

## MAGMAP: Mapping Spherical Harmonic Models of the Geomag Field

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This program can evaluate a magnetic field model, specified as a set of spherical harmonic coefficients, at an individual point, or on a grid in several different map projections. The program requires a single input diskfile containing the spherical harmonic model formatted as described under the command **file** or it can use internally stored values from the IGRF model series. An array of magnetic field values may be output to disk as an intermediate product. A script file is generated and executed to contour the field map using either *color* or *contour*, programs in the software suite.

*Magmap* runs as a command interpreter rather than under a fixed menu. This means that within each command group instructions may be entered in any order from the terminal. Options not required may be omitted.

The following is an example of a short program; remarks after the percent signs are treated as comments by the program so that you may document input files like this one:

```
igrf 2010           % Map from coeffs in IGRF 2010
field R            % Calculate radial component of vector
radius 0.547      % Draw map at surface of core
proj O            % Use orthographic projection
center 90 0       % Center at north pole
coast             % Add coastline to the map
output polar.dat  % Name of output array
color polar.col   % Use program color to draw map
exec             % Perform calculations given so far
quit             % Cease
```

Below is an explanation of each of the command groups.

### Command Catalog

Each command takes the following form: a command word, which can always be abbreviated to its first four letters and which may appear alone or may be followed by one or more spaces, then numbers or text. The command word must begin in the first column; lines starting with a blank are treated as comments and are ignored. In this list, the first group of commands is concerned with reading the spherical harmonic model from a diskfile, the second with evaluation of the model. Default values are those the program assigns if you do not explicitly set them; you may rely on these defaults as sensible choices in most cases. In runs with a sequence of input files, options selected remain in force until changed. An exception to this rule are the **site** commands, which are cleared after they are executed.

#### *General and Input Commands*

?: Print a brief version of this catalog.

**clear** *cmd*: Remove all instances of the command *cmd* from the instruction stack. For example, **nondipole** can be canceled, or **silent**.

**execute**: With the model saved in memory, compute the field values and map as requested. When these calculations have been completed *magmap* returns asking for further work, such as finding another map from the same model or calculations with a different model. The contour maps (if any) are generated after the **quit** command.

**earth** *a, b, aref*: The coefficients are computed with respect to a reference radius, *aref* in km. In the **site** command (but not on the maps) the geographic positions are specified with respect to an ellipsoid, equatorial and polar radii *a* and *b* (km). The default values are: 6378.17, 6356.91 and 6371.20 km. With this command you can degrade the earth model to a spherical approximation by setting *a=b=aref*. Setting the radii equal is useful for geocentric coordinate calculations needed in satellite data reduction.

**file** *filename*: The diskfile containing the SH coefficients is named here. Each line of the input file must contain four numbers: *l*, the spherical harmonic degree; *m* the order; *g(l,m)* the cosine coefficient; *h(l,m)* the sine term. When *m=0* the sine term is always zero, but it must be present in the file nonetheless. With this scheme the lines of the file can be in any order. If the degree is negative, the coefficient is taken describe a field with an exterior source. Lines in the file may begin with the percent sign (%); then they are treated as comments and skipped by *magmap*. SH data can be supplied in an ordered list without *m* and *l*; see **serial**. The standard IGRF field models are stored internally and accessed with the **igrf** command.

If \* is entered for the filename *magmap* will read the coefficients from the terminal immediately after the **execute** command. The end of input is signaled with degree  $l < -499$ .

**igrf** *year*: Instead of opening an external diskfile for the Gauss coefficients use one of the internal set of IGRF field models from the years 1900-2010 in steps of 5 years. The data set is the IUGG year 2010 version. See <http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html>. The entered year will be rounded to the nearest allowed integer.

**list**: Print listings of the field model coefficients. Two listings are produced: the first is exactly as read from the file (with some caveats; see below); the second is in the F1 normalization, scaled to the requested referenced sphere radius, which is how the coefficients are stored internally. When serial input is requested, the first listing includes the degree and order of the coefficients, even though these are absent from the data file.

**lmax** *L* : Accept spherical harmonic coefficients only up to degree *L*, and skip any in the file of higher degree.

**nondipole** [*l*]: Delete the dipole ( $l=1$ ) terms in this and subsequent input files, thus allowing a map of the nondipole field to be made. If the optional *l* follows, delete only the axial  $m=0$  term. In **serial** input mode all dipole terms are deleted, even if the integer *l* is present. Use **clear** to revoke this command. See also **serial**.

