The International Geomagnetic Reference Field (IGRF) and its use in prediction

Chris Finlay

National Space Institute, Technical University of Denmark

Acknowledgement: IGRF-11 task force, esp. Nils Olsen and Ciaran Beggan.

Univ. of Leeds, 13th June, 2012

Talk Outline

1. The International Geomagnetic Reference Field
2. Data Sources
3. Results from IGRF-11: Internal Field 2010-2015
4. Prediction Problems
5. Outlook

Talk Outline

1. The International Geomagnetic Reference Field
2. Data Sources
3. Results from IGRF-11: Internal Field 2010-2015
4. Prediction Problems
5. Outlook

1.1 What is the IGRF?

1.1 What is the IGRF?

- The International Geomagnetic Reference Field (IGRF) is an **observation-based, global model of Earth's large scale internal magnetic field**.

1.1 What is the IGRF?

- The International Geomagnetic Reference Field (IGRF) is an **observation-based, global model of Earth's large scale internal magnetic field**.
- Revised every 5 years by an IAGA task force.

1.1 What is the IGRF?

- The International Geomagnetic Reference Field (IGRF) is an **observation-based, global model of Earth's large scale internal magnetic field**.
- Revised every 5 years by an IAGA task force.
- Includes a description of both the present field and an estimate of the linear secular variation (rate of change) **for the upcoming 5 years.**

1.1 What is the IGRF?

- The International Geomagnetic Reference Field (IGRF) is an **observation-based, global model of Earth's large scale internal magnetic field**.
- Revised every 5 years by an IAGA task force.
- Includes a description of both the present field and an estimate of the linear secular variation (rate of change) **for the upcoming 5 years.**
- **Goal:** To provide a reliable, stable, reference field agreed apon by geomagnetic modellers for the use of wider community.

1.2 Who uses the IGRF?

1.2 Who uses the IGRF?

- Scientists

1.2 Who uses the IGRF?

- Scientists
  - Crustal studies e.g. Subtracted to obtain magnetic anomalies.

1.2 Who uses the IGRF?

- Scientists
  - Crustal studies e.g. Subtracted to obtain magnetic anomalies.
  - Space Physics:
    - Co-ordinate systems e.g. CGM, QD, GSM
    - Models e.g. Tsyganenko, Open-GGCM etc.
    - Interpretations e.g. Ion drift, scintillation

1.2 Who uses the IGRF?

- Scientists
  - Crustal studies e.g. Subtracted to obtain magnetic anomalies.
  - Space Physics:
    - Co-ordinate systems e.g. CGM, QD, GSM
    - Models e.g. Tsyganenko, Open-GGCM etc.
    - Interpretations e.g. Ion drift, scintillation
  - Biologists e.g. Studying animal migration

1.2 Who uses the IGRF?

- Scientists
  - Crustal studies e.g. Subtracted to obtain magnetic anomalies.
  - Space Physics:
    - Co-ordinate systems e.g. CGM, QD, GSM
    - Models e.g. Tsyganenko, Open-GGCM etc.
    - Interpretations e.g. Ion drift, scintillation
  - Biologists e.g. Studying animal migration
- Engineers/Industry
  - Geophysical Exploration
  - Directional Drilling
  - Aviation
  - Handheld devices

1.2 Who uses the IGRF?

- Scientists
  - Crustal studies e.g. Subtracted to obtain magnetic anomalies.
  - Space Physics:
    - Co-ordinate systems e.g. CGM, QD, GSM
    - Models e.g. Tsyganenko, Open-GGCM etc.
    - Interpretations e.g. Ion drift, scintillation
  - Biologists e.g. Studying animal migration
- Engineers/Industry
  - Geophysical Exploration
  - Directional Drilling
  - Aviation
  - Handheld devices
- Private individuals
  - esp. navigation/directional
  - $\sim$ 2 million queries per year at NGDC online declination calculators.

Example: study of GPS scintillation

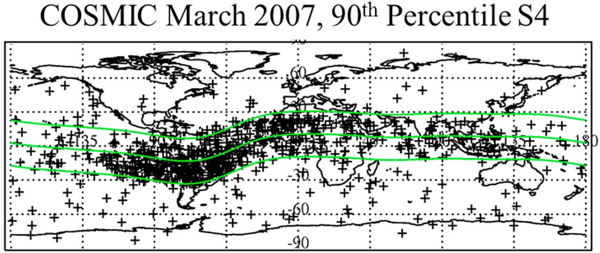


Fig 1.1: Map of maximum S4 scintillation index from March 2007, 18-06 LT, 150-500km (F region), altitude from the COSMIC satellite constellation; 1 Hz, L band GPS (radio wave) data. From Dymond et al. (2012).

