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International Geomagnetic Reference Field: the thirteenth generation

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Abstract
In December 2019, the International Association of Geomagnetism and Aeronomy (IAGA) Division V Working Group (V-MOD) adopted the thirteenth generation of the International Geomagnetic Reference Field (IGRF). This IGRF updates the previous generation with a definitive main field model for epoch 2015.0, a main field model for epoch 2020.0, and a predictive linear secular variation for 2020.0 to 2025.0. This letter provides the equations defining the IGRF, the spherical harmonic coefficients for this thirteenth generation model, maps of magnetic declination, inclination and total field intensity for the epoch 2020.0, and maps of their predicted rate of change for the 2020.0 to 2025.0 time period.

Keywords: IGRF, Magnetic field modeling, Geomagnetism

Introduction
The International Geomagnetic Reference Field (IGRF) is a set of spherical harmonic coefficients which can be input into a mathematical model in order to describe the large-scale, time-varying portion of Earth's internal magnetic field between epochs 1900 A.D. and the present. The IGRF is produced and maintained by an international task force of scientists under the auspices of the International Association of Geomagnetism and Aeronomy (IAGA) Working Group V-MOD. This thirteenth generation IGRF has been derived from observations recorded by satellites, ground observatories, and magnetic surveys (see Appendix 1 for a list of World Data System data centers and services). IGRF is routinely used by the scientific community to study Earth's core field, space weather, electromagnetic induction, and local magnetic anomalies in the lithosphere. It is also widely used in satellite attitude determination and control systems and other applications requiring orientation information.

Earth's core field changes continuously and unpredictably on timescales ranging from months to millions of years. In order to account for temporal changes on timescales of a few years, the IGRF is regularly revised, typically every 5 years. Table 1 summarizes the current and past generations of IGRF. Each generation is composed of a set of model coefficients representing the internal time-varying geomagnetic field, which are provided in 5-year intervals. The years for which coefficients are provided are called model epochs. The coefficients of a certain epoch represent a snapshot of the geomagnetic field at that time, and can be labeled either as a Definitive Geomagnetic Reference Model (DGRF) or as an IGRF.
DGRF models are so labeled because they have been built from the best available data sources of that time period and therefore are unlikely to be improved in future IGRF revisions. Models labeled as IGRF are non-definitive, and will likely be revised in the future as more data are collected. DGRF models have been built only starting in 1945. Details of the history of IGRF can be found in Barton (1997) and Macmillan and Finlay (2011). Past generations of IGRF models are archived at https://www.ngdc.noaa.gov/IAGA/vmod/igrf_old_models.html. Since later IGRFs can revise model parameters for past epochs, it is important to record which generation of IGRF was used to process a particular dataset, so that the original data can be recovered and reprocessed with the latest generation of IGRF if needed.

In this paper, we focus on the thirteenth generation of IGRF, known hereafter as IGRF-13. IGRF-13 provides a DGRF model for epoch 2015.0, an IGRF model for epoch 2020.0, and a predictive IGRF secular variation model for the 5-year time interval 2020.0 to 2025.0. For epochs 1900.0 to 2010.0, the IGRF-13 model coefficients are unchanged from IGRF-12. IGRF-13 was finalized in December 2019 by a task force of IAGA Working Group V-MOD. In the following sections, we will describe the IGRF model, provide the final set of IGRF-13 coefficients, and briefly discuss large-scale features of the geomagnetic field at Earth’s surface as revealed by the updated model.

### Mathematical formulation of the IGRF model

The IGRF describes the main geomagnetic field \( \mathbf{B}(r, \theta, \phi, t) \) which is produced by internal sources primarily inside Earth’s core. The IGRF is valid on and above Earth’s surface, where the main geomagnetic field can be described as the gradient of a scalar potential, \( \mathbf{B} = - \nabla V \), and the potential function \( V(r, \theta, \phi, t) \) is represented as a finite series expansion in terms of spherical harmonic coefficients, \( g_n^m, h_n^m \), also known as the Gauss coefficients:

\[
V(r, \theta, \phi, t) = \sum_{n=1}^{\infty} \sum_{m=0}^{n} \frac{(2n+1)}{r} P_n^m(\cos \phi) g_n^m(t) \cos m\phi + h_n^m(t) \sin m\phi
\]

Here, \( r, \theta, \phi \) refer to coordinates in a geocentric spherical coordinate system, with \( r \) being radial distance from the center of the Earth, and \( \theta, \phi \) representing geocentric co-latitude and longitude, respectively. A reference radius \( a = 6371.2 \) km is chosen to approximate the mean Earth radius. The \( P_n^m(\cos \phi) \) are Schmidt semi-normalized associated Legendre functions of degree \( n \) and order \( m \) (Winch et al. 2005). The parameter \( n \) specifies the maximum spherical harmonic degree of expansion, and was chosen to be 10 up to and including epoch 1995, after which it increases to 13 to account for the smaller scale internal signals which can be captured by high-resolution satellite missions such as Ørsted, CHAMP and Swarm. The Gauss coefficients \( g_n^m(t), h_n^m(t) \) change in time and are provided in units of nanoTesla (nT) in IGRF-13 at 5-year epoch intervals. The time dependence of these parameters is modeled as piecewise linear, and is given by

\[
g_n^m(t) = g_n^m(T_t) + (t - T_t) \delta g_n^m(T_t),
\]

\[
h_n^m(t) = h_n^m(T_t) + (t - T_t) \delta h_n^m(T_t),
\]

where \( g_n^m(T_t), h_n^m(T_t) \) are the Gauss coefficients at epoch \( T_t \), which immediately precedes time \( t \). The model epochs in IGRF-13 are provided in exact multiples of 5 years starting in 1900 and ending in 2020 (see Table 2), so that \( T_t \leq t < T_t + 5 \). For \( T_t < 2020 \), the parameters

| Full name                      | Short name | Validity period   | Definitive period | Release year | Reference                          |
|-------------------------------|------------|-------------------|-------------------|--------------|------------------------------------|
| IGRF 13th generation          | IGRF-13    | 1900.0 to 2025.0  | 1945.0 to 2015.0  | 2019         | This article                       |
| IGRF 12th generation          | IGRF-12    | 1900.0 to 2020.0  | 1945.0 to 2010.0  | 2014         | Thébault et al. (2015)             |
| IGRF 11th generation          | IGRF-11    | 1900.0 to 2015.0  | 1945.0 to 2005.0  | 2009         | Finlay et al. (2010a)              |
| IGRF 10th generation          | IGRF-10    | 1900.0 to 2010.0  | 1945.0 to 2000.0  | 2004         | Maus et al. (2005); Macmillan and Maus (2005) |
| IGRF 9th generation           | IGRF-9     | 1900.0 to 2005.0  | 1945.0 to 2000.0  | 2003         | Macmillan et al. (2003)            |
| IGRF 8th generation           | IGRF-8     | 1900.0 to 2005.0  | 1945.0 to 1990.0  | 1999         | Mandea and Macmillan (2000)        |
| IGRF 7th generation           | IGRF-7     | 1900.0 to 2000.0  | 1945.0 to 1990.0  | 1995         | Barton (1997)                      |
| IGRF 6th generation           | IGRF-6     | 1945.0 to 1995.0  | 1945.0 to 1985.0  | 1991         | Langel (1992)                      |
| IGRF 5th generation           | IGRF-5     | 1945.0 to 1990.0  | 1945.0 to 1980.0  | 1987         | Barraclough et al. (1987); Langel et al. (1988) |
| IGRF 4th generation           | IGRF-4     | 1945.0 to 1990.0  | 1965.0 to 1980.0  | 1985         | Barraclough (1987)                |
| IGRF 3rd generation           | IGRF-3     | 1965.0 to 1985.0  | 1965.0 to 1975.0  | 1981         | Peddie (1982)                     |
| IGRF 2nd generation           | IGRF-2     | 1955.0 to 1980.0  | -                 | 1975         | IAGA Division I Study Group (1975) |
| IGRF 1st generation           | IGRF-1     | 1955.0 to 1975.0  | -                 | 1968         | Cain and Cain (1971); Zmuda (1971a, 1971b) |
Table 2  13th generation International Geomagnetic Reference Field

