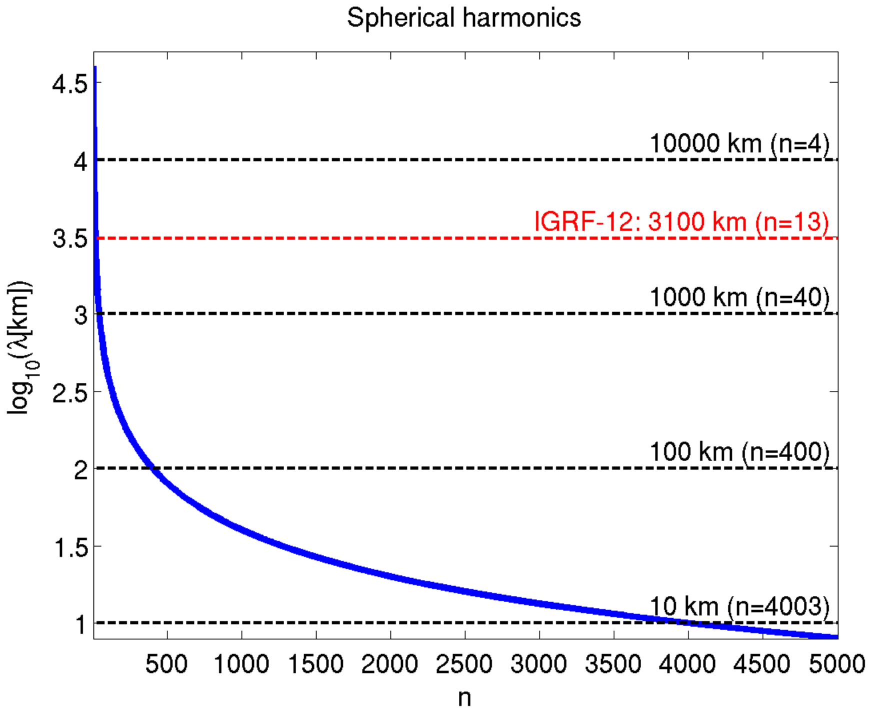
Chapter 6
Local and regional magnetic field measurements and models

Previously

- For the global spherical harmonic expansion model of the Earth's magnetic field (e.g., IGRF), the maximum degree is typically n = 13, which corresponds to a wavelength of λ = 3100 km.
- 3100 km is too coarse for regional representations of the magnetic field, which require λ = 10 – 100 km

  → the spherical harmonic expansion would have to have a degree n = 400 – 4000

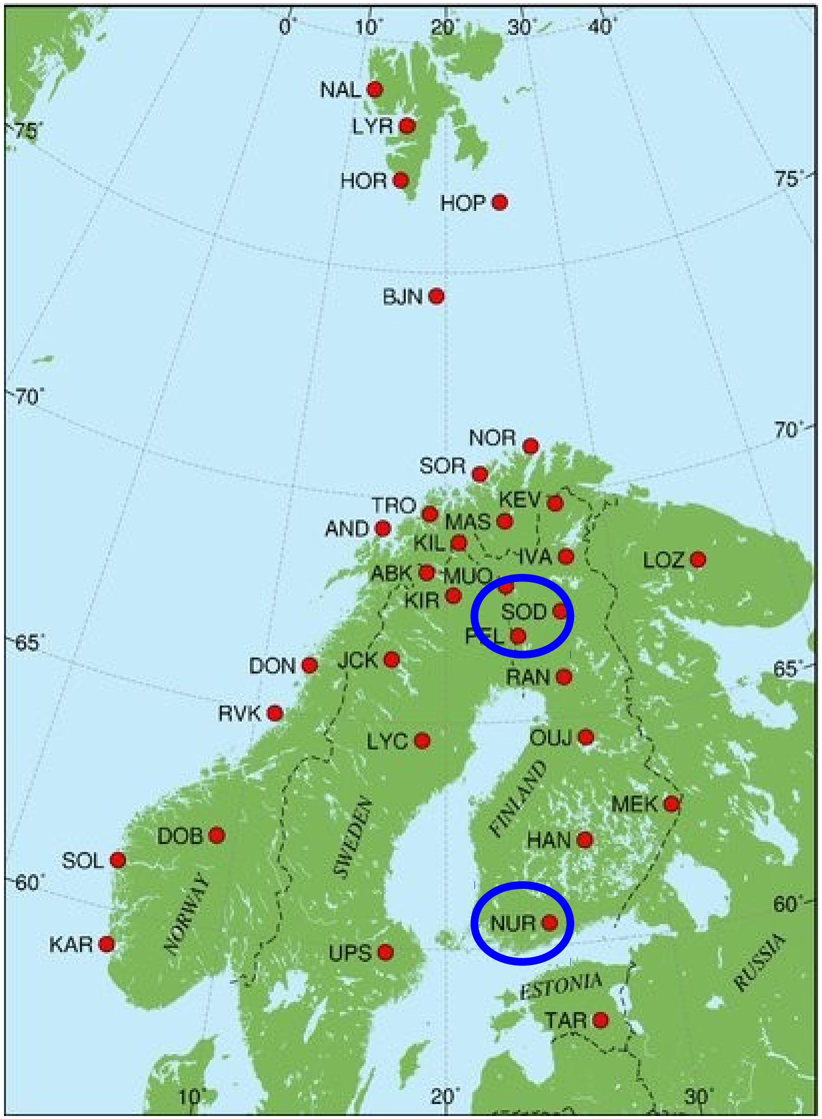
  → not an ideal approach.