- Field geometry (e.g. IGRF) affects the frequency of observation of scintillations, indicative of plasma bubbles in the ionosphere.

1.3 Form of the IGRF model

- IGRF represents the geomagnetic field **B** produced by internal sources in a source free region where $\mathbf{B} = -\nabla V$ and

$$V(r,\theta,\phi,t) = a\sum_{n=1}^{N}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n+1}\left[g_n^m(t)\cos m\phi + h_n^m(t)\sin m\phi\right]P_n^m(\cos\theta). \quad (1)$$

- Gauss coefficients g_n^m and h_n^m are provided for the main field at epochs separated by 5 year intervals between 1900.0 and 2010.0.
- Predicted (linear) time-dependence in upcoming five years:

$$g_n^m(t) = g_n^m(T_0) + \dot{g}_n^m(T_0)(t - T_0), \quad (2)$$

  for a reference epoch T_0 and $\dot{g}_n^m$ the linear rate of change of g_n^m.
- g_n^m and $\dot{g}_n^m$ are determined by fitting to geomagnetic observations.

1.4 Latest IGRF update in 2010

- 8 institutions submitted candidate models for latest IGRF-11 revision:
  - NGDC/NOAA USA (Led by S. Maus)
  - IPGP, France (Led by E. Thébault)
  - DTU Space, Denmark (Led by N. Olsen)
  - GFZ, Germany, (Led by V. Lesur)
  - IZMIRAN, Russia, (Led by T. Bondar)
  - EOST, France, (Led by A. Chambodut)
  - BGS, U.K., (Led by B. Hamilton)
  - NASA, GSFC, USA, (Led by W. Kuang)

- Candidate models were assessed by task force and weighted to obtain final model (see Finlay et al., 2010 in EPS special issue).

Talk Outline

1. The International Geomagnetic Reference Field
2. **Data Sources**
3. Results from IGRF-11: Internal Field 2010-2015
4. Prediction Problems
5. Outlook

2.1 Data sources: Observatories

- High quality, long-term observations from worldwide network.

Fig 2.1: Magnetic observatories in San Juan, Puerto Rico (left) and Godhavn, Greenland (right).

2.2 Observatory coverage

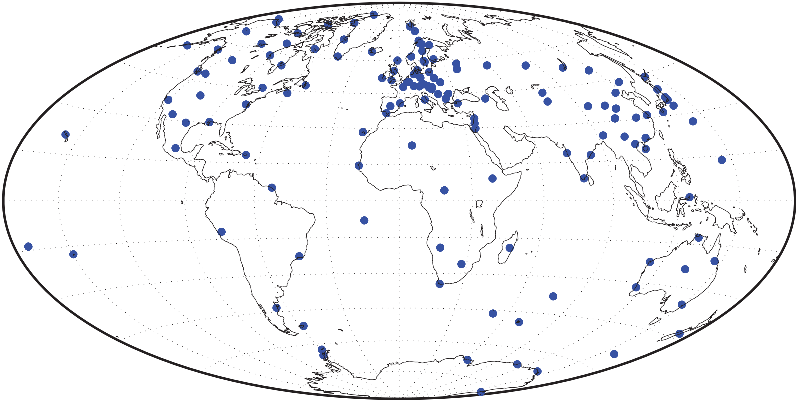


Fig 2.2: Locations of observatories used in determination of recent internal field models.

2.3 Data sources: Satellites

- Low Earth Orbit Satellites: short term but excellent global coverage.

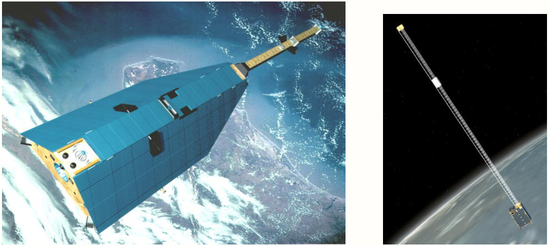
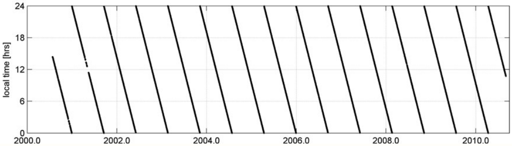
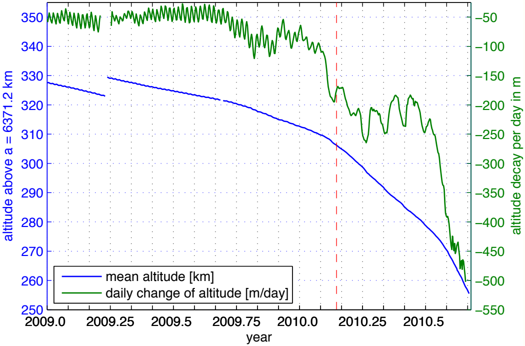


Fig 2.3: Satellites CHAMP (left) and Ørsted (right).

