONF + DEL

IF(PHIO .LT. 0.)

PHIO = PHIO + TWOPI

RETURN

END
ONEMG5

SUBROUTINE ONEMG5(TM,RKM,ST,CT,SPH,CPH,RH,BTHETA,BPHI,B)

* * *

IM3S ROUTINE CALCULATES THE MAGNETIC FIELD VECTOR AT A SPECIFIED POINT USING MODEL 5 OF STASSINOPOULOS AND MEAD (N3PDC 72-12). THE ROUTINE IS A MODIFIED VERSION OF ONEMAG FOR THE INTERNATIONAL GEOMAGNETIC REFERENCE FIELD (IGRF 1965.0).

INPUT PARAMETERS
TM = TIME IN YEARS FOR DESIRED FIELD
RKM = GEOCENTRIC DISTANCE OF POINT (KM)
ST = SINE OF GEOCENTRIC COLATITUDE OF POINT
CT = COSINE OF GEOCENTRIC COLATITUDE OF POINT
SPH = SINE OF GEOCENTRIC LONGITUDE OF POINT (POSITIVE EAST)
CPH = COSINE OF GEOCENTRIC LONGITUDE OF POINT (POSITIVE EAST)

OUTPUT PARAMETERS
BR = RADIAL FIELD COMPONENT (GAUSS)
BTHETA = POSITIVE SOUTH FIELD COMPONENT (GAUSS)
BPHI = POSITIVE EAST FIELD COMPONENT (GAUSS)
F = TOTAL FIELD MAGNITUDE (GAUSS)

DIMENSION LG(9,9),LGT(9,9),G(9,9),GG(9,9),GGT(9,9),
SHMIT(9,9)
DIMENSION CONST(9,9),FN(9),FM(9)
DIMENSION P(9,9),DP(9,9),SP(9),CP(9)

EQUIVALENCE (LG(1,1),GG(1,1)),(LGT(1,1),GGT(1,1))

DATA LG/1.3039,-1654,1297,958,-223,47,71,10.5758,-213,2994,
A =2036,805,357,60,-54,9,-200,130,1567,1289,492,246.4,0,-5,403/,
R =242,-176,683,592,-26,-229,12,-12,149,-280,8,-265,256,-26,-161,3,25/.
C =4,16,125,-123,107,77,51,4,-9,4,106,68,32,10,13,112/,
D =13,-5,457,27,6,9,23,19,17,2,12,3,13,5,17,4,22,3,16,6/.
DATA LG/10,153,266,7,17,19,-1,-5,1,-23,87,3,-108,2,11,3,3,6/.
DATA LG/16,167,-167,7,16,-167,30,29,7,177,54,1,6,19,9,0,1,16/.
F =29,2,0,21,0,4,3,0,23,17,24,8,3,11,4,0,1,9,4,20,11,1,9/.
G =2,2,3,11,3,4,2,4,2,3,6,3,1,2,3,2,3,4,3,3,6,5/.
DATA SHMIT(1,1)/0,0,THOLD/0,0,1ZERU/1965,0,NMAX/.
DATA P(1,1),CP(1),DP(1,1),SP(1,1) / 2*1,1,2*0,0/.

IF (SHMIT(1,1),EQ,-1.) GO TO 8

***** INITIALIZE ONCE ONLY, FIRST TIME SUBROUTINE IS CALLED

16 SHMIT(1,1)=1.
16 DM=18 NAME=1.
20 FM=13 NAME=1.
27 DM=18 NAME=1.
37 FM=1 NAME=1.
41 18 CONST(N,M) = FLOAT(N2) +2(N1) +2) / (12(N-3)+2(N=5))
50 DM=2 NAME=9.
57 SHMIT(N,1) = (2N3) + SHMIT(N-1,1) / (N=1)
66 JJ#2.
70 DM=2 NAME=2.

45
ONEMG5 (Cont'd)

71 \( \text{SHMIT}(N,M) = \text{SHMIT}(N,M) + \text{SORT}(	ext{FLOAT}((N\text{=M})\times J/J)/(N\text{=M})) \)

107 \( \text{SHMIT}(N,M) = \text{SHMIT}(N,M) \)