Content

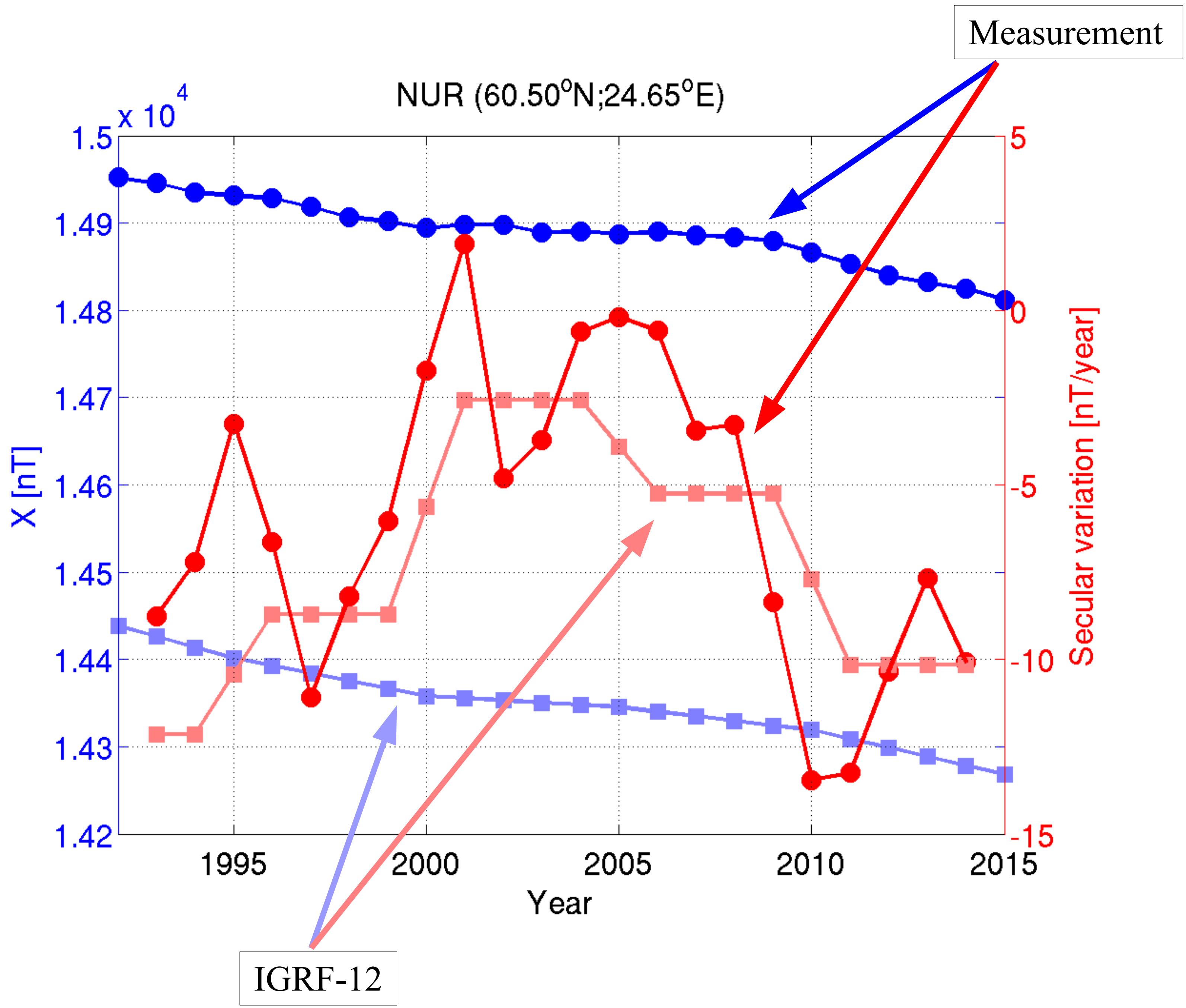
- Examples of local magnetic field measurements in Finland and comparison with IGRF
- Regional modeling of the magnetic field
- Magnetic maps of Finland