2.4 Data sources: CHAMP Orbit





Local time evolution of the ascending node of the CHAMP orbit (top) and decay of CHAMP orbital altitude (bottom). Courtesy of Nils Olsen.

Talk Outline

3.1 IGRF-11 Declination for Epoch 2010

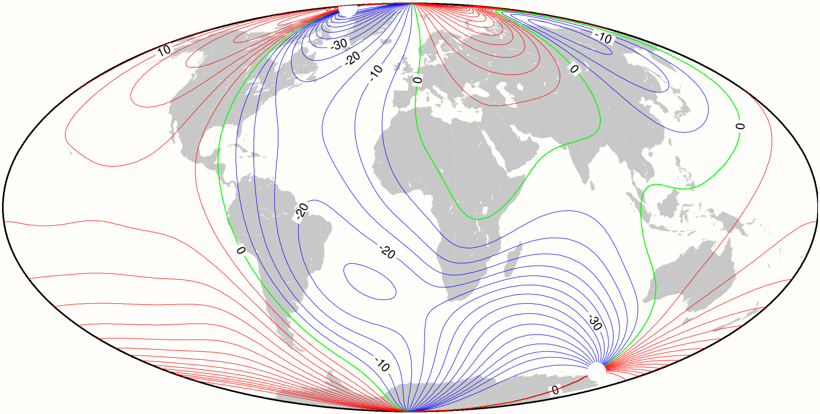


Fig 3.1: Declination D at Earth's surface in 2010.0 : units degrees.

3.2 IGRF-11 Inclination for Epoch 2010

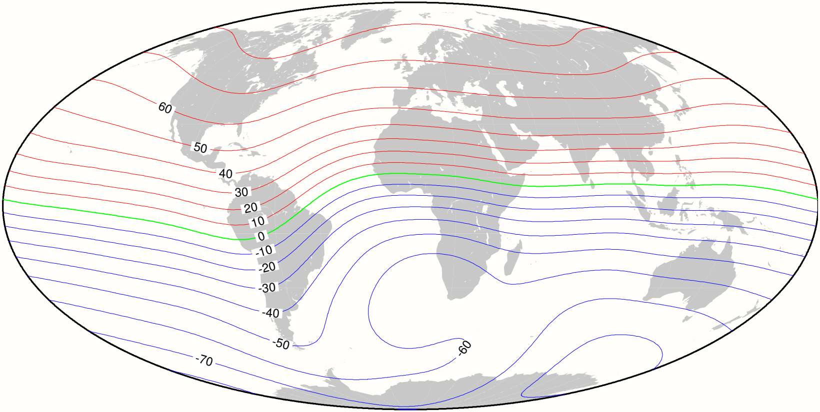


Fig 3.2: Inclination *I* at Earth's surface in 2010.0 : units degrees.

3.3 IGRF-11 Intensity for Epoch 2010

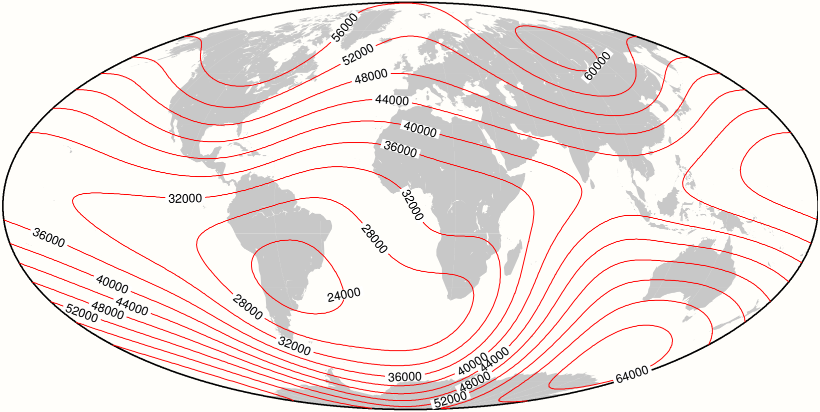


Fig 3.3: Field intensity F at Earth's surface in 2010.0 : units nanoTesla.