| g/h | Deg | Ord | IGRF 1900.0 | IGRF 1905.0 | IGRF 1910.0 | IGRF 1915.0 | IGRF 1920.0 | IGRF 1925.0 | IGRF 1930.0 | IGRF 1935.0 | IGRF 1940.0 | DGRF 1945.0 | DGRF 1950.0 | DGRF 1955.0 | DGRF 1960.0 |
|-----|-----|-----|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| g   | 1   | 0   | -31543      | -31464      | -31354      | -31212      | -31060      | -30926      | -30805      | -30715      | -30654      | -30594      | -30554      | -30500      | -30421      |
| g   | 1   | 1   | -2298       | -2297       | -2290       | -2317       | -2318       | -2316       | -2306       | -2292       | -2285       | -2230       | -2215       | -2196       |             |
| h   | 2   | 0   | -677        | -728        | -769        | -802        | -839        | -893        | -951        | -1018       | -1106       | -1244       | -1341       | -1440       | -1555       |
| h   | 2   | 1   | 2905        | 2928        | 2948        | 2956        | 2999        | 2969        | 2980        | 2984        | 2981        | 2990        | 2998        | 3003        | 3002        |
| h   | 2   | 2   | 1061        | 1086        | 1128        | 1191        | 1259        | 1334        | 1424        | 1520        | 1614        | 1702        | 1810        | 1898        | 1967        |
| h   | 2   | 3   | 1121        | 1065        | 1000        | 917         | 823         | 728         | 644         | 586         | 528         | 477         | 381         | 291         | 206         |
| g   | 3   | 0   | 1022        | 1037        | 1058        | 1084        | 1111        | 1140        | 1172        | 1206        | 1240        | 1282        | 1297        | 1302        | 1302        |
| g   | 3   | 1   | -1469       | -1494       | -1524       | -1559       | -1600       | -1645       | -1692       | -1740       | -1790       | -1834       | -1889       | -1944       | -1992       |
| h   | 3   | 2   | 1256        | 1239        | 1223        | 1212        | 1205        | 1202        | 1205        | 1215        | 1232        | 1255        | 1274        | 1288        | 1289        |
| g   | 3   | 3   | 572         | 635         | 705         | 778         | 839         | 881         | 907         | 918         | 916         | 913         | 896         | 882         | 878         |
| g   | 4   | 0   | 523         | 480         | 425         | 360         | 298         | 229         | 166         | 101         | 43          | -11         | -46         | -83         | -130        |
| g   | 4   | 1   | 876         | 880         | 884         | 887         | 889         | 891         | 896         | 903         | 914         | 944         | 954         | 958         | 957         |
| g   | 4   | 2   | 628         | 643         | 660         | 678         | 695         | 711         | 727         | 744         | 762         | 776         | 792         | 796         | 800         |
| g   | 4   | 3   | 195         | 203         | 211         | 218         | 220         | 216         | 205         | 188         | 169         | 144         | 136         | 133         | 135         |
| g   | 4   | 4   | 660         | 653         | 644         | 631         | 616         | 601         | 594         | 565         | 550         | 544         | 528         | 510         | 504         |
| h   | 4   | 5   | -69         | -77         | -90         | -109        | -134        | -163        | -195        | -226        | -252        | -276        | -278        | -274        | -278        |
| g   | 5   | 0   | -361        | -380        | -400        | -416        | -424        | -426        | -422        | -415        | -405        | -421        | -408        | -397        | -394        |
| g   | 5   | 1   | 134         | 146         | 160         | 178         | 199         | 217         | 234         | 249         | 265         | 304         | 303         | 290         | 269         |
| h   | 5   | 5   | -184        | -192        | -201        | -211        | -221        | -230        | -237        | -241        | -253        | -240        | -229        | -222        |             |
| g   | 5   | 6   | 328         | 328         | 327         | 326         | 326         | 326         | 329         | 334         | 346         | 349         | 360         | 362         |             |
| h   | 5   | 7   | -210        | -193        | -172        | -148        | -122        | -96         | -72         | -51         | -33         | -12         | 3           | 15          | 16          |
| g   | 6   | 5   | 264         | 259         | 253         | 245         | 236         | 226         | 218         | 211         | 208         | 194         | 211         | 230         | 242         |
| g   | 6   | 6   | 53          | 56          | 57          | 58          | 58          | 58          | 60          | 64          | 71          | 95          | 103         | 110         | 125         |
| g   | 6   | 7   | 5            | -9           | -16          | -23         | -28          | -32          | -33          | -20          | -20          | -23          | -26          |            |             |
| g/h | Deg  | Ord  | IGRF 1900.0 | IGRF 1905.0 | IGRF 1910.0 | IGRF 1915.0 | IGRF 1920.0 | IGRF 1925.0 | IGRF 1930.0 | IGRF 1935.0 | IGRF 1940.0 | DGRF 1945.0 | DGRF 1950.0 | DGRF 1955.0 | DGRF 1960.0 |
|-----|------|------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| h   | 6    | 1    | -9          | -9          | -7          | -7          | -5          | -5          | -2          | 0           | 3           | 4           | 4           | 4           | 1           | -1          | -9          | -10         |
| g   | 6    | 2    | -11         | -11         | -11         | -11         | -10         | -10         | -9          | -9          | -8          | -8          | -7          | 6           | 4           | 3           | 1           |
| h   | 6    | 2    | 83           | 86          | 89          | 93          | 96          | 99          | 102         | 104         | 105         | 105         | 100         | 99          | 96          | 99          |
| g   | 6    | 3    | -361         | -224        | -228        | -233        | -238        | -242        | -246        | -249        | -246        | -247        | -247        | -237        |             |
| h   | 6    | 3    | 2            | 4           | 5           | 8           | 11          | 14          | 19          | 25          | 33          | 16          | 33          | 48          | 60          |
| g   | 6    | 4    | -58          | -57         | -54         | -51         | -49         | -40         | -32         | -25         | -25         | -25         | -25         | -16         | -8          | -1          |
| h   | 6    | 4    | -35          | -32         | -29         | -26         | -22         | -18         | -16         | -15         | -15         | -9          | -12         | -16         | -20         |
| g   | 6    | 5    | 59           | 57          | 54          | 49          | 44          | 39          | 32          | 25          | 18          | 21          | 12          | 7           | -2          |
| h   | 6    | 5    | 36           | 32          | 28          | 23          | 18          | 13          | 8           | 4           | 0           | -16         | -12         | -12         | -11         |
| g   | 6    | 6    | 5312         | -25         | -21         | -27         | -18         | -16         | -14         | -12         | -11         | -9          | -10         | -7          | -11         | -2          |
| h   | 6    | 6    | -81          | -57         | -54         | -51         | -49         | -50         | -53         | -53         | -40         | -55         | -56         | -56         | -56         |
| g   | 7    | 0    | 70           | 70          | 71          | 72          | 73          | 73          | 74          | 74          | 74          | 70          | 65          | 65          | 67          |
| h   | 7    | 0    | -55          | -54         | -54         | -54         | -54         | -54         | -53         | -53         | -40         | -55         | -56         | -56         | -56         |
| g   | 7    | 1    | -14          | -14         | -14         | -14         | -14         | -14         | -15         | -15         | -17         | -18         | -18         | -17         | -24         | -28         |
| h   | 7    | 1    | -14          | -14         | -14         | -14         | -14         | -14         | -14         | -14         | -14         | -14         | -14         | -14         | -4          | -6          |
| g   | 7    | 2    | -21          | -20         | -19         | -18         | -16         | -14         | -12         | -11         | -9          | -10         | -7          | -11         | -7          |             |
| h   | 7    | 2    | -22          | -22         | -22         | -22         | -22         | -21         | -20         | -19         | -19         | -22         | -16         | -18         | -17         |             |
| g   | 8    | 0    | 11           | 11          | 11          | 11          | 11          | 11          | 11          | 11          | 11          | 11          | 11          | 11          | 13          | 22          | 11          |
| h   | 8    | 0    | -22          | -22         | -22         | -22         | -22         | -21         | -20         | -19         | -19         | -22         | -16         | -18         | -17         |             |
| g   | 8    | 1    | -4           | -4          | -4          | -4          | -3          | -3          | -3          | -3          | -8          | -4          | -6          | -4          |             |
| h   | 8    | 1    | -4           | -4          | -4          | -4          | -4          | -3          | -3          | -3          | -8          | -4          | -6          | -4          |             |
| g   | 8    | 2    | -15          | -15         | -15         | -15         | -15         | -15         | -15         | -15         | -15         | -15         | -15         | -15         | -15         |             |
| h   | 8    | 2    | -14          | -15         | -15         | -15         | -15         | -15         | -15         | -15         | -15         | -15         | -15         | -15         | -15         |             |
| g   | 8    | 3    | -9           | -9          | -9          | -9          | -9          | -9          | -9          | -9          | -9          | -10         | -5          | -1          | -14         | -11         |
| h   | 8    | 3    | -9           | -9          | -9          | -9          | -9          | -9          | -9          | -9          | -9          | -10         | -5          | -1          | -14         | -11         |
| g   | 8    | 4    | 2            | 1           | 1           | 2           | 1           | 2           | 1           | 1           | 9           | 11          | 6           | 2           |             |
| h   | 8    | 4    | 2            | 1           | 1           | 2           | 1           | 2           | 1           | 1           | 9           | 11          | 6           | 2           |             |
| g   | 8    | 5    | 3            | 4           | 4           | 4           | 5           | 6           | 6           | 6           | 7           | 15          | 10          | 10          |             |
| g/h | Deg | Ord | IGRF 1900.0 | IGRF 1905.0 | IGRF 1910.0 | IGRF 1915.0 | IGRF 1920.0 | IGRF 1925.0 | IGRF 1930.0 | IGRF 1935.0 | IGRF 1940.0 | IGRF 1945.0 | DGRF 1950.0 | DGRF 1955.0 | DGRF 1960.0 |
|-----|-----|-----|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| h   | 8   | 5   | 5           | 5           | 5           | 5           | 5           | 5           | 5           | 5           | 5           | 5           | 8           | 3           | 4           |
| g   | 8   | 6   | -9          | -8          | -8          | -8          | -7          | -7          | -6          | -6          | -5          | -10         | -13         | -7          | -5          |
| h   | 8   | 6   | 16          | 16          | 16          | 16          | 17          | 17          | 18          | 18          | 19          | 18          | 17          | 23          | 23          |
| g   | 8   | 7   | 5           | 5           | 5           | 6           | 6           | 7           | 8           | 8           | 9           | 7           | 5           | 6           | 10          |
| h   | 8   | 7   | -5          | -5          | -5          | -5          | -5          | -5          | -5          | -5          | 3           | -4          | -4          | 1           |
| g   | 8   | 8   | 8           | 8           | 8           | 8           | 8           | 8           | 7           | 7           | 7           | 2           | -1          | 9           | 8           |
| h   | 8   | 8   | -18         | -18         | -18         | -18         | -19         | -19         | -19         | -19         | -19         | -11         | -17         | -13         | -20         |
| g   | 9   | 0   | 8           | 8           | 8           | 8           | 8           | 8           | 8           | 8           | 8           | 5           | 3           | 4           | 4           |
| g   | 9   | 1   | 10          | 10          | 10          | 10          | 10          | 10          | 10          | 10          | 10          | 21          | -7          | 9           | 6           |
| h   | 9   | 1   | -20         | -20         | -20         | -20         | -20         | -20         | -20         | -20         | -21         | -27         | -24         | -11         | -18         |
| g   | 9   | 2   | 1           | 1           | 1           | 1           | 1           | 1           | 1           | 1           | 1           | 1           | -1          | -4          | 0           |
| h   | 9   | 2   | 14          | 14          | 14          | 14          | 14          | 14          | 14          | 15          | 15          | 17          | 19          | 12          | 12          |
| g   | 9   | 3   | -11         | -11         | -11         | -11         | -11         | -11         | -12         | -12         | -12         | -11         | -25         | -5          | -9          |
| h   | 9   | 3   | 5           | 5           | 5           | 5           | 5           | 5           | 5           | 5           | 5           | 29          | 12          | 7           | 2           |
| g   | 9   | 4   | 12          | 12          | 12          | 12          | 12          | 12          | 11          | 11          | 11          | 3           | 10          | 2           | 1           |
| h   | 9   | 4   | -3          | -3          | -3          | -3          | -3          | -3          | -3          | -3          | -3          | -9          | 2           | 6           | 0           |
| g   | 9   | 5   | 1           | 1           | 1           | 1           | 1           | 1           | 1           | 1           | 1           | 16          | 5           | 4           | 4           |
| h   | 9   | 5   | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -3          | -3          |
| g   | 9   | 6   | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -3          | -5          |
| h   | 9   | 6   | 8           | 8           | 8           | 8           | 8           | 9           | 9           | 9           | 9           | 8           | 10          | 9           |
| g   | 9   | 7   | 2           | 2           | 2           | 2           | 2           | 2           | 3           | 3           | 3           | -4          | -2          | 2           | -2          |
| h   | 9   | 7   | 10          | 10          | 10          | 10          | 10          | 10          | 11          | 11          | 6           | 8           | 7           | 8           |
| g   | 9   | 8   | -1          | 0           | 0           | 0           | 0           | 0           | 0           | 0           | 1           | -3          | 3           | 2           | 3           |
| h   | 9   | 8   | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -4          |
| g   | 9   | 9   | -1          | -1          | -1          | -1          | -1          | -1          | -1          | -2          | -2          | -2          | -4          | 8           | 5           |
| h   | 9   | 9   | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 8           | 7           |
| g   | 10  | 0   | -3          | -3          | -3          | -3          | -3          | -3          | -3          | -3          | -3          | -3          | -8          | -3          | 1           |
| g   | 10  | 1   | -4          | -4          | -4          | -4          | -4          | -4          | -4          | -4          | -4          | -4          | -4          | 11          | 4           | -5          |
| h   | 10  | 1   | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 5           | 13          | -4          |
| g   | 10  | 2   | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 1           | -1          |
| h   | 10  | 2   | 1           | 1           | 1           | 1           | 1           | 1           | 1           | 1           | 1           | 1           | -2          | 0           | 1           |
| g   | 10  | 3   | -5          | -5          | -5          | -5          | -5          | -5          | -5          | -5          | -5          | 2           | 13          | 2           | 0           |
| h   | 10  | 3   | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | 2           | -20         | -10         | -8          |
| g   | 10  | 4   | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -2          | -5          | -4          | -3          | -1          |
| h   | 10  | 4   | 6           | 6           | 6           | 6           | 6           | 6           | 6           | 6           | 6           | 6           | 6           | 2           | -2          | 2           |
Table 2 (continued)