**normalization** *X*: where *X* must be one of S, F1, F2, G, U. Here S means Schmidt normalization; *X*=F1 means fully normalized coefficients with integral of the squared spherical harmonic equal to 1 with factor  $(-1)^{*m}$ ; *X*=F2

means fully normalized, but with the integral equal to  $4\pi$ ; G1 means normalized for gravity coefficients, like F2, but with  $(-1)^m$  factor omitted; U means unnormalized basis functions are used. Most magnetic field models are of so-called Gauss coefficients, and then  $X=S$ . A normalization must be given or the program will stop, unless the **igrf** command was used, when the correct normalization is automatically assigned. Maps will be drawn with contours scaled by 0.001 on the assumption the input data are in nT, and the maps are in  $\mu\text{T}$ ; this arrangement does not apply to  $X=U$ , however.

**quit**: Cease. Plot any contour maps first.

**radius** *r*: The map is computed on a sphere radius =  $r \cdot r_{\text{ref}}$  (see **earth**). The internally stored coefficients are renormalized to this radius, so this is effectively an input command. Thus maps of the field on the core (almost the only use for this command) take  $r=0.547$ . Default value is unity, of course.

**serial** [*without zeros*]: Instead of holding to the standard format of two Gauss coefficients per line preceded by the degree and order, the input file of coefficients is arranged in a serial listing in the normal order, beginning at  $l=1$ ,  $m=0$ . Any number of coefficients may appear on each line. If the optional phrase appears in the command, the coefficients for the sine part when  $m=0$  (which are conventionally set to zero) are omitted from the list, otherwise it is assumed they are present. When **nondipole** is turned on, the series must begin at degree  $l=2$ . To cancel this command use **clear**. Exterior source fields cannot be specified in serial mode.

**silent**: Once issued all printing to the screen (except error messages) is suppressed. This command can be reversed with **clear**.

### *Commands Governing Calculation*

#### **center** *long*

**center** *lat, long*: Geographic coordinates of the map center when both are present. However, for the Hammer-Aitoff, Mercator and rectilinear projections the center is always on the equator so that the latitude is ignored if both are given; alternatively, if only one coordinate is supplied it is taken to be the longitude. Default value is the Greenwich meridian, longitude zero, and latitude 90 degrees if appropriate. For polar projections the map is oriented so that a meridian through the center is vertical on the page. See **projection**.

**dimensions** *m, n*: The array dimensions of the field map. Default values are 40, 79 for Hammer-Aitoff and rectilinear, 40, 40 for the others. These are usually adequate.

**field** *E*: The field element to be computed for the map where *E* is one of X, Y, Z, H, F, R or V. The names are the conventional geomagnetic field elements: X north, Y east, Z vertical positive down, H horizontal component, F field magnitude, and  $R=-Z$ , which is the default; V gives the scalar potential divided by the reference radius.

**magnify** *f*: The scale of the mapping is changed to enlarge the image by the factor *f*. The magnified image is plotted around the center of the map; see **center**. If *f* is less than unity the command is ignored.

**output** *filename*: The name of the output file to contain the regular grid of points defining a magnetic map is specified. The numbers are written in

sequence across rows of the matrix, one number per line in ASCII. If multiple maps are to be plotted, each one must be assigned its own file with an **output** command or previous values will be overwritten by subsequent calculations. If this command is not provided, results will be sent to files in a sequence, fort.9, fort.90, fort.91, ... .

**color script**: Create a *color* contouring program to display the map and put it in the file *script*. If there are several maps, and the command **color** has been issued only once, write all the programs to the same file; note that different **output** files must be named for each. Alternatively each map can have its own **color** command with a different *script* file in each. *Magmap* launches a shell that plots the map to the screen at the end of the run, or whenever the name *script* is changed. If the word *script* is omitted, a default name *tmp.plt* is supplied.

**contour filename**: the same as **color**, but a contour program is written.

**projection p**: where p is one of A, L, O, M, R. Here A gives Hammer-Aitoff equal area projection; p=L gives Lambert equal area; p=O gives orthographic projection; p=R gives rectilinear, or longitude-latitude coordinates; p=M gives Mercator conformal projection. Orthographic projection (O) yields rather disappointing results because of the foreshortening at the map edges; Lambert is generally superior.

If no map is required enter p=N for None, or just omit the projection command. This option is useful if only point values are needed.

All the map projections are performed in a spherical approximation, and the Earth's ellipticity is neglected in the component evaluations for the maps too. For the small-scale synoptic maps of the kind normally required in geomagnetic work, the error in this approximation is unimportant. Accurate values on the spheroid with proper accounting of ellipticity are computed by the **site** command. See also **center**, **color**, **coast**.