3.4 Evolution of South Atlantic Anomaly

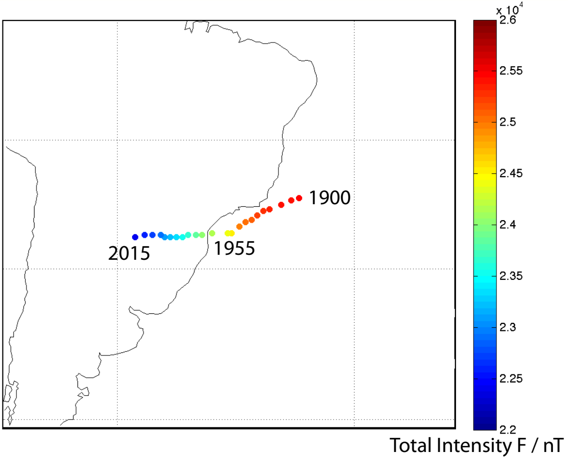


Fig 3.4: Location of the point of lowest field magnitude with time; the colour scale indicates the magnitude of F, with blue representing smallest F, units are nT.

- South Atlantic anomaly is continuing to deepen and move westward (Talk of V. Lesur).

Talk Outline

1. The International Geomagnetic Reference Field
2. Data Sources
3. Results from IGRF-11: Internal Field 2010-2015
4. **Prediction Problems**
5. Outlook

4.1 Prediction problems

- For 5 years after an IGRF update, predictions for the expected field change are used to obtain the desired field configuration.

4.1 Prediction problems

- For 5 years after an IGRF update, predictions for the expected field change are used to obtain the desired field configuration.
- Changes per year are rather small (typically less than 0.2 % per year in F).

4.1 Prediction problems

- For 5 years after an IGRF update, predictions for the expected field change are used to obtain the desired field configuration.
- Changes per year are rather small (typically less than 0.2 % per year in F).
- But methods of prediction are known to be poor and lead to a cumulative error after 5 years of $\sim$ 100nT.

4.1 Prediction problems

- For 5 years after an IGRF update, predictions for the expected field change are used to obtain the desired field configuration.
- Changes per year are rather small (typically less than 0.2 % per year in F).
- But methods of prediction are known to be poor and lead to a cumulative error after 5 years of $\sim$ 100nT.
- Mostly based on linear or quadratic extrapolation of change inferred at time of analysis or from the preceeding few years.

4.2 IGRF-11 Inclination Change 2010-2015

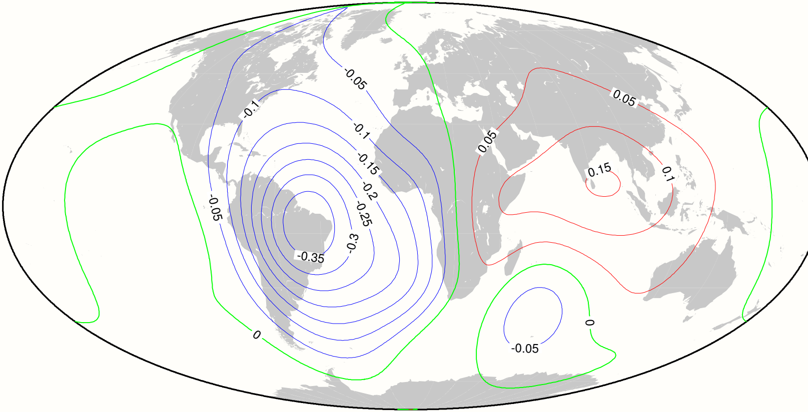


Fig 5.1: Predicted annual change in *I* at Earth's surface between 2010.0 and 2015.0 : units degrees/yr.

4.3 IGRF-11 Intensity Change 2010-2015

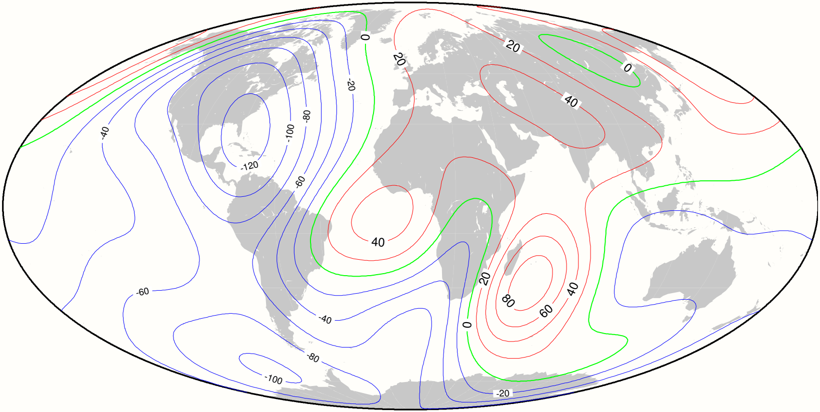


Fig 5.2: Predicted annual change in F at Earth's surface between 2010.0 and 2015.0 : units nT/yr.