| g/h | Deg | Ord | IGRF 1900.0 | IGRF 1905.0 | IGRF 1910.0 | IGRF 1915.0 | IGRF 1920.0 | IGRF 1925.0 | IGRF 1930.0 | IGRF 1935.0 | IGRF 1940.0 | IGRF 1945.0 | IGRF 1950.0 | IGRF 1955.0 | IGRF 1960.0 |
|-----|-----|-----|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| g   | 10  | 5   | 6  | 6  | 6  | 6  | 6  | 6  | 6  | 6  | -1 | 4  | 7  | 4  |          |
| h   | 10  | 5   | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -5  |          |
| g   | 10  | 6   | 4  | 4  | 4  | 4  | 4  | 4  | 4  | 4  | 8  | 12 | 4  | 6  |      |          |
| h   | 10  | 6   | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 6  | 6  | 1  | 1  |          |
| g   | 10  | 7   | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | -1 | 3  | -2 | 1  |          |
| h   | 10  | 7   | -2 | -2 | -2 | -2 | -2 | -2 | -1 | -1 | -4 | -3 | -3 | -1 |      |          |
| g   | 10  | 8   | 2  | 2  | 2  | 1  | 1  | 1  | 1  | 2  | 2  | -3 | 2  | 6  | -1 |          |
| h   | 10  | 8   | 4  | 4  | 4  | 4  | 4  | 4  | 4  | 4  | -2 | 6  | 7  | 6  |      |          |
| g   | 10  | 9   | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 11 | -1 | 0  |    |          |
| h   | 10  | 9   | 10 | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |    |          |
| g   | 10  | 10  | -6 | -6 | -6 | -6 | -6 | -6 | -6 | -6 | -2 | 8  | -3 | -7 |    |          |
| h   | 11  | 0   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| g   | 11  | 1   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| h   | 11  | 1   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| g   | 11  | 2   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| h   | 11  | 2   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| g   | 11  | 3   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| h   | 11  | 3   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| g   | 11  | 4   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| h   | 11  | 4   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| g   | 11  | 5   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| h   | 11  | 5   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| g   | 11  | 6   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| h   | 11  | 6   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| g   | 11  | 7   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| h   | 11  | 7   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| g   | 11  | 8   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| h   | 11  | 8   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| g   | 11  | 9   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| h   | 11  | 9   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| g   | 11  | 10  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
| h   | 11  | 10  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |    |          |
Table 2 (continued)

| g/h | Deg | Ord | IGRF | IGRF | IGRF | IGRF | IGRF | IGRF | IGRF | IGRF | IGRF | DGRF | DGRF | DGRF | DGRF | DGRF |
|-----|-----|-----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| n   | m   | 1900.0 | 1905.0 | 1910.0 | 1915.0 | 1920.0 | 1925.0 | 1930.0 | 1935.0 | 1940.0 | 1945.0 | 1950.0 | 1955.0 | 1960.0 |
| g   | 11  | 11   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 11  | 11   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 12  | 0    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 12  | 1    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 12  | 2    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 12  | 2    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 12  | 3    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 12  | 3    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 12  | 4    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 12  | 4    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 12  | 5    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 12  | 5    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 12  | 6    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 12  | 6    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 12  | 7    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 12  | 7    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 12  | 8    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 12  | 8    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 12  | 9    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 12  | 9    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 12  | 10   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 12  | 10   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 12  | 11   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 12  | 11   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 12  | 12   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 12  | 12   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 13  | 0    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 13  | 1    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 13  | 1    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 13  | 2    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 13  | 2    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 13  | 3    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 13  | 3    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| g   | 13  | 4    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| h   | 13  | 4    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
Table 2 (continued)

| g/h | Deg | Ord | IGRF | IGRF | IGRF | IGRF | IGRF | IGRF | IGRF | DGRF | DGRF | DGRF | DGRF | DGRF |
|-----|-----|-----|------|------|------|------|------|------|------|------|------|------|------|------|
|     |     |     | 1900.0 | 1905.0 | 1910.0 | 1915.0 | 1920.0 | 1925.0 | 1930.0 | 1935.0 | 1940.0 | 1945.0 | 1950.0 | 1955.0 | 1960.0 |
| g   | 13  | 5   | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| h   | 13  | 5   | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| g   | 13  | 6   | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| h   | 13  | 6   | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| g   | 13  | 7   | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| h   | 13  | 7   | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| g   | 13  | 8   | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| h   | 13  | 8   | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| g   | 13  | 9   | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| h   | 13  | 9   | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| g   | 13  | 10  | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| h   | 13  | 10  | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| g   | 13  | 11  | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| h   | 13  | 11  | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| g   | 13  | 12  | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| h   | 13  | 12  | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| g   | 13  | 13  | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| h   | 13  | 13  | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| g/h | Deg | Ord | DGRF | DGRF | DGRF | DGRF | DGRF | DGRF | DGRF | DGRF | DGRF | DGRF | IGRF | SV  |
|-----|-----|-----|------|------|------|------|------|------|------|------|------|------|------|-----|
|     |     |     | 1965.0 | 1970.0 | 1975.0 | 1980.0 | 1985.0 | 1990.0 | 1995.0 | 2000.0 | 2005.0 | 2010.0 | 2015.0 | 2020.0 |
| g   | 1   | 0   | -30334 | -30220 | -30100 | -29992 | -29873 | -29775 | -29692 | -296194 | -2955463 | -2949657 | -2944146 | -294048.57 |
| h   | 1   | 1   | -2119  | -2068  | -2013  | -1956  | -1905  | -1848  | -1784  | -1728.2 | -166905  | -159642  | -150177  | -1450.9 |
| g   | 2   | 0   | 5776   | 5737   | 5675   | 5604   | 5500   | 5406   | 5306   | 5186.1  | 5077.99  | 4944.26  | 4795.99  | 4652.5  |
| h   | 2   | 1   | 2997   | 3000   | 3010   | 3027   | 3044   | 3059   | 3070   | 3068.4  | 3047.69  | 3026.34  | 3012.20  | 2982.0  |
| g   | 2   | 1   | -2016  | -2047  | -2067  | -2129  | -2197  | -2279  | -2366  | -2481.6  | -2594.50  | -2708.54  | -2845.41  | -2991.6  |
| h   | 2   | 2   | 1594   | 1611   | 1632   | 1663   | 1687   | 1686   | 1681   | 1670.9  | 1657.76  | 1668.17  | 1676.35  | 1677.0 |
| g   | 3   | 0   | 1297   | 1287   | 1276   | 1281   | 1296   | 1314   | 1335   | 13396   | 1336.30  | 13398.5  | 1350.33  | 1363.2  |
| h   | 3   | 1   | -2038  | -2091  | -2144  | -2180  | -2208  | -2239  | -2267  | -2288.0  | -2305.83  | -2326.54  | -2352.26  | -2381.2  |
| g   | 3   | 1   | -404   | -366   | -333   | -336   | -310   | -284   | -262   | -227.6   | -198.86   | -160.40   | -115.29   | -82.1    |
| h   | 3   | 2   | 1292   | 1278   | 1260   | 1251   | 1247   | 1248   | 1249   | 1252.1   | 1246.39   | 1233.10   | 1225.85   | 1236.2  |
| g   | 3   | 2   | 240    | 251    | 262    | 271    | 284    | 293    | 302    | 293.4    | 269.72    | 251.75    | 245.04    | 241.9    |
| h   | 3   | 3   | 856    | 838    | 830    | 833    | 829    | 802    | 759    | 714.5    | 672.51    | 633.73    | 581.69    | 525.7    |
| g   | 3   | 3   | -165   | -196   | -223   | -252   | -297   | -352   | -427   | -491.1   | -524.72   | -537.03   | -538.70   | -543.4  |
Table 2 (continued)