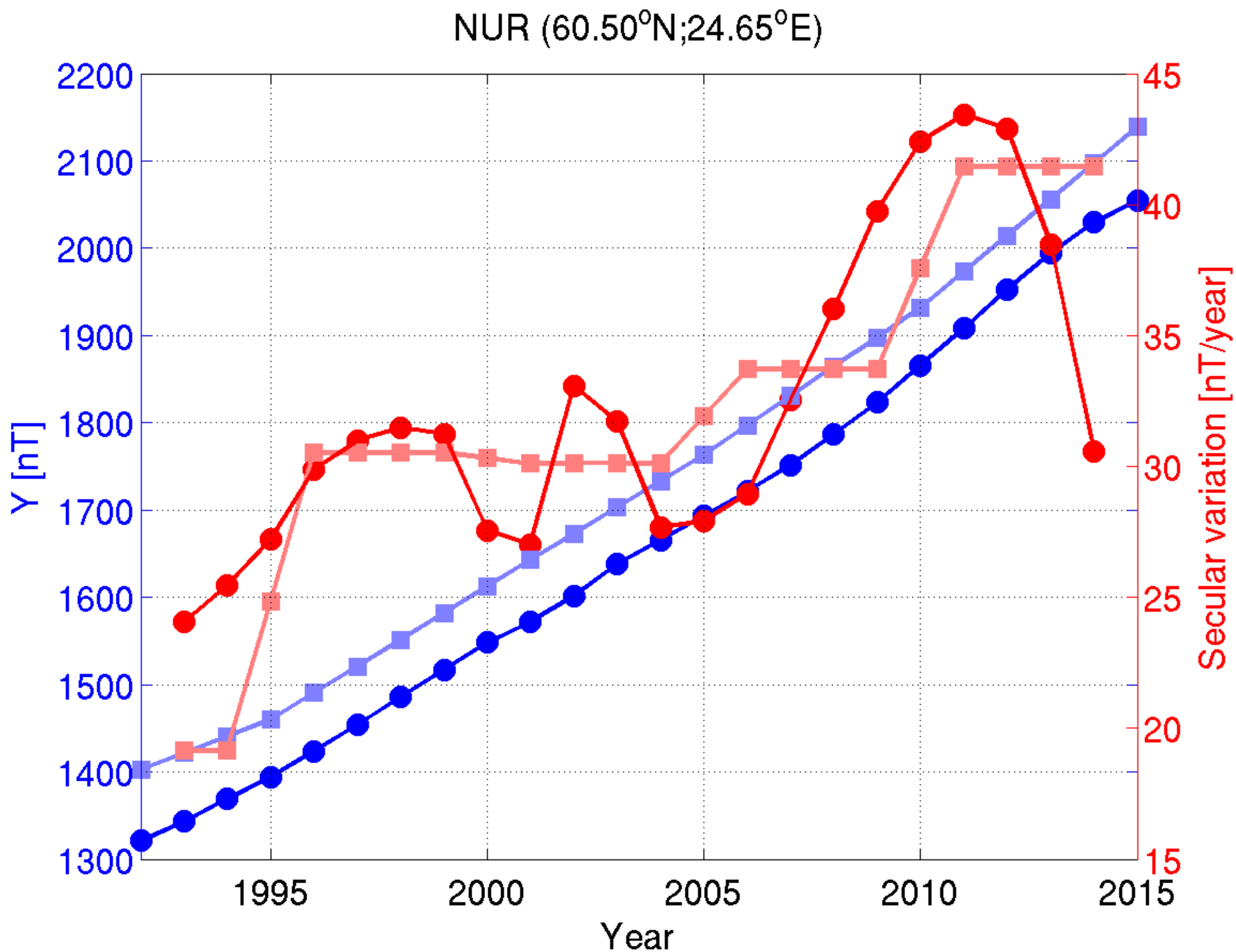
Geophysical observatories in Finland



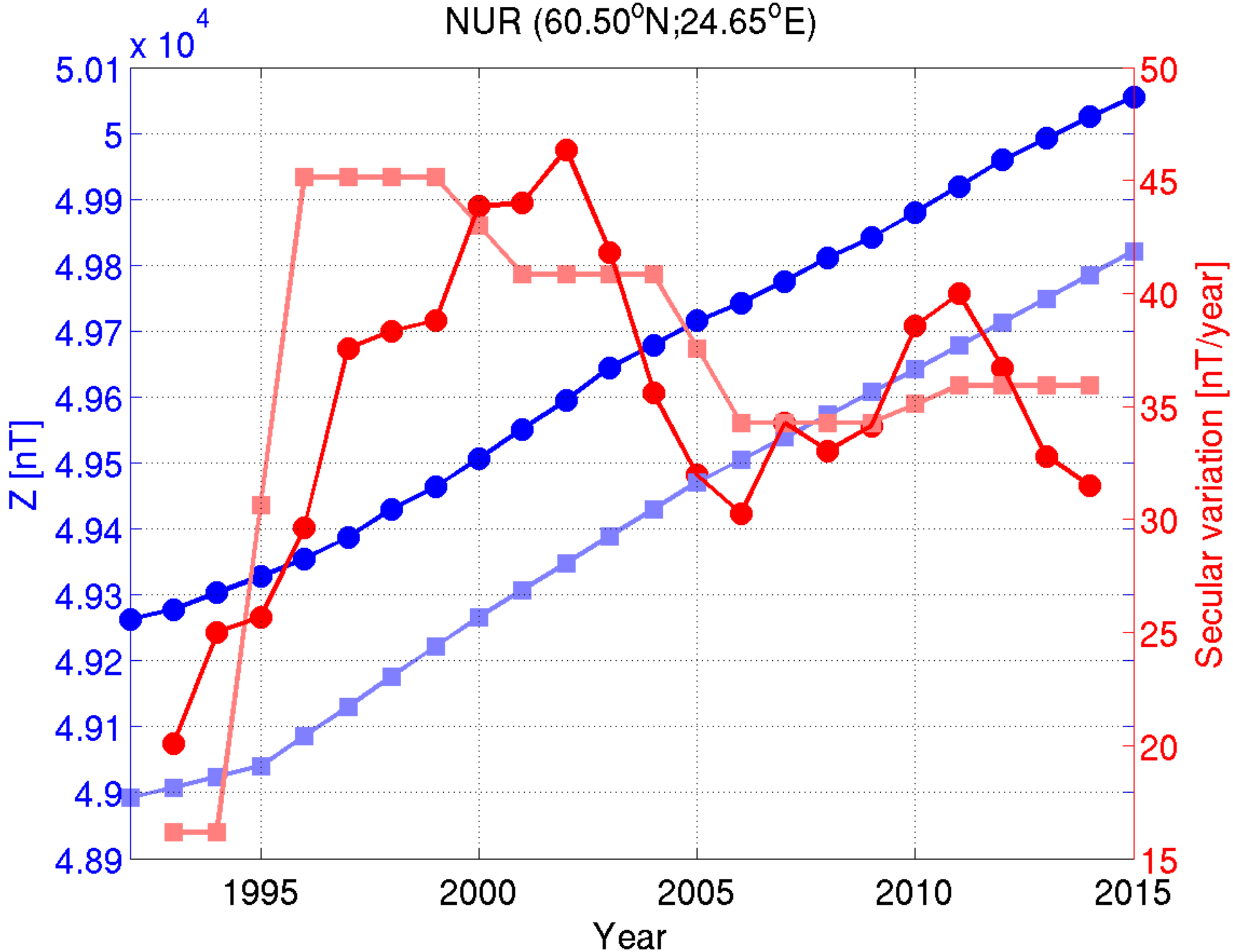
Nurmijärvi (NUR):
60.50ºN;24.65ºE

Sodankylä (SOD):
67.37ºN;26.63ºE