Comparison of IGRF SV predictions with Obs. data

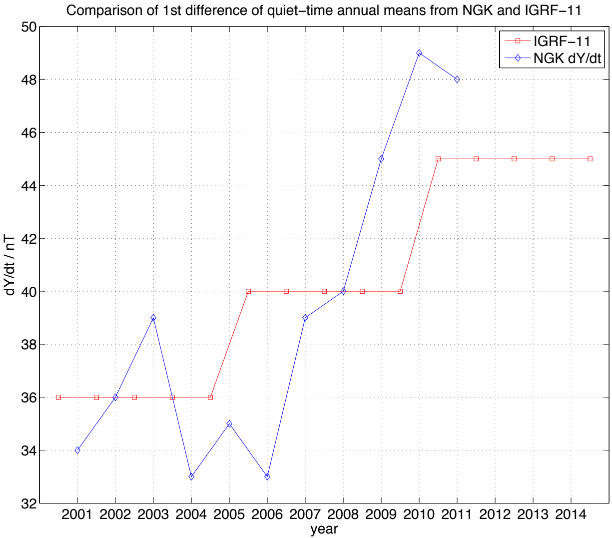


Fig 5.3: Comparison of IGRF-11 SV predictions with 1st differences of quiet time annual means.

Talk Outline

1. The International Geomagnetic Reference Field
2. Data Sources
3. Results from IGRF-11: Internal Field 2010-2015
4. Prediction Problems
5. **Outlook**

5.1 Outlook

5.1 Outlook

- IGRF predictions designed only for up to 5 years ahead.

5.1 Outlook

- IGRF predictions designed only for up to 5 years ahead.
- For space climate predictions on longer decadal time scales should concentrate on impact of major core processes (esp. westward drift, dipole decay) on largest scale field (degrees 1 and 2).

5.1 Outlook

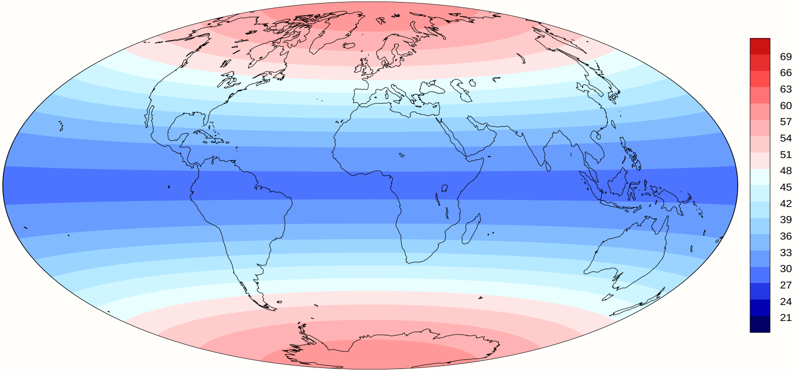
- IGRF predictions designed only for up to 5 years ahead.
- For space climate predictions on longer decadal time scales should concentrate on impact of major core processes (esp. westward drift, dipole decay) on largest scale field (degrees 1 and 2).
- Predictions based on geodynamo simulations (Kuang et al., 2010) and empirical core flows (Beggan and Whaler, 2010) beginning to be used but not yet an obvious an improvement (Talk of C. Beggan).