| g/h | Deg | Ord | DGRF 1965.0 | DGRF 1970.0 | DGRF 1975.0 | DGRF 1980.0 | DGRF 1985.0 | DGRF 1990.0 | DGRF 1995.0 | DGRF 2000.0 | DGRF 2005.0 | DGRF 2010.0 | DGRF 2015.0 | DGRF 2020.0 | IGRF SV |
|-----|-----|-----|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| g   | 4   | 1   | 148         | 167         | 191         | 212         | 232         | 247         | 262         | 272.6       | 282.07      | 286.48      | 283.54      | 281.9       | 280.26     |
| g   | 4   | 2   | 479         | 461         | 438         | 398         | 361         | 325         | 290         | 250.0       | 210.65      | 166.38      | 120.49      | 86.3        | 59.0       |
| h   | 4   | 3   | -269        | -266        | -265        | -257        | -249        | -240        | -236        | -231.9      | -225.23     | -211.03     | -188.43     | -158.4      | 6.5        |
| h   | 4   | 4   | -300        | -305        | -405        | -419        | -424        | -423        | -418        | -403.0      | -379.86     | -356.83     | -334.85     | -309.4      | 5.2        |
| h   | 4   | 5   | 13          | 26          | 39          | 53          | 69          | 84          | 97          | 119.8       | 145.15      | 164.46      | 180.95      | 199.7       | 3.6        |
| h   | 4   | 6   | -269        | -266        | -265        | -257        | -249        | -240        | -236        | -231.9      | -225.23     | -211.03     | -188.43     | -158.4      | 6.5        |
| g   | 5   | 1   | 358         | 359         | 356         | 357         | 355         | 353         | 352         | 351.4       | 354.41      | 357.29      | 360.14      | 363.2       | 0.5        |
| h   | 5   | 2   | 254         | 262         | 264         | 261         | 253         | 245         | 235         | 222.3       | 208.95      | 200.26      | 192.35      | 187.8       | -0.6       |
| h   | 5   | 3   | 128         | 139         | 148         | 150         | 150         | 154         | 165         | 171.9       | 180.25      | 189.01      | 196.98      | 208.3       | 2.5        |
| h   | 5   | 4   | -31         | -42         | -59         | -74         | -93         | -109        | -118        | -130.4      | -136.54     | -141.05     | -140.94     | -140.7      | 0.2        |
| h   | 5   | 5   | -126        | -139        | -152        | -151        | -154        | -153        | -143        | -133.1      | -123.45     | -118.06     | -119.14     | -121.2      | -0.6       |
| g   | 6   | 0   | 81          | 83          | 88          | 92          | 95          | 97          | 107         | 106.3       | 103.85      | 101.04      | 100.12      | 98.9        | 0.3        |
| g   | 6   | 1   | 45          | 43          | 45          | 48          | 53          | 61          | 68          | 72.3        | 73.60       | 72.78       | 69.55       | 66.0        | -0.5       |
| h   | 6   | 2   | 61          | 64          | 66          | 66          | 65          | 65          | 67          | 68.2        | 69.56       | 68.69       | 67.57       | 65.5        | -0.3       |
| h   | 6   | 3   | -11         | -12         | -13         | -15         | -16         | -16         | -17         | -17.4       | -20.33      | -20.90      | -20.61      | -19.1       | 0.0        |
| h   | 6   | 4   | 8           | 15          | 28          | 42          | 51          | 59          | 68          | 74.2        | 76.74       | 75.92       | 72.79       | 72.9        | 0.4        |
| h   | 6   | 5   | 100         | 100         | 99          | 93          | 88          | 82          | 72          | 63.7        | 54.75       | 44.18       | 33.30       | 25.1        | -1.6       |
| h   | 6   | 6   | -228        | -212        | -198        | -192        | -185        | -178        | -170        | -160.9      | -151.34     | -141.40     | -129.85     | -121.5      | 1.3        |
| h   | 6   | 7   | 68          | 72          | 75          | 71          | 69          | 69          | 67          | 65.1        | 63.63       | 61.54       | 58.74       | 52.8        | -1.3       |
| g   | 7   | 1   | 4           | 2           | 1           | 4           | 4           | 3           | 1           | -5.9        | -14.58      | -22.83      | -28.93      | -36.2       | -1.4       |
| g   | 7   | 2   | -32         | -37         | -41         | -43         | -48         | -52         | -58         | -61.2       | -63.53      | -66.26      | -66.64      | -64.5       | 0.8        |
| g   | 7   | 3   | 1           | 3           | 6           | 14          | 16          | 18          | 19          | 16.9        | 14.58       | 13.10       | 13.14       | 13.5        | 0.0        |
| g   | 7   | 4   | -8          | -6          | -4          | -2          | -2          | -1          | 1           | 0.7         | 0.24        | 0.32        | 7.35        | 8.9         | 0.0        |
| g   | 7   | 5   | -111        | -112        | -111        | -108        | -102        | -96         | -93         | -90.4       | -86.36      | -78.09      | -70.85      | -64.7       | 0.9        |
| g   | 7   | 6   | -7          | 11          | 17          | 21          | 24          | 36          | 43.8        | 50.94       | 55.40       | 62.41       | 68.1        | 1.0        |
| g   | 7   | 7   | 75          | 72          | 71          | 72          | 74          | 77          | 77          | 79.0        | 79.88       | 80.44       | 81.29       | 80.6        | -0.1       |
| g   | 7   | 8   | -57         | -57         | -56         | -59         | -62         | -64         | -72         | -74.46      | -75.00      | -75.99      | -76.79      | -76.7       | 0.2        |
| h   | 7   | 1   | -61         | -70         | -77         | -82         | -83         | -80         | -69         | -64.6       | -61.14      | -57.80      | -54.27      | -51.5       | 0.6        |

Alken et al., Earth, Planets and Space (2021) 73:49
Table 2 (continued)