**noplot**: Do not create a color or contour script after computing the map array; simply save the array to the file named in **output**. Overrides **color** and **contour** commands.

**coast grid**

**coast [filename]**: With a blank field, a new file called *coast10* is created from an internal dataset of about 3200 points of a coastline, transformed according to the map projection; *coast10* is read by the mapping script, named *tmp.plt* by default; see **color**. If a filename is specified, coastline data are read from that file, which must contain latitude-longitude pairs; breaks are indicated by latitudes greater than 90. Obviously your input filename should not be called *coast10*. When several maps are drawn in one run of *magmap*, using different coastlines or map projections, the numerical part of new the coast file name is augmented by one for every new case, eg, coast11, coast12, etc. If the projection is changed, a new file of transformed coastlines will be created based on the last set of data points used. Finally, if the filename is set to *grid* a latitude-longitude grid is superimposed on the map instead of a coastline.

**symbols filename type h [color=X]**: It is sometimes useful to be able to plot points on the finished map. This command reads latitude-longitude pairs from the specified file, transforms them according to the current map projection, and creates a new file, *symxx*, containing the mapped coordinates to be

read at plot time; here *xx* is a 2-digit integer. The symbol *type* and height *h*, hold for all points in the file. When several symbol types are required, each kind of symbol must be assigned its own file with a separate **symbols** command; there can be as many such files as needed. If the map projection remains constant, the symbols will be carried forward onto subsequent plots, but upon changing the projection, the current symbol set is lost unless the **symbols** commands are repeated. The symbol code *type* follows the convention in the program *color*: 0 square; 1 triangle; 2 octagon; 3 diamond; 4 plus; 5 asterisk; 6 cross; 7 5-ray; 8 Y upside down; 9 pentagon; 10 triangle, base up; 11 hexagon; 12 Y; 13 bar; 14 6-ray; 15 dot; 16 heptagon; 17 circle; 18 large circle (double height); 19 small filled circle; 20 small filled square; 21 small filled triangle. Colors are set by choosing *X* from the list: black, white, red, blue, green, yellow, orange, purple.

A blank command field deletes the current symbol set. If a new symbol set is read for a later map, this action automatically deletes any earlier symbol data because **symbols** commands are not cumulative across multiple maps.

Currently (Jan, 2003) this command applies only to maps made with the **color** command.

**scale factor**: Multiply the SH coefficients by the quantity factor before all other calculations. Except in the U normalization, it is assumed the coefficients are in nT and the contour map is required in  $\mu\text{T}$ , so there is an implicit internal factor of 0.001 applied to the contour maps.

#### **site filename**

**site** *lat, long, alt*: in the second form, enter on the command line the geographic coordinates and altitude (in meters above the geoid) of a single site where the field is to be computed. As many of these commands as desired can be issued and these are independent of any map that may be computed. For each site, all magnetic elements are found and printed at the terminal. The results are also written to the file fort.8. The **site** commands are cleared as they are executed, so that if a second file of coefficients is input, the sites for evaluation must be repeated.

In the first form you may enter the name of a diskfile containing locations in the same format as the in-line command: lat, long, altitude, one site per line in the file. This file is read to the end-of-file. Results are printed and written to fort.8 as before.

**sums**: Print the values of certain sums at the terminal. The sums are of the fully normalized coefficients, squared and weighted by a function the degree *l*:  $w_1=l+1$ , proportional to the field energy outside the Earth's core;  $w_2=(l+1)**2$ ;  $w_3=(l+1)(2l+1)**2*(2l+3)/l$ , proportional to the Ohmic heating within the core;  $w_4=l(l+1)**3$ .

#### **Notes**

Fortran source is on the website <http://igppweb.ucsd.edu/~parker/Software/> together with this documentation.

Geocentric coordinates are often given for satellite positions. Since the **site** command always uses geographic coordinates (that is, corrected for ellipticity) to apply this command to satellite positions you must first make a spherical earth with the **earth** command. Notice that then, not only are the

locations in a geocentric system, but so are the local coordinates for the magnetic elements as required.

*Magmap* can be used to generate maps of spherical harmonic developments of any function on a sphere, not just magnetic fields. The coefficients of the function to be mapped must be formatted as before, with one of the permitted normalizations. Then the following commands will be needed:

```
field V  
radius 1  
scale 1000
```

The last command cancels the implicit conversion from nanotesla to microtesla normally applied when geomagnetic models are calculated.

### Example

Here is the result of the script given at the beginning of this document. If you are looking at the PDF version you will see the graphic below. Details of this map, like its size and color palette can be changed by editing the file *polar.col* with knowledge of the workings of the program *color*.