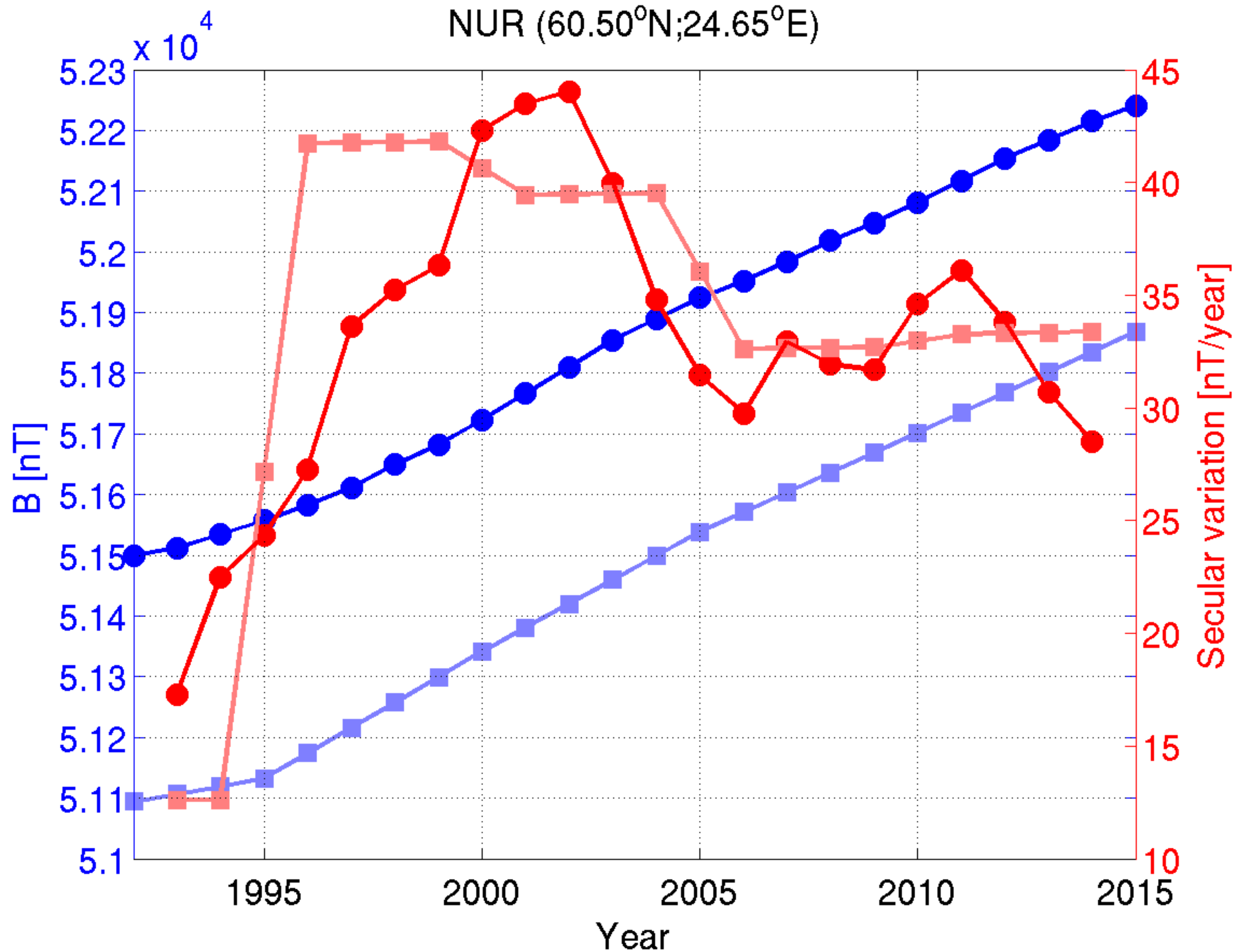

NUR (60.50°N;24.65°E)
x 10^4
X [nT]
Secular variation [nT/year]
Year
1.5
1.49
1.48
1.47
1.46
1.45
1.44
1.43
1.42
5
0
-5
-10
-15
1995
2000
2005
2010
2015
Measurement
IGRF-12