| g/h | Deg | Ord | DGRF 1965.0 | DGRF 1970.0 | DGRF 1975.0 | DGRF 1980.0 | DGRF 1990.0 | DGRF 1995.0 | DGRF 2000.0 | DGRF 2005.0 | DGRF 2010.0 | DGRF 2015.0 | DGRF 2020.0 | SV |
|-----|-----|-----|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-----|
| g   | 7   | 2   | 4           | 1           | 1           | 2           | 3           | 2           | 1           | 0           | -1.65       | -4.55       | -6.79       | -8.2       | 0.0 |
| h   | 7   | 2   | -27         | -27         | -26         | -27         | -27         | -26         | -25         | -242        | -22.57      | -21.20      | -19.53      | -16.9      | 0.6 |
| g   | 7   | 3   | 13          | 14          | 16          | 21          | 24          | 26          | 28          | 33.3        | 38.73       | 45.24       | 51.82       | 56.5       | 0.7 |
| h   | 7   | 3   | -2          | -4          | -5          | -5          | -2          | 0           | 4           | 6.2         | 6.82        | 6.54        | 5.59        | 2.2        | -0.8 |
| g   | 7   | 4   | -26         | -22         | -14         | -12         | -6          | -1          | 5           | 9.1         | 12.30       | 14.00       | 15.07       | 15.8       | 0.1 |
| h   | 7   | 4   | 6           | 8           | 10          | 16          | 20          | 21          | 24          | 24.0        | 25.35       | 24.96       | 24.45       | 23.5       | -0.2 |
| g   | 7   | 5   | -6          | -2          | 0           | 1           | 4           | 5           | 4           | 69.9        | 9.37        | 10.46       | 9.32        | 6.4        | -0.5 |
| h   | 7   | 5   | 26          | 23          | 22          | 18          | 17          | 17          | 17          | 14.8        | 10.93       | 7.03        | 3.27        | -2.2       | -1.1 |
| g   | 7   | 6   | -23         | -23         | -23         | -23         | -23         | -23         | -24         | -254        | -26.32      | -27.61      | -27.50      | -27.2      | 0.1 |
| h   | 7   | 7   | 1           | -2          | -5          | -2          | 0           | 0           | -2          | -12         | 1.94        | 49.2        | 6.61        | 9.8        | 0.8 |
| g   | 8   | 0   | 13          | 14          | 14          | 18          | 21          | 23          | 25          | 24.4        | 24.80       | 24.41       | 23.98       | 23.7       | 0.0 |
| h   | 8   | 1   | 5           | 6           | 6           | 6           | 5           | 6           | 6           | 66.6        | 6.72        | 8.21        | 8.89        | 9.7        | 0.1 |
| g   | 8   | 1   | -4          | -2          | -1          | 0           | 0           | -1          | -6          | -9.2        | -11.73      | -14.50      | -16.78      | -17.6      | -0.2 |
| h   | 8   | 2   | -12         | -15         | -16         | -18         | -19         | -19         | -21         | -21.5       | -20.88      | -2003       | -18.26      | -15.3      | 0.6 |
| g   | 8   | 2   | -14         | -13         | -12         | -11         | -11         | -10         | -9          | -7.9        | -6.88       | -5.59       | -3.16       | -0.5       | 0.4 |
| h   | 8   | 3   | 9           | 9           | 4           | 4           | 5           | 6           | 8           | 8.5         | 9.83        | 11.83       | 13.18       | 12.8       | -0.2 |
| g   | 8   | 4   | 0           | 3           | -8          | -7          | -9          | -12         | -14         | -166        | -18.11      | -19.34      | -20.56      | -21.1      | -0.1 |
| h   | 8   | 4   | -16         | -17         | -19         | -22         | -23         | -22         | -23         | -21.5       | -19.71      | -17.41      | -14.60      | -11.7      | 0.5 |
| g   | 8   | 5   | 8           | 5           | 4           | 4           | 4           | 3           | 9           | 9.1         | 10.17       | 11.61       | 13.33       | 15.3       | 0.4 |
| h   | 8   | 5   | 4           | 6           | 6           | 9           | 12          | 15          | 15          | 15.5        | 16.22       | 16.71       | 16.16       | 14.9       | -0.3 |
| g   | 8   | 6   | -1          | 0           | 0           | 3           | 4           | 4           | 6           | 7.0         | 9.36        | 10.85       | 11.76       | 13.7       | 0.3 |
| h   | 8   | 6   | 24          | 21          | 18          | 16          | 14          | 12          | 11          | 8.9         | 7.61        | 6.96        | 5.69        | 3.6        | -0.4 |
| g   | 8   | 7   | 11          | 11          | 10          | 6           | 4           | 2           | 5           | -7.9        | -11.25      | -14.05      | -15.98      | -16.5      | -0.1 |
| h   | 8   | 7   | -3          | -6          | -10         | -13         | -15         | -16         | -16         | -149        | -12.76      | -10.74      | -9.10       | -6.9       | 0.5 |
| g   | 8   | 8   | 4           | 3           | 1           | -1          | -4          | -6          | -7          | -70         | -4.87       | -3.54       | -2.02       | -0.3       | 0.4 |
| h   | 8   | 8   | -17         | -16         | -17         | -15         | -11         | -10         | -4          | -21         | -0.06       | 1.64        | 2.26        | 2.8        | 0.0 |
| g   | 9   | 0   | 8           | 8           | 7           | 5           | 5           | 4           | 4           | 50          | 5.58        | 5.50        | 5.33        | 5.0        | -    |
| h   | 9   | 1   | 10          | 10          | 10          | 10          | 9           | 9           | 9           | 94.9        | 9.76        | 9.45        | 8.83        | 8.4        | -    |
| g   | 9   | 1   | -22         | -21         | -21         | -21         | -20         | -20         | -19.7       | -20.11      | -20.54      | -21.77      | -23.4       | -        | -    |
| h   | 9   | 2   | 2           | 2           | 2           | 1           | 1           | 1           | 3           | 3.0         | 3.98        | 3.45        | 3.02        | 2.9        | -    |
| g   | 9   | 2   | 15          | 16          | 16          | 15          | 15          | 15          | 15          | 13.4        | 12.69       | 11.51       | 10.76       | 11.0       | -    |
| h   | 9   | 3   | -13         | -12         | -12         | -12         | -12         | -10         | -8.4        | -6.94       | -5.27       | -3.22       | -1.5        | -        | -    |
| g   | 9   | 3   | 7           | 6           | 7           | 9           | 9           | 11          | 12          | 12.5        | 12.67       | 12.75       | 11.74       | 9.8        | -    |
| g/h | Deg | Ord | DGRF 1965.0 | DGRF 1970.0 | DGRF 1975.0 | DGRF 1980.0 | DGRF 1985.0 | DGRF 1990.0 | DGRF 1995.0 | DGRF 2000.0 | DGRF 2005.0 | DGRF 2010.0 | DGRF 2015.0 | DGRF 2020.0 | IGRF | SV |
|-----|-----|-----|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------|-----|
| g   | 9   | 4   | 10           | 10          | 10          | 9           | 9           | 9           | 8           | 6.3         | 5.01        | 3.13        | 0.67        | -1.1        | -     |     |
| h   | 9   | 4   | -4           | -4          | -4          | -5          | -6          | -7          | -6          | -62         | -672        | -7.14       | -6.74       | -5.1        | -     |     |
| g   | 9   | 5   | -5           | -5          | -5          | -6          | -6          | -7          | -8          | -89         | -10.76      | -12.38      | -13.20      | -13.2        | -     |     |
| h   | 9   | 5   | -5           | -5          | -5          | -6          | -6          | -7          | -8          | -84         | -8.16       | -7.42       | -6.88       | -6.3        | -     |     |
| g   | 9   | 6   | 0            | -1          | -1          | -1          | -1          | -1          | -1          | -15         | -1.25       | -0.76       | -0.10       | 1.1         | -     |     |
| h   | 9   | 6   | 10           | 10          | 10          | 9           | 9           | 9           | 9           | 84          | 8.10        | 7.97        | 7.79        | 7.8         | -     |     |
| g   | 9   | 7   | 5            | 3           | 4           | 7           | 7           | 7           | 10          | 9.3         | 8.76        | 8.43        | 8.68        | 8.8         | -     |     |
| h   | 9   | 7   | 10           | 11          | 11          | 10          | 9           | 8           | 5           | 3.8         | 2.92        | 2.14        | 1.04        | 0.4         | -     |     |
| g   | 9   | 8   | 1            | 1           | 1           | 2           | 1           | 1           | -2          | -4.3        | -6.66       | -8.42       | -9.06       | -9.3        | -     |     |
| h   | 9   | 8   | -4           | -2          | -3          | -6          | -7          | -7          | -8          | -8.2        | -7.73       | -6.08       | -3.89       | -1.4        | -     |     |
| g   | 9   | 9   | -2           | -1          | -2          | -5          | -5          | -6          | -8          | -8.2        | -9.22       | -10.08      | -10.54      | -11.9       | -     |     |
| h   | 9   | 9   | 1            | 1           | 1           | 2           | 2           | 2           | 3           | 48          | 6.01        | 7.01        | 8.44        | 9.6         | -     |     |
| g   | 10  | 0   | -2           | -3          | -3          | -4          | -4          | -3          | -3          | -26         | -2.17       | -1.94       | -2.01       | -1.9        | -     |     |
| h   | 10  | 0   | -3           | -3          | -3          | -4          | -4          | -4          | -6          | -6.0        | -6.12       | -6.24       | -6.26       | -6.2        | -     |     |
| g   | 10  | 1   | 2            | 2           | 2           | 2           | 2           | 3           | 2           | 1.7         | 2.19        | 2.73        | 3.28        | 3.4         | -     |     |
| h   | 10  | 1   | 2            | 2           | 2           | 2           | 3           | 2           | 2           | 1.7         | 1.42        | 0.89        | 0.17        | -0.1        | -     |     |
| g   | 10  | 2   | 1            | 1           | 1           | 0           | 0           | 1           | 0           | 0.0         | 0.10        | -0.10       | -0.40       | -0.2        | -     |     |
| h   | 10  | 2   | -5           | -5          | -5          | -5          | -5          | -4          | -3.1        | -2.35       | -1.07       | 0.55        | 1.7         | -     |     |
| g   | 10  | 3   | 2            | 3           | 3           | 3           | 3           | 3           | 4           | 4.0         | 4.46        | 4.71        | 4.55        | 3.6         | -     |     |
| h   | 10  | 4   | -2           | -1          | -2          | -2          | -2          | -2          | -1          | -0.5        | -0.15       | -0.16       | -0.55       | -0.9        | -     |     |
| g   | 10  | 4   | 6            | 4           | 4           | 6           | 6           | 5           | 4.9         | 4.76        | 4.44        | 4.40        | 4.8         | -     |     |
| h   | 10  | 5   | 6            | 5           | 5           | 5           | 5           | 4           | 4           | 3.7         | 3.06        | 2.45        | 1.70        | 0.7         | -     |     |
| g   | 10  | 5   | -4           | -4          | -4          | -4          | -4          | -4          | -5          | -5.9        | -6.58       | -7.22       | -7.92       | -8.6        | -     |     |