117 2 JJ = 1

124 F1 = LGT(1,1)

125 FP = LGT(1,1)

127 DO 7 M=1,NMAX

130 DO 7 W=1,NMAX

140 GG(N,M) = LGT(N,M)*SHMIT(N,M)/F1

143 DO 7 GGT(N,M) = LGT(N,M)*SHMIT(N,M)/F2

155 IF(TM.EQ.TMOLD) GO TO 11

157 T = TM - TZERO

160 DO 10 N=1,NMAX

163 DO 10 N=1,NMAX

173 DO 10 G(N,M) = GG(N,M) + T*GGT(N,M)

176 **** CALCULATION USUALLY BEGINS HERE

204 IF(2P(2)<>SPH)

205 CP(2) = CPH

206 DO 12 M=3,NMAX

215 SP(M) = SP(2)*CP(2)*SP(M)

220 CP(M) = CP(2)*SP(M)

227 AOR = 371/N*M

230 AR = AR*M

231 BR = 0

232 BT = 0

233 BP = 0

234 DO 21 N=2,NMAX

242 P(N,N) = 0

243 DO 21 N=1,NMAX

245 DO 17 N=2,NMAX

252 AR = AR*M

253 DN 17 M=1,N

255 IF(M.EQ.N) GO TO 13

256 IF(N.EQ.2) GO TO 19

262 P(N,M) = P(N-1,M) + CONST(N,M)*P(N-2,M)

265 DP(N,M) = CT*DP(N-1,M) + ST*P(N-1,M) + CONST(N,M)*DP(N-2,M)

272 GO TO 12

301 IF(P(N,M) = CT)

302 DP(N,M) = ST

304 GO TO 14

307 IF(P(N,M) = ST*P(N-1,N-1))

311 DP(N-1,N) = ST*P(N-1,N-1) + CT*P(N-1,N-1)

317 IF(P(N,M) = P(N,M))

323 IF(M.EQ.1) GO TO 15

332 TEMP = G(N,M)*SP(M)

335 BPHI = (N,M)*SP(M) + (M,N)*CP(M) + FM(M)

342 GO TO 16

346 TEMP = G(N,M)

352 IF(BR = BR*TEMP + P(N,M) + PAR)

357 SP = SP + TEMP*P(N,M)

361 BPHI = BR/ST/100000.

373 RR = 100000.

379 BTHETA = RT/100000.

378 B = 3PRT(RR*RR + BTHETA + BTHETA + BPHI*8PHI)

400 RETURN

405 END
### Fitted Dipole Parameters

**Position 1**

- **Latitude**: 0.00 (deg)
- **Longitude**: -80.00 (deg)
- **Altitude**: 200.00 (deg)
- **Time**: 1975.00 (yrs)

<table>
<thead>
<tr>
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<th>TEST LON</th>
<th>TEST ALT</th>
<th>DIPOLE B</th>
<th>DIPANG</th>
<th>DECANG</th>
<th>INTERS ALT</th>
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**Position 2**

- **Latitude**: 0.00 (deg)
- **Longitude**: 0.00 (deg)
- **Altitude**: 200.00 (deg)
- **Time**: 1975.00 (yrs)

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<th>TEST ALT</th>
<th>DIPOLE B</th>
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**FITTED DIPOLAR PARAMETERS**

**NUO** = 0.607022E+10 GAUSS H/M

**COBLO** = 1.52400E-01

**SINLO** = 0.607022E+01

**PHIG** = 1.79768E+00 LONITUDE EAST (RADIANS)

<table>
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</table>

**LOCATION OF POINT THAT IS FITTED**

**LATITUDE** = 0.00 (NEG)

**LONGITUDE** = 60.00 (NEG)

**ALTITUDE** = 200.00 (NEG)

**TIME** = 1975.00 (YR8)

**FITTED DIPOLAR PARAMETERS**

**NUO** = 1.618830E+11 GAUSS H/M

**COBLO** = 1.603079E-01

**SINLO** = 0.607022E+01

**PHIG** = 1.79768E+00 LONITUDE EAST (RADIANS)

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<th>DECANG</th>
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<th>AJUG</th>
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**LOCATION OF POINT THAT IS FITTED**

**LATITUDE** = 0.00 (NEG)

**LONGITUDE** = 120.00 (NEG)

**ALTITUDE** = 200.00 (NEG)

**TIME** = 1975.00 (YR8)
### LOCATION OF POINT THAT IS FITTED

**LATITUDE** = 0.00 (DEG)
**LONGITUDE** = 180.00 (DEG)
**ALTITUDE** = 200.00 (DEG)
**TIME** = 1975.00 (YRS)

### FITTED DIPOLE PARAMETERS

**Mulg** = \( R_{177839F=10} \) GAUSS W1**3
**COSLTO** = \( 1.144935F=01 \)
**SINLTO** = \( 9.420542F=01 \)
**PHIO** = \( 2.11144F=00 \) LONGITUDE EAST (RADIANS)

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### LOCATION OF POINT THAT IS FITTED

**LATITUDE** = 0.00 (DEG)
**LONGITUDE** = 240.00 (DEG)
**ALTITUDE** = 200.00 (DEG)
**TIME** = 1975.00 (YRS)

### FITTED DIPOLE PARAMETERS

**Mulg** = \( R_{1777123F=10} \) GAUSS W1**3
**COSLTO** = \( 1.777912F=01 \)
**SINLTO** = \( 9.440625F=01 \)
**PHIO** = \( 2.11144F=00 \) LONGITUDE EAST (RADIANS)

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**SINLTO** = 9.972586E+00

**PHIO** = 1.728176F+00 LONITUDE EAST (RADIANS)

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### Location of Point That Is Fitted

**LATITUDE** = 30.00 (DEG)

**LONITUDE** = 30.00 (DEG)

**ALTITUDE** = 200.00 (DEG)

**TIME** = 1974.00 (YRS)
### Fitted Dipole Parameters

#### Latitude = 49.00 (deg)
#### Longitude = 180.00 (deg)
#### Altitude = 200.00 (deg)
#### Time = 1975,00 (yr)

#### Location of Point that is fitted

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#### Location of Point that is fitted