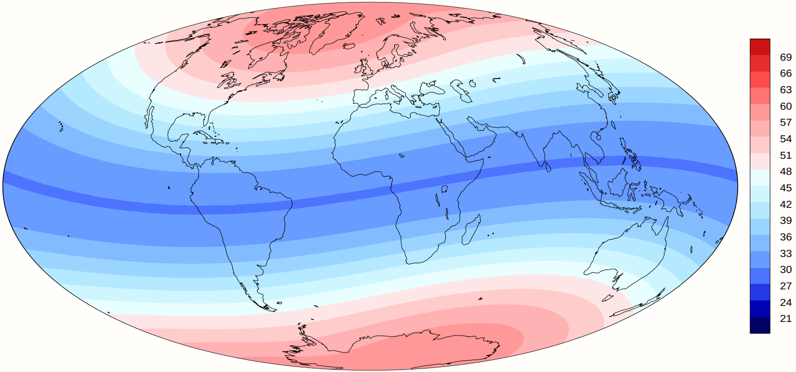
5.1 Outlook

- IGRF predictions designed only for up to 5 years ahead.
- For space climate predictions on longer decadal time scales should concentrate on impact of major core processes (esp. westward drift, dipole decay) on largest scale field (degrees 1 and 2).
- Predictions based on geodynamo simulations (Kuang et al., 2010) and empirical core flows (Beggan and Whaler, 2010) beginning to be used but not yet an obvious an improvement (Talk of C. Beggan).
- More appropriate prognostic physics and better accounting for observational uncertainties via data assimilation should help.

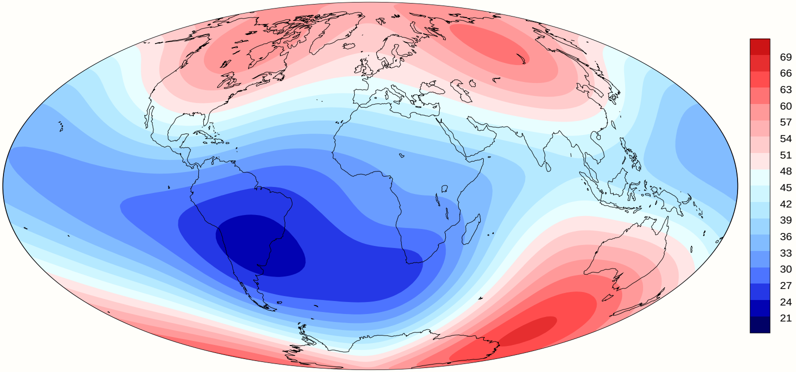
5.1 Outlook

- IGRF predictions designed only for up to 5 years ahead.
- For space climate predictions on longer decadal time scales should concentrate on impact of major core processes (esp. westward drift, dipole decay) on largest scale field (degrees 1 and 2).
- Predictions based on geodynamo simulations (Kuang et al., 2010) and empirical core flows (Beggan and Whaler, 2010) beginning to be used but not yet an obvious an improvement (Talk of C. Beggan).
- More appropriate prognostic physics and better accounting for observational uncertainties via data assimilation should help.
- IGRF can be a useful framework for testing new prediction techniques and driving improvements.