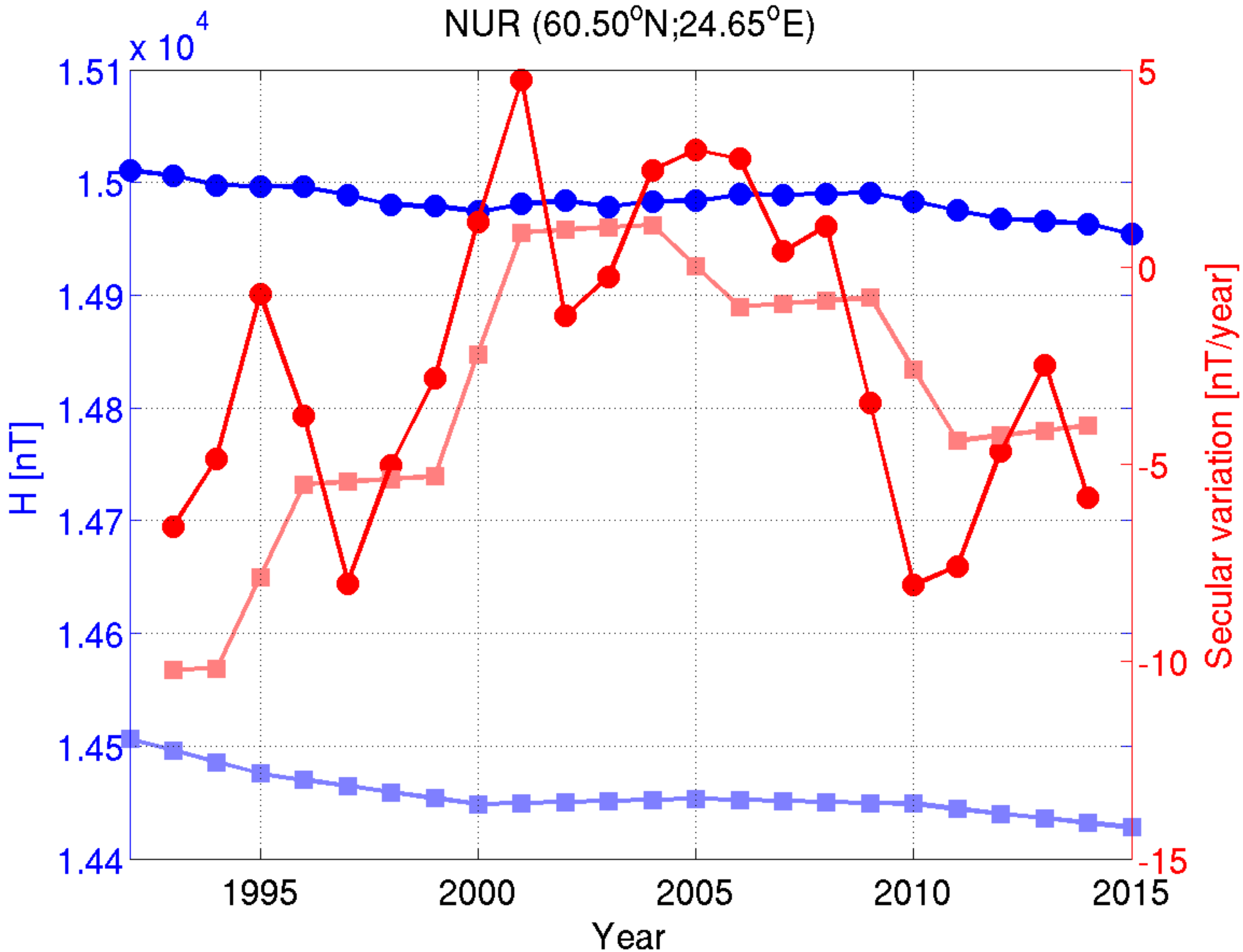
NUR (60.50°N;24.65°E)
Y [nT]
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
Secular variation [nT/year]
45
40
35
30
25
20
15
1995
2000
2005
2010
2015
Year