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<th>Dipole L</th>
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### Fitted Dipole Parameters

#### Latitude = 59.00 (deg)
#### Longitude = 290.00 (deg)
#### Altitude = 200.00 (deg)
#### Time = 1975,00 (yr)

#### Location of Point that is fitted

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### Location of Point That Is Fitted

**Latitude:** 60.00 (N)

**Longitude:** 120.00 (E)

**Altitude:** 200.00 (M)

**Time:** 1979.00 (YRS)

### Fitted Dipole Parameters

**WDO:** 1.0036E+10 GAsSE Mtes

**COSLO:** 1.21995E+01

**SINLO:** -4.49235E+00

**PMO:** 4.148345E+00 LONGITUDE EAST (RADIANS)

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**Fitted Dipole Parameters**

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**COSLO:** 1.31358E-01

**SINLO:** 2.066355E+00 LONGITUDE EAST (RADIANS)

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<th>INTERB ALT</th>
<th>AJUG</th>
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FITTED DIPOLE PARAMETERS

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| CMBLT | 3,431003E+01            |
| SLMLT | -9,451190E-01           |
| PHIO  | 1,453200E+00 LUNGTUOF EAST (RADIANS) |

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<th>DIPOLE B</th>
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<th>INTERS LAT</th>
<th>INTERS LON</th>
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LOCATION OF POINT THAT IS FITTED

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| LATTITUDE = 0.00 (NEG)           |
| ALTITUDE = 200.00 (NEG)          |
| TIME = 1975.00 (Ytd)             |

FITTED DIPOLE PARAMETERS

| MJD  | 9,453798E+10 GAUSS KMS   |
| CMBLT | 3,431003E+01            |
| SLMLT | -9,451190E-01           |
| PHIO  | 1,453200E+00 LUNGTUOF EAST (RADIANS) |

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### Location of Point that is Fitted

**Latitude:** 60.00 (deg)  
**Longitude:** 60.00 (deg)  
**Altitude:** 200.00 (deg)  
**Time:** 1975.00 (YRS)

### Fitted Dipole Parameters

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### Location of Point that is Fitted

**Latitude:** 60.00 (deg)  
**Longitude:** 0.00 (deg)  
**Altitude:** 200.00 (deg)  
**Time:** 1975.00 (YRS)

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**Mag:** 7.437012E+10 Gauß Kms
**Cuslt:** 6.320405E+01
**Sint:** 4.974409E+01
**Phio:** 2.487794E+00

**Location of Point That is Fitted**

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### Location of Point That is Fitted

**Mag:** 7.448070E+10 Gauß Kms
**Cuslt:** 4.352355E+01
**Sint:** 9.027191E+01
**Phio:** 2.490364E+00

**Fitted Dipole Parameters**

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### Location of Point That Is Fitted

**Latitude** = +60.00 (deg)
**Longitude** = 180.00 (deg)
**Altitude** = 200.00 (deg)
**Time** = 1975.00 (YR8)

### Fitted Dipole Parameters

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**COUL** = 3.355291E+01
**SILTU** = 4.405633E+01
**PHIO** = 2.381895E+00 LONITUDE EAST (RADIANS)

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### Location of Point That Is Fitted

**Latitude** = +60.00 (deg)
**Longitude** = 280.00 (deg)
**Altitude** = 200.00 (deg)
**Time** = 1974.00 (YR8)

### Fitted Dipole Parameters

**HUOS** = 8.306516E+10 GAUSS KM**3**
**COUL** = 9.382195E+01
**SILTU** = 9.150183E+01
**PHIO** = 2.369943E+00 LONITUDE EAST (RADIANS)

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LOCATION OF POINT THAT IS FITTED
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LONGITUDE = 180.00 (DEG)
ALTITUDE = 204.00 (DEG)
TIME     = 1974.00 (YRS)

FITTED DIPOLE PARAMETERS
MU0    = 8.856591E+10 GAUSS KM**3
CUBLTO = 4.775595E+01
SINALTO = 6.765956E+01
PHIO   = 2.987554E+00 LONGITUDE EAST (RADIANS)

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SINALTO = 4.755205E+01
PHIO   = 2.969685AE+00 LONGITUDE EAST (RADIANS)

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END OF TEST PROBLEM
Table A8. Summary of Running Time Experience for Ambient Magnetic Field Module on a CDC 7600 Computer.

Timing runs have been made for the various subroutines in the ambient magnetic field model, with the following results obtained on the Berkeley CDC 7600 computer:

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<td>BFIELD</td>
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<td>CONJUG</td>
<td>0.067 msecs(^c)</td>
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<td>ONEMG5</td>
<td>0.21 msecs(^a) or 0.56 msecs(^b)</td>
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</tbody>
</table>

\(^a\)For a 6-page Fortran version containing no DO-loops.

\(^b\)For a 2-page Fortran version containing DO-loops.

\(^c\)This number should be contrasted with a value of 26.7 msecs required if ONEMG5 (i.e., the multipole field) were used instead of BFIELD (i.e., the dipole field) in tracing the field line to the conjugate region.
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