| h   | 10  | 6   | 4            | 4           | 4           | 3           | 3           | 3           | 2           | 1.0         | 0.29        | -0.33       | -0.67       | -0.9        | -     |     |
| g   | 10  | 6   | 0            | 0           | -1          | 0           | 0           | 0           | 0           | -1.2        | -1.01       | -0.96       | -0.61       | -0.1        | -     |     |
| h   | 10  | 7   | 0            | 1           | 1           | 1           | 1           | 1           | 2           | 2.0         | 2.06        | 2.13        | 2.13        | 1.9         | -     |     |
| g   | 10  | 7   | -2           | -1          | -1          | -1          | -1          | -2          | -2          | -2.9        | -3.47       | -3.95       | -4.16       | -4.3        | -     |     |
| h   | 10  | 8   | 2            | 0           | 0           | 2           | 2           | 3           | 5           | 4.2         | 3.77        | 3.09        | 2.33        | 1.4         | -     |     |
| g   | 10  | 8   | 3            | 3           | 3           | 4           | 4           | 3           | 1           | 0.2         | -0.06       | -1.99       | -2.85       | -3.4        | -     |     |
| h   | 10  | 9   | 2            | 3           | 3           | 3           | 3           | 3           | 1           | 0.3         | -0.21       | -1.03       | -1.80       | -2.4        | -     |     |
| g   | 10  | 9   | 0            | 1           | 1           | 0           | 0           | 0           | -1          | -22         | -2.31       | -1.97       | -1.12       | -0.1        | -     |     |
| h   | 10  | 10  | -1           | -1          | 0           | 0           | 0           | 0           | 0           | -11         | -2.09       | -2.80       | -3.59       | -3.8        | -     |     |
| g   | 10  | 10  | -6           | -4          | -5          | -6          | -6          | -7          | -7          | -7.4        | -7.93       | -8.31       | -8.72       | -8.8        | -     |     |
| h   | 11  | 0   | -            | -           | -           | -           | -           | -           | -           | -           | 2.7         | 2.95        | 3.05        | 3.00        | 3.0        | -     |     |
| g   | 11  | 1   | -            | -           | -           | -           | -           | -           | -           | -           | -1.7        | -1.60       | -1.48       | -1.40       | -1.4        | -     |     |
| g/h | Deg | Ord | DGRF 1965.0 | DGRF 1970.0 | DGRF 1975.0 | DGRF 1980.0 | DGRF 1985.0 | DGRF 1990.0 | DGRF 1995.0 | DGRF 2000.0 | DGRF 2005.0 | DGRF 2010.0 | DGRF 2015.0 | DGRF 2020.0 | IGRF 20-25 | SV |
|-----|-----|-----|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|---------|
| h   | 11-2| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 11-2| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 11-3| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 11-3| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 11-4| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 11-4| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 11-5| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 11-5| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 11-6| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 11-6| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 11-7| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 11-7| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 11-8| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 11-8| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 11-9| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 11-9| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 11-10| 0  | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 11-10| 0 | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 11-11| 0  | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 11-11| 0 | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 11-12| 0  | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 11-12| 0 | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 12-1| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 12-1| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 12-2| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 12-2| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 12-3| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 12-3| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 12-4| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 12-4| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 12-5| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 12-5| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 12-6| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 12-6| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| h   | 12-7| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g   | 12-7| 0   | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -       |
| g/h | Deg | Ord | DGRF 1965.0 | DGRF 1970.0 | DGRF 1975.0 | DGRF 1980.0 | DGRF 1985.0 | DGRF 1990.0 | DGRF 1995.0 | DGRF 2000.0 | DGRF 2005.0 | DGRF 2010.0 | DGRF 2015.0 | DGRF 2020.0 | IGRF | SV |
|-----|-----|-----|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|--------|----|
| h   | 12  | 7   | -           | -           | -           | -           | -           | -           | -           | 0.0         | 0.01        | 0.00        | -0.09       | -0.2       | -     |
| g   | 12  | 8   | -           | -           | -           | -           | -           | -           | -           | -0.3        | -0.35       | -0.39       | -0.37       | -0.3       | -     |
| h   | 12  | 8   | -           | -           | -           | -           | -           | -           | -           | 0.0         | 0.02        | 0.13        | 0.29        | 0.6       | -     |
| g   | 12  | 9   | -           | -           | -           | -           | -           | -           | -           | -0.4        | -0.36       | -0.37       | -0.43       | -0.5       | -     |
| h   | 12  | 9   | -           | -           | -           | -           | -           | -           | -           | 0.3         | 0.28        | 0.27        | 0.23        | 0.2       | -     |
| g   | 12  | 10  | -           | -           | -           | -           | -           | -           | -           | -0.1        | 0.08        | 0.21        | 0.22        | 0.1       | -     |
| h   | 12  | 10  | -           | -           | -           | -           | -           | -           | -           | -0.9        | -0.87       | -0.86       | -0.89       | -0.9       | -     |
| g   | 12  | 11  | -           | -           | -           | -           | -           | -           | -           | -0.2        | -0.49       | -0.77       | -0.94       | -1.1       | -     |
| h   | 12  | 11  | -           | -           | -           | -           | -           | -           | -           | -0.4        | -0.34       | -0.23       | -0.16       | 0.0        | -     |
| g   | 12  | 12  | -           | -           | -           | -           | -           | -           | -           | -0.4        | -0.08       | 0.04        | -0.03       | -0.3       | -     |
| h   | 12  | 12  | -           | -           | -           | -           | -           | -           | -           | 0.8         | 0.88        | 0.87        | 0.72        | 0.5       | -     |
| g   | 13  | 0   | -           | -           | -           | -           | -           | -           | -           | -0.2        | -0.16       | -0.09       | -0.02       | 0.1        | -     |
| g   | 13  | 1   | -           | -           | -           | -           | -           | -           | -           | -0.9        | -0.88       | -0.89       | -0.92       | -0.9       | -     |
| h   | 13  | 1   | -           | -           | -           | -           | -           | -           | -           | -0.9        | -0.76       | -0.87       | -0.88       | -0.9       | -     |
| g   | 13  | 2   | -           | -           | -           | -           | -           | -           | -           | 0.3         | 0.30        | 0.31        | 0.42        | 0.5       | -     |
| g   | 13  | 3   | -           | -           | -           | -           | -           | -           | -           | 0.2         | 0.33        | 0.30        | 0.49        | 0.6       | -     |
| h   | 13  | 3   | -           | -           | -           | -           | -           | -           | -           | 0.1         | 0.28        | 0.42        | 0.63        | 0.7       | -     |
| g   | 13  | 4   | -           | -           | -           | -           | -           | -           | -           | 1.8         | 1.72        | 1.66        | 1.56        | 1.4       | -     |
| g   | 13  | 5   | -           | -           | -           | -           | -           | -           | -           | -0.4        | -0.43       | -0.45       | -0.42       | -0.3       | -     |
| h   | 13  | 5   | -           | -           | -           | -           | -           | -           | -           | 1.3         | 1.18        | 1.08        | 0.96        | 0.8       | -     |
| g   | 13  | 6   | -           | -           | -           | -           | -           | -           | -           | -0.4        | -0.37       | -0.31       | -0.19       | 0.0        | -     |
| h   | 13  | 6   | -           | -           | -           | -           | -           | -           | -           | -0.1        | -0.04       | -0.07       | -0.10       | -0.1       | -     |
| g   | 13  | 7   | -           | -           | -           | -           | -           | -           | -           | 0.7         | 0.75        | 0.78        | 0.81        | 0.8       | -     |
| h   | 13  | 7   | -           | -           | -           | -           | -           | -           | -           | 0.7         | 0.63        | 0.54        | 0.42        | 0.3       | -     |
| g   | 13  | 8   | -           | -           | -           | -           | -           | -           | -           | -0.4        | -0.26       | -0.18       | -0.13       | 0.0        | -     |
| h   | 13  | 8   | -           | -           | -           | -           | -           | -           | -           | 0.3         | 0.21        | 0.10        | -0.04       | -0.1       | -     |
| g   | 13  | 9   | -           | -           | -           | -           | -           | -           | -           | 0.3         | 0.35        | 0.38        | 0.38        | 0.4       | -     |
| h   | 13  | 9   | -           | -           | -           | -           | -           | -           | -           | 0.6         | 0.53        | 0.49        | 0.48        | 0.5       | -     |
| g   | 13  | 10  | -           | -           | -           | -           | -           | -           | -           | -0.1        | -0.05       | 0.02        | 0.08        | 0.1       | -     |
| h   | 13  | 10  | -           | -           | -           | -           | -           | -           | -           | 0.3         | 0.38        | 0.44        | 0.48        | 0.5       | -     |
| g   | 13  | 11  | -           | -           | -           | -           | -           | -           | -           | 0.4         | 0.41        | 0.42        | 0.46        | 0.5       | -     |
| h   | 13  | 11  | -           | -           | -           | -           | -           | -           | -           | -0.2        | -0.22       | -0.25       | -0.30       | -0.4       | -     |
\(\dot{g}^m_{n}(T_t), \dot{h}^m_{n}(T_t)\) represent the linear approximation to the change in the Gauss coefficients over the 5-year interval spanning \([T_t, T_t + 5]\). They may be computed in units of nanoTesla per year (nT/year) as