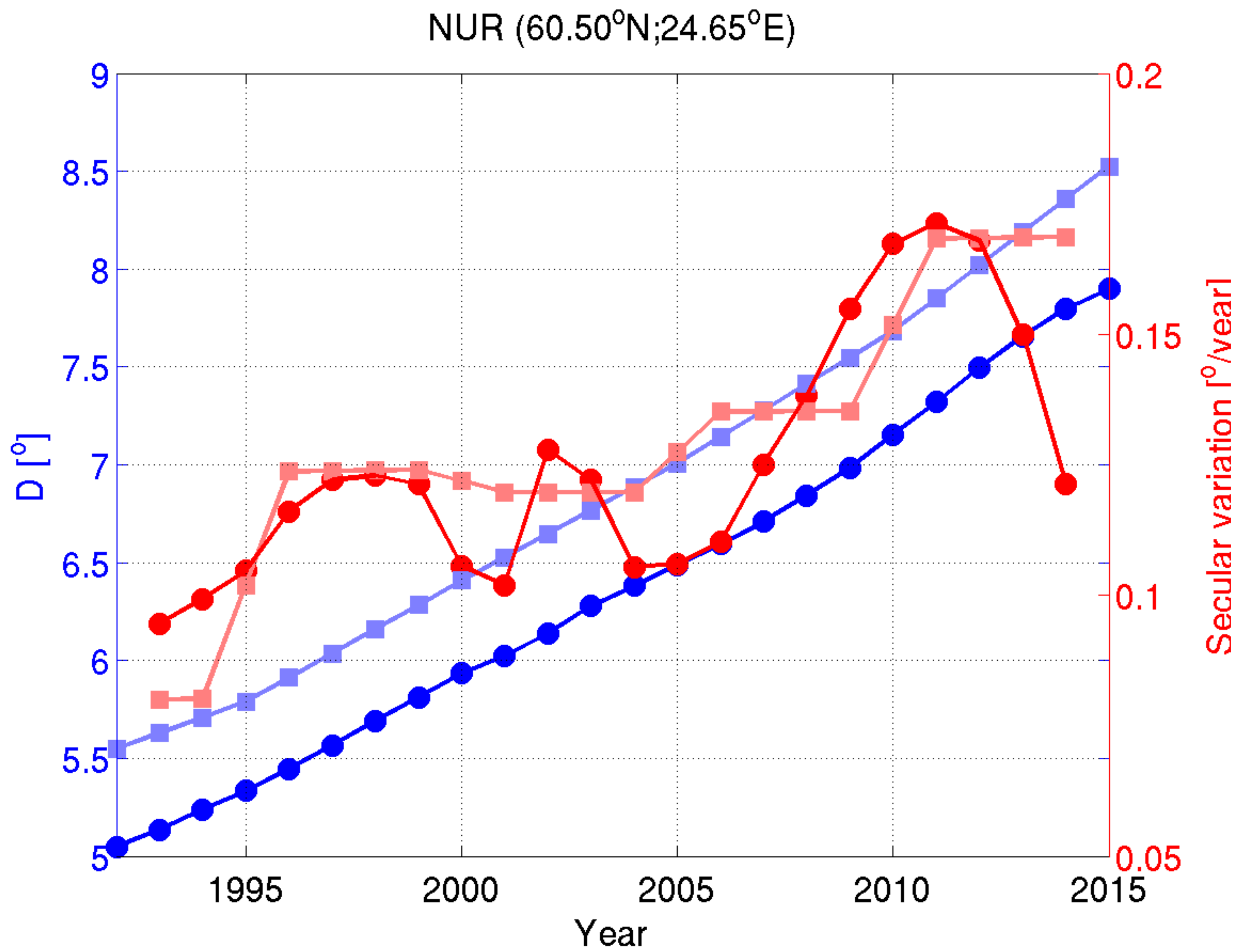
NUR (60.50°N;24.65°E)
x 10^4
5.01
5
4.99
4.98
4.97
4.96
4.95
4.94
4.93
4.92
4.91
4.9
4.89
Z [nT]
50
45
40
35
30
25
20
15
Secular variation [nT/year]
1995
2000
2005
2010
2015
Year