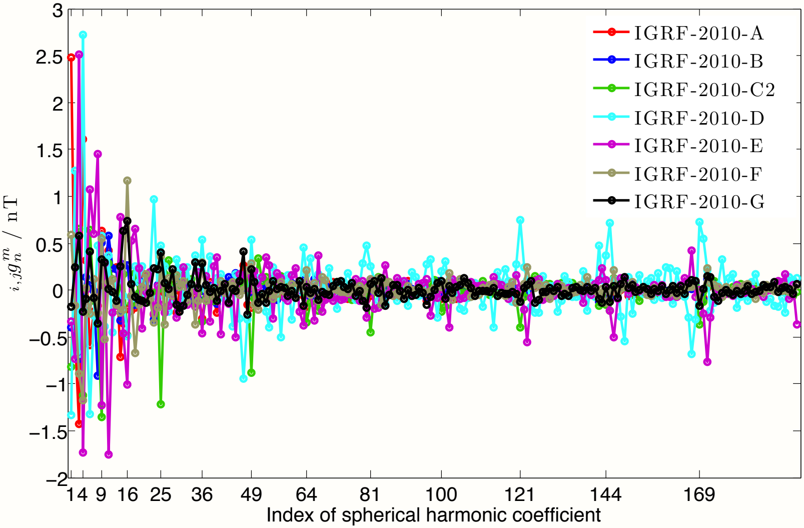

69
66
63
60
57
54
51
48
45
42
39
36
33
30
27
24
21



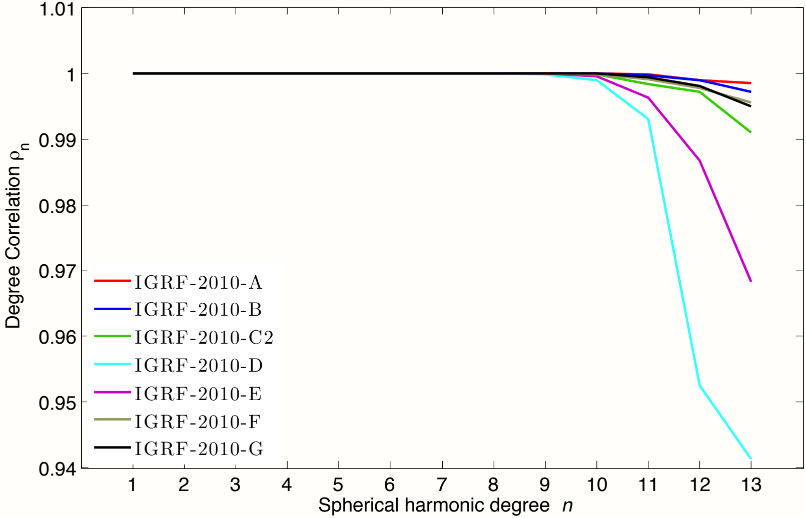
Univ. of Leeds, 2012



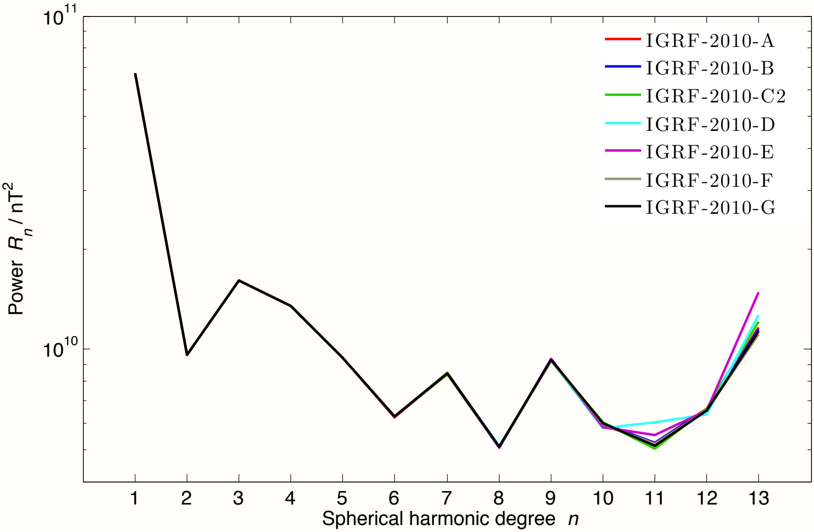
Univ. of Leeds, 2012



IGRF-2010-A
IGRF-2010-B
IGRF-2010-C2
IGRF-2010-D
IGRF-2010-E
IGRF-2010-F
IGRF-2010-G
$_{i,j}g_n^m$ / nT
Index of spherical harmonic coefficient
3
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
1 4 9 16 25 36 49 64 81 100 121 144 169