\[
\dot{g}^m_{n}(T_t) = \frac{1}{5} \left( g^m_{n}(T_t + 5) - g^m_{n}(T_t) \right),
\]

\(\dot{h}^m_{n}(T_t) = \frac{1}{5} \left( h^m_{n}(T_t + 5) - h^m_{n}(T_t) \right).\)

The main field coefficients are not yet known for \(T_t = 2025\), and so for the final 5 years of model validity (2020 to 2025 for IGRF-13), the coefficients \(\dot{g}^m_{n}(2020), \dot{h}^m_{n}(2020)\) are explicitly provided (see last column of Table 2) in units of nT/year. Details on the individual candidate secular variation forecasts and the procedure used to combine them into a final set of \(\dot{g}^m_{n}(2020), \dot{h}^m_{n}(2020)\) may be found in Alken et al. (2020b) and references therein.

### The 13th generation IGRF

In August 2017, during an IAGA V-MOD Working Group meeting held in Cape Town, South Africa, a task force of volunteer geomagnetic modelers was assembled to oversee the call for IGRF-13 candidate models and their evaluation. In March 2019, the task force issued an international call for three candidates:

- A DGRF main field model for the epoch 2015.0
- An IGRF main field model for the epoch 2020.0
- An IGRF linear secular variation model for the time period 2020.0 to 2025.0.

Fifteen teams representing over 30 international institutes responded to the call. The number of teams and institutions who participated in IGRF-13 exceeded that of any previous generation. The task force received 11 DGRF main field candidates for epoch 2015.0, 12 IGRF main field candidates for 2020.0, and 14 IGRF secular variation candidates for 2020.0-2025.0. Following recent IGRF conventions, the main field candidates for IGRF-13 describe the spatial variation of the field to a maximum spherical harmonic degree and order of 13, while the secular variation candidates extend to a maximum degree and order of 8. Each of the 15 teams was managed by a team leader from the **lead institution**, and many teams also included personnel from supporting institutions.

The 15 lead institutions for IGRF-13, including references to their candidate model papers, are: (1) British Geological Survey (UK) (Brown et al. 2020); (2) Institute of Crustal Dynamics, China Earthquake Administration (China) (Yang et al. 2020); (3) Universidad Complutense de
The main field coefficients are given in units of nT, and the predictive secular variation coefficients (last column) are given in units of nT/year. These coefficients are available in digital form from https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html along with software to compute magnetic field components at different times and spatial locations, in both geocentric and geodetic coordinate systems.

Figure 1 shows global maps of the IGRF-13 declination (D), inclination (I), and total field magnitude (F) on Earth’s surface at 2020 in Miller cylindrical projection. Taken together, these three quantities fully describe the vector magnetic field at Earth’s surface. The green contour lines represent zero. For the declination component (top panel), these are the agonic lines on which a magnetic compass needle would point to true geographic north. For the inclination map (middle panel), the green contour line of zero inclination shows the magnetic dip equator, which approximately aligns with the geographic equator except for a large, well-known southward deviation over South America. The F map (bottom panel) shows that the largest field intensities occur in Siberia in the northern hemisphere and in the Southern Ocean between Australia and Antarctic in the southern hemisphere. We also see a region of significantly weaker field (compared to an idealized dipole), centered over South America, which is known as the South Atlantic Anomaly. In this region, the inner Van Allen radiation belt comes closest to Earth’s surface, which has important consequences for satellite instrumentation and human safety in low Earth orbit. Interestingly, a new second minimum is becoming more pronounced over the southern Atlantic. This feature is described in more detail in Rother et al. (2020) and Finlay et al. (2020) and was earlier reported by Terra-Nova et al. (2019).

Figure 2 shows the predicted average change of the D, I, and F components on Earth’s surface during the 2020 to 2025 interval from IGRF-13. At low and middle latitudes, the map of \( dD/dt \) (top panel) predicts the largest declination changes in the South Atlantic Anomaly region and also in the polar regions, with northern polar declination changing more than in the southern polar region. The \( dI/dt \) map (middle panel) predicts the largest changes over Brazil, where the magnetic dip equator has moved relatively rapidly over the past few decades. The features seen in \( dF/dt \) (bottom panel) near South America predict a deepening and westward movement of the South Atlantic Anomaly, continuing a trend observed over the past century (Finlay et al. 2010a, Fig. 3).
### Table 3 Magnetic observatories contributing data used in the construction of IGRF-13

| Supporting agencies                                           | Country          | Observatory IAGA code |
|-------------------------------------------------------------|------------------|------------------------|
| Centre de Recherche en Astronomie, Astrophysique et Geophysique | Algeria          | TAM                    |
| Universidad Nacional de la Plata                            | Argentina        | TRW, ORC               |
| Servicio Meteorologico Nacional                             | Argentina        | ASP, CRI, CNB, CSY, CTA, DVS |
| Geoscience Australia                                        | Australia        | GNA, GNG, KDU, LRM, MAW, MCQ |
| Zentralanstalt für Meteorologie und Geodynamik              | Austria          | WIC                    |
| National Academy of Sciences                                | Belarus          | MNK                    |
| Institut Royal Météorologique                               | Belgium          | DOU, MAB               |
| CNPq-Observatorio Nacional                                   | Brazil           | VSS, TTB               |
| Academy of Sciences                                         | Bulgaria         | PAG                    |
| Geological Survey of Canada                                 | Canada           | ALE, BLC, BRD, CB8, FCC, IQA |
| Centro Meteorológico Regional Pacifico                      | Chile            | IPM                    |
| Academy of Sciences                                         | China            | BMT, SSH               |
| China Earthquake Administration                              | China            | CDP, CNH, GLM, GZH, KSH, LZH |
| Instituto Geographico Agustin Codazzi                        | Columbia         | FUQ                    |
| University of Zagreb                                        | Croatia          | LON                    |
| Academy of Sciences                                         | Czech Republic   | BDV                    |
| Technical University of Denmark, DTU Space                  | Denmark          | BFE, NAQ, GDH, THL     |
| Addis Ababa University                                       | Ethiopia         | AAE                    |
| Finnish Meteorological Institute                            | Finland          | NUR                    |
| Geophysical Observatory                                     | Finland          | SOD                    |
| Institut de Physique du Globe de Paris                      | France           | AAE, BOX, CLF, DLT, KOU, IPM |
| Ecole et Observatoire des Sciences de la Terre              | France           | AMS, CZT, DMC, DRV, PAF, TAN |
| Institut de recherche pour le développement                 | France           | BNG, MBO               |
| Georgian Academy of Sciences                                | Georgia          | TFS                    |
| Universität München                                         | Germany          | FUR                    |
| Alfred-Wegener-Institute for Polar Marine Research          | Germany          | VNA                    |
| GFZ German Research Centre for Geosciences                  | Germany          | ABG, BFO, GAN, HYD, KMH, MGD, NGK, PAG |
| Universität Stuttgart and KIT                                | Germany          | BFO                    |
| Institute of Geology and Mineral Exploration                | Greece           | PEG                    |
| Academy of Sciences                                         | Hungary          | NCK                    |
| Mining and Geological Survey of Hungary                     | Hungary          | THY                    |
| University of Iceland                                       | Iceland          | LRV                    |
| Indian Institute of Geomagnetism                            | India            | ABG, JAI, NGP, PND, SIL |
| National Geophysical Research Institute                     | India            | SIR, TIR, UJJ, VSK    |
| Meteorological and Geophysical Agency                       | Indonesia        | KPG, PLR, TND, TUN    |
| Meteorological Service                                      | Ireland          | VAL                    |
| Survey of Israel                                            | Israel           | AMT, BGY, ELT         |
| Instituto Nazionale di Geofisica e Vulcanologia              | Italy            | AQU, CTS, DMC         |
| Japan Coast Guard                                           | Japan            | HTY                    |
| Japan Meteorological Agency                                 | Japan            | CBI, KAK, KNY, MMB    |
| Geographical Survey Institute                               | Japan            | ESA, KNZ, KNY          |
| Institute of the Ionosphere                                 | Kazakhstan       | AAA                    |
| Korean Meteorological Administration                         | Rep of Korea     | CYG                    |
Figure 3 presents the positions of the geomagnetic poles and dip poles as given by IGRF-13 for 1900 to 2020, and the predicted positions in 2025. The geomagnetic poles are calculated from the three dipole \((n=1)\) Gauss coefficients and correspond to where the magnetic dipole axis intersects a sphere of mean Earth radius 6371.2 km. These poles are antipodal and are also known as centered dipole poles (Laundal and Richmond 2017, Eq. 14). The geomagnetic poles can be used to specify the relative orientation of Earth’s magnetic field with respect to the Sun, and they are often used in magnetospheric studies for this purpose. The magnetic dip poles are defined as the locations where the main magnetic field as a whole is normal to Earth’s surface, represented by the WGS84 reference ellipsoid. Equivalently, they can be defined as the locations where the magnetic field component tangent to the ellipsoid vanishes. Here, we use the full set of IGRF-13 coefficients to spherical harmonic degree \(N\). Magnetic dip poles provide a key reference for local orientation when navigating on or close to Earth’s surface at high-latitudes. For a perfect dipole field, the geomagnetic and dip poles would nearly coincide, but not exactly since the geomagnetic poles are defined with respect to a sphere of mean Earth radius, while the dip poles are defined with respect to the WGS84 ellipsoid. However, as can be seen in the figure, there are significant differences between the two due to the non-dipolar structure.