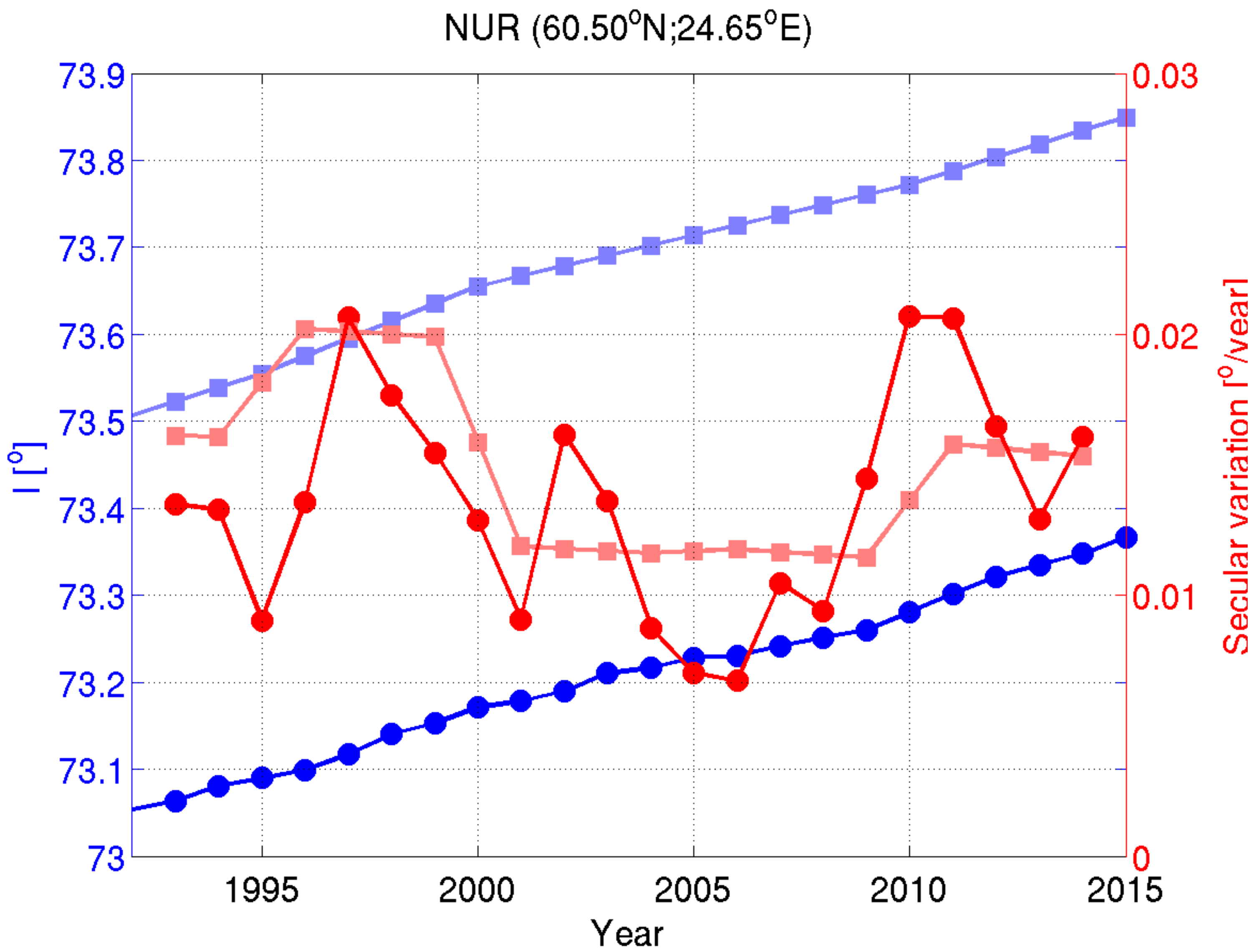


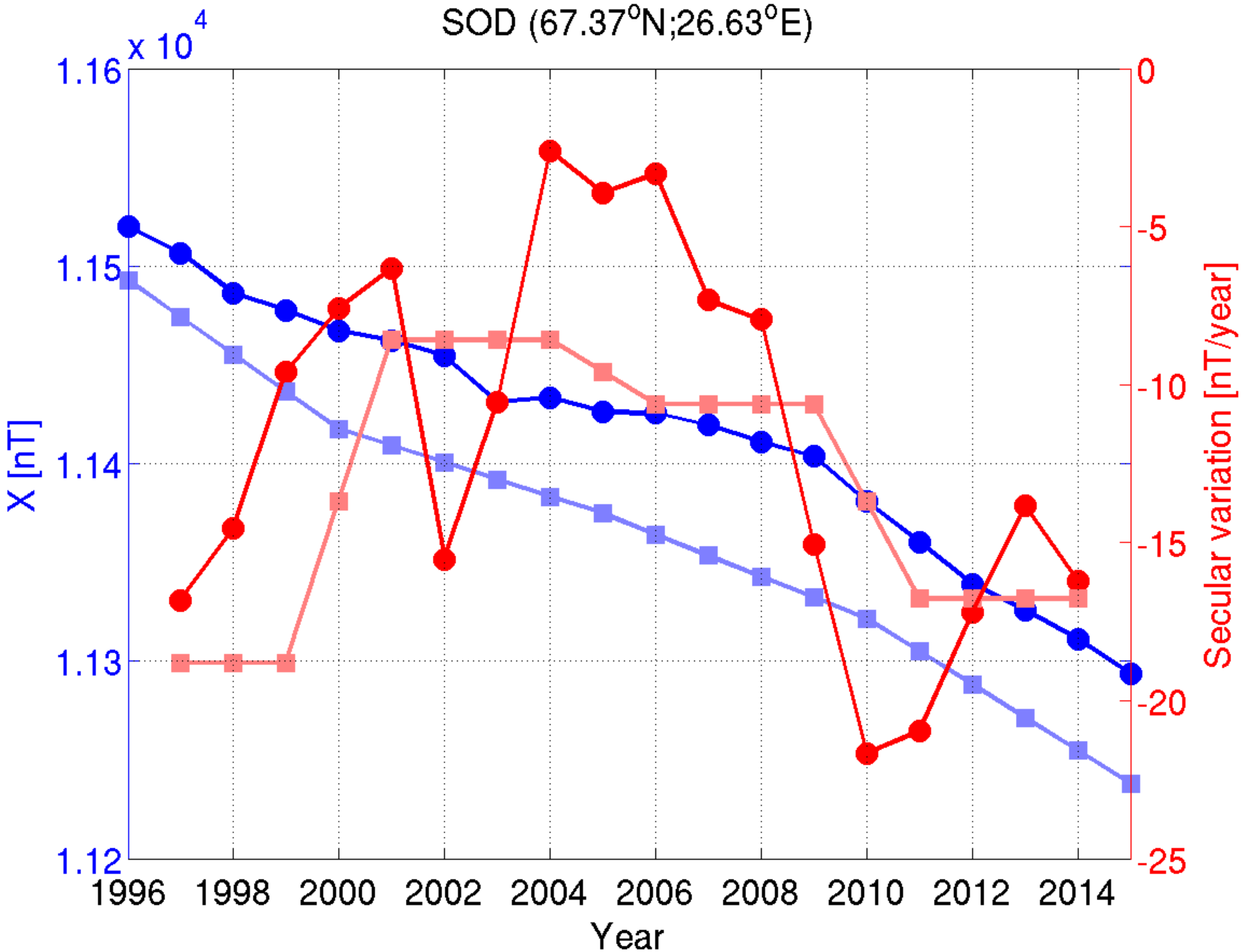
Although globally the magnetic field weakens, in Nurmijärvi (and Finland in general) it strengthens.