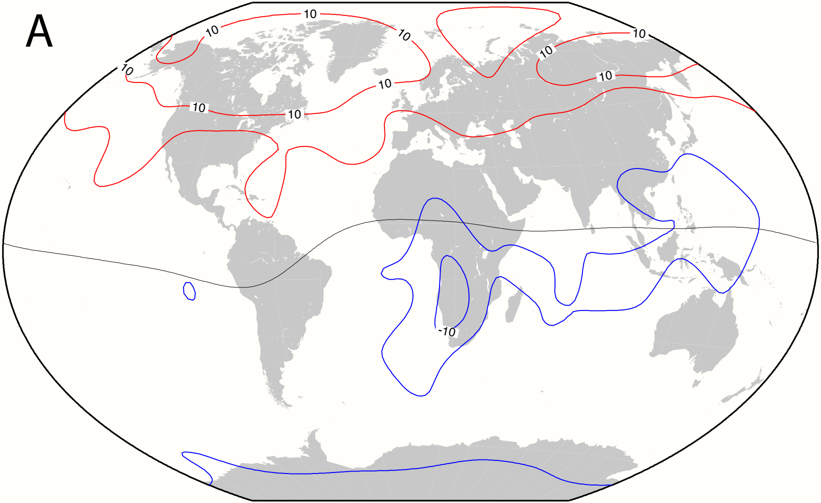


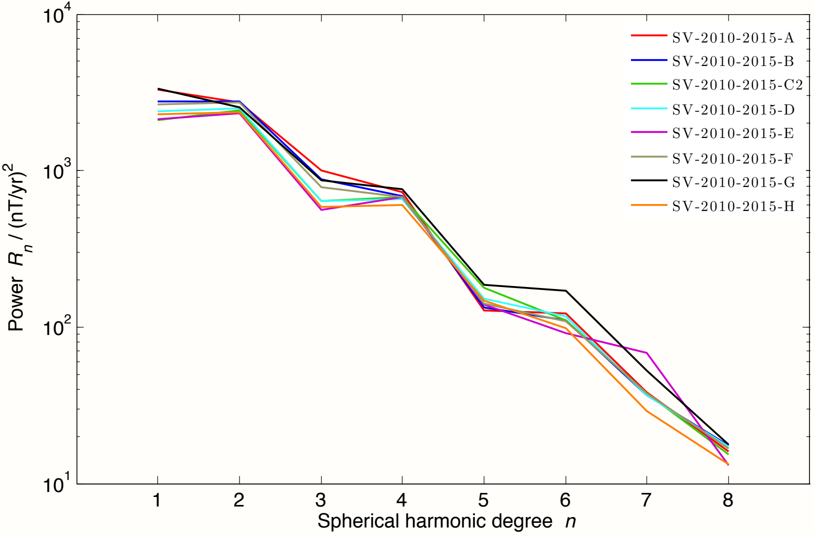
1.01
1
0.99
0.98
0.97
0.96
0.95
0.94
Degree Correlation ρ_n
1 2 3 4 5 6 7 8 9 10 11 12 13
Spherical harmonic degree n
IGRF-2010-A
IGRF-2010-B
IGRF-2010-C2
IGRF-2010-D
IGRF-2010-E
IGRF-2010-F
IGRF-2010-G

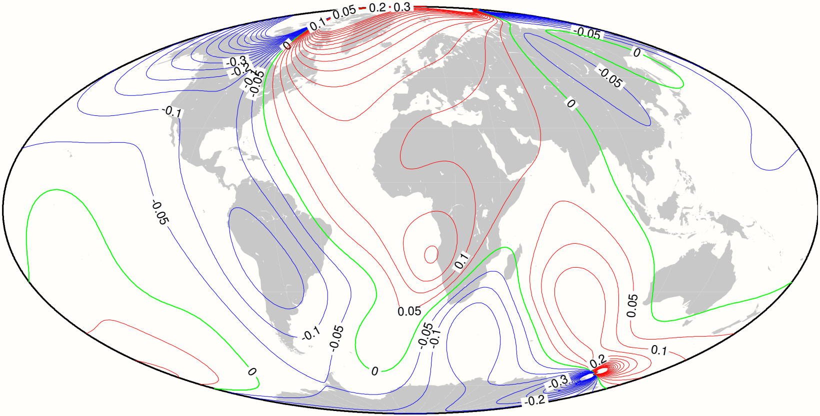


10^{11}
10^{10}
Power R_n / nT^2
1
2
3
4
5
6
7
8
9
10
11
12
13
Spherical harmonic degree n
IGRF-2010-A
IGRF-2010-B
IGRF-2010-C2
IGRF-2010-D
IGRF-2010-E
IGRF-2010-F
IGRF-2010-G

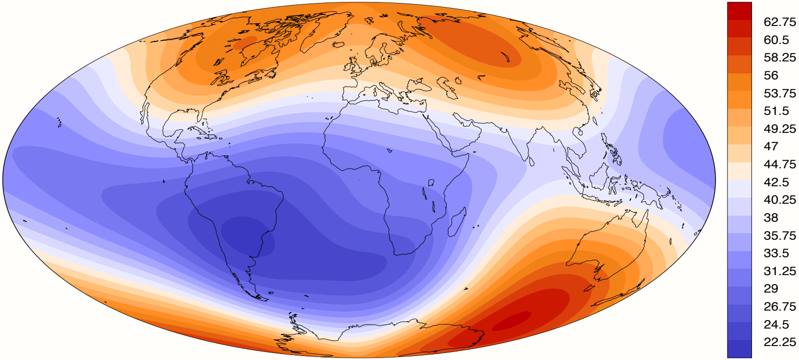
A




SV-2010-2015-A
SV-2010-2015-B
SV-2010-2015-C2
SV-2010-2015-D
SV-2010-2015-E
SV-2010-2015-F
SV-2010-2015-G
SV-2010-2015-H
Power R_n / (nT/yr)^2
Spherical harmonic degree n
10^1
10^2
10^3
10^4
1
2
3
4
5
6
7
8



Predicted annual change in D at Earth's surface between 2010.0 and 2015.0 : units degrees/yr.


62.75
60.5
58.25
56
53.75
51.5
49.25
47
44.75
42.5
40.25
38
35.75
33.5
31.25
29
26.75
24.5
22.25