### Table 3 (continued)

| Supporting agencies | Country | Observatory IAGA code |
|---------------------|---------|------------------------|
| Institut et Observatoire Géophysique d’Antananarivo | Madagascar | TAN |
| Gan Meteorological Office | Maldives | GAN |
| Direção Provincial de Recursos Minerais e Energia de Tete | Mozambique | LMM, NMP |
| Instituto de Geofísica de UNAM | Mexico | TEO |
| Institute of Geological and Nuclear Sciences | New Zealand | API, EYR, SBA |
| University of Tromsø | Norway | BJN, DOB, TRO |
| Instituto Geofisico del Peru | Peru | HUA |
| Academy of Sciences | Poland | BEL, HLP, HRN |
| Universidade de Coimbra | Portugal | COI |
| Geological Survey of Romania | Romania | SUA |
| AARI | Russia | VOS |
| GC RAS | Russia | ARS, BOX, SPG |
| IG UB RAS | Russia | ARS |
| IKIR-RAS | Russia | KHB, MGD, PET |
| IFGG SB RAS | Russia | NVS |
| ISTP SB RAS | Russia | IRT |
| SHICRA SB RAS | Russia | YAK |
| Dept. of Agriculture, Forestry, Fisheries & Meteorology | Samoa | API |
| Geomagnetic College Grocka | Serbia & Montenegro | GCK |
| Slovenska Akademia Vied | Slovakia | HRB |
| National Research Foundation | South Africa | HKB, HER, KMH, TSU |
| Observatori de l’Ebre | Spain | EBR, LIV |
| Real Instituto y Observatorio de la Armada | Spain | SFS |
| Instituto Geográfico Nacional | Spain | GUI, SPT |
| Sveriges Geologiska Undersökning | Sweden | ABK, Lyc, UPS |
| Swedish Institute of Space Physics | Sweden | KIR |
| ETH Zurich | Switzerland | GAN |
| Bõgaziçi University | Turkey | IZN |
| Academy of Sciences | Ukraine | AIA, LVV, KIV |
| British Geological Survey | United Kingdom | ASC, ESK, HAD, JCO, KEP, LER, PST, SBL |
| US Geological Survey | United States | BRW, BOU, BSL, CMO, DED, FRD, FRN, GLIA, HON, NEW, SIT, SJG, SHJ, TUC |
| Academy of Science and Technology | Vietnam | DLT, PHU |
Fig. 1  Maps of declination (top), inclination (middle) and total field (bottom) at the WGS84 ellipsoid surface for epoch 2020. The zero contour is shown in green, positive contours in red, and negative contours in blue. White asterisks indicate locations of the magnetic dip poles. Projection is Miller cylindrical
Predicted average change in Declination (D) for 2020-2025 (degrees/year)

Predicted average change in Inclination (I) for 2020-2025 (degrees/year)

Predicted average change in Total Field (F) for 2020-2025 (nT/year)

Fig. 2 Maps of predicted annual secular variation in declination (top), inclination (middle) and total field (bottom) at the WGS84 ellipsoid surface averaged over 2020 to 2025. The zero contour is shown in green, positive contours in red, and negative contours in blue. White asterisks indicate locations of the magnetic dip poles. Projection is Miller cylindrical.
of Earth’s magnetic field. The geomagnetic and dip pole locations are provided in Table 4.

Figure 4 shows the speed of the two magnetic dip poles. The north magnetic dip pole experienced a strong acceleration from about 1960 to 2000, but has seen a modest deceleration over the past 20 years, peaking at 55.8 km/year in 2002.5 and slowing slightly to 50.6 km/year in 2017.5. IGRF-13 forecasts a speed of 39.8 km/year in 2022.5, however we caution that past IGRF forecasts contained significant errors (Finlay et al. 2010b). As an example, IGRF-12 predicted a north dip pole speed of 42.6 km/year for 2017.5 (Thébault et al. 2015), compared with the IGRF-13 value of 50.6 km/year. Uncertainties present in IGRF models are further discussed by Lowes (2000).

At Earth’s surface in 2020, the contribution from the dipole terms $g_0^0$, $g_1^1$, $h_1^1$ accounts for over 93% of the power in the main geomagnetic field. It is therefore instructive to monitor the temporal change in the dipole moment, which is defined as:
Table 4 Magnetic pole position since 1900 determined from IGRF-13 in units of degrees. Latitudes are provided in the WGS84 geodetic system

| Epoch | North dip pole | South dip pole | North geomagnetic pole | South geomagnetic pole |
|-------|----------------|----------------|------------------------|------------------------|
|       | Latitude       | Longitude      | Latitude               | Longitude              |
| 1900.0| 70.46          | -96.19         | -71.72                 | 148.32                 |
| 1905.0| 70.66          | -96.48         | -71.46                 | 148.54                 |
| 1910.0| 70.79          | -96.72         | -71.15                 | 148.64                 |
| 1915.0| 71.03          | -97.03         | -70.80                 | 148.54                 |
| 1920.0| 71.34          | -97.38         | -70.41                 | 148.20                 |
| 1925.0| 71.79          | -97.99         | -69.99                 | 147.62                 |
| 1930.0| 72.27          | -98.68         | -69.52                 | 146.79                 |
| 1935.0| 72.80          | -99.33         | -69.06                 | 145.76                 |
| 1940.0| 73.30          | -99.87         | -68.57                 | 144.59                 |
| 1945.0| 73.93          | -100.24        | -68.15                 | 144.44                 |
| 1950.0| 74.64          | -100.86        | -67.89                 | 143.55                 |
| 1955.0| 75.18          | -101.42        | -67.19                 | 141.50                 |
| 1960.0| 75.30          | -101.03        | -66.70                 | 140.23                 |
| 1965.0| 75.63          | -101.34        | -66.33                 | 139.53                 |
| 1970.0| 75.88          | -100.97        | -66.02                 | 139.40                 |
| 1975.0| 76.15          | -100.64        | -65.74                 | 139.52                 |
| 1980.0| 76.91          | -101.68        | -65.42                 | 139.35                 |
| 1985.0| 77.40          | -102.61        | -65.13                 | 139.18                 |
| 1990.0| 78.10          | -103.69        | -64.91                 | 138.90                 |
| 1995.0| 79.04          | -105.29        | -64.79                 | 138.73                 |
| 2000.0| 80.97          | -109.64        | -64.66                 | 138.30                 |
| 2005.0| 83.19          | -118.22        | -64.55                 | 137.85                 |
| 2010.0| 85.02          | -132.84        | -64.43                 | 137.32                 |
| 2015.0| 86.31          | -160.34        | -64.28                 | 136.60                 |
| 2020.0| 86.49          | 162.87         | -64.08                 | 135.87                 |
| 2025.0| 85.78          | 138.06         | -63.85                 | 135.06                 |

\[ M(t) = \frac{4\pi}{\mu_0} g^3 \sqrt{g_1^0(t)^2 + g_1^1(t)^2 + h_1^1(t)^2}. \] (6)

Figure 5 presents the change in the dipole moment of the geomagnetic field since 1900 as predicted by IGRF-13 (red). We see a clear downward trend in the dipole strength since the beginning of the last century, which is continued in 2020 and also in the forecast for 2025. This steady downward trend extends back at least as far as 1600 (Merrill et al. 1996; Constable and Korte 2015), although archeomagnetic and paleomagnetic records have revealed much lower dipole moments thousands of years in the past (Panovska et al. 2019). Due to sparsity of data, archeomagnetic and paleomagnetic studies often estimate the dipole strength along the rotation axis, ignoring the off-axis terms \( g_1^1, h_1^1 \). This so-called axial dipole moment is defined as \( M_A(t) = 4\pi a^3|g_1^0(t)|/\mu_0 \) and is shown in blue in the figure.

IGRF-13 online data products

Further general information about IGRF: https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html

Coefficients of IGRF-13 in ASCII format: https://www.ngdc.noaa.gov/IAGA/vmod/coefs/igrf13coeffs.txt

Fortran software to compute magnetic field components from coefficients: https://www.ngdc.noaa.gov/IAGA/vmod/igrf13.f

Linux C software to compute magnetic field components from coefficients: https://www.ngdc.noaa.gov/IAGA/vmod/geomag70_linux.tar.gz

Windows C software to compute magnetic field components from coefficients: https://www.ngdc.noaa.gov/IAGA/vmod/geomag70_windows.zip

Python software to compute magnetic field components from coefficients: https://www.ngdc.noaa.gov/IAGA/vmod/pyIGRF.zip

Online calculation of magnetic field components for IGRF-13: https://www.ngdc.noaa.gov/geomag/calculator/magcalc.shtml and http://geomag.bgs.ac.uk/data_servi
ce/models_compass/igrf_calc.html and http://wdc.kugi.kyoto-u.ac.jp/igrf/point/index.html

Archive of previous generations of IGRF: https://www.ngdc.noaa.gov/IAGA/vmod/igrf_old_models.html

Candidate models contributing to IGRF-13 and task force evaluation reports: https://www.ngdc.noaa.gov/IAGA/vmod/IGRF13/

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Fig. 4 Average speed of the magnetic dip poles over each 5-year epoch, plotted at the midpoint between epochs (i.e., the speed over 2015–2020 is shown at 2017.5). The value for 2020–2025 is a forecast.

Fig. 5 Dipole and axial dipole moment time series derived from IGRF-13. The value for 2025 is a forecast.
Appendix 1: World data system

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TEL: +1 303 497 5480
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INTERNET: https://www.ngdc.noaa.gov

WORLD DATA CENTER FOR GEOMAGNETISM, COPENHAGEN
Technical University of Denmark, DTU Space, Centrifugevej, Building 356, DK 2800, Kgs. Lyngby, DENMARK
TEL: +45 4525 9713
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EMAIL: anna@space.dtu.dk
INTERNET: http://www.space.dtu.dk/English/Research/Scientific_data_and_models

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EMAIL: wdcgeomag@bgs.ac.uk
INTERNET: http://www.wdc.bgs.ac.uk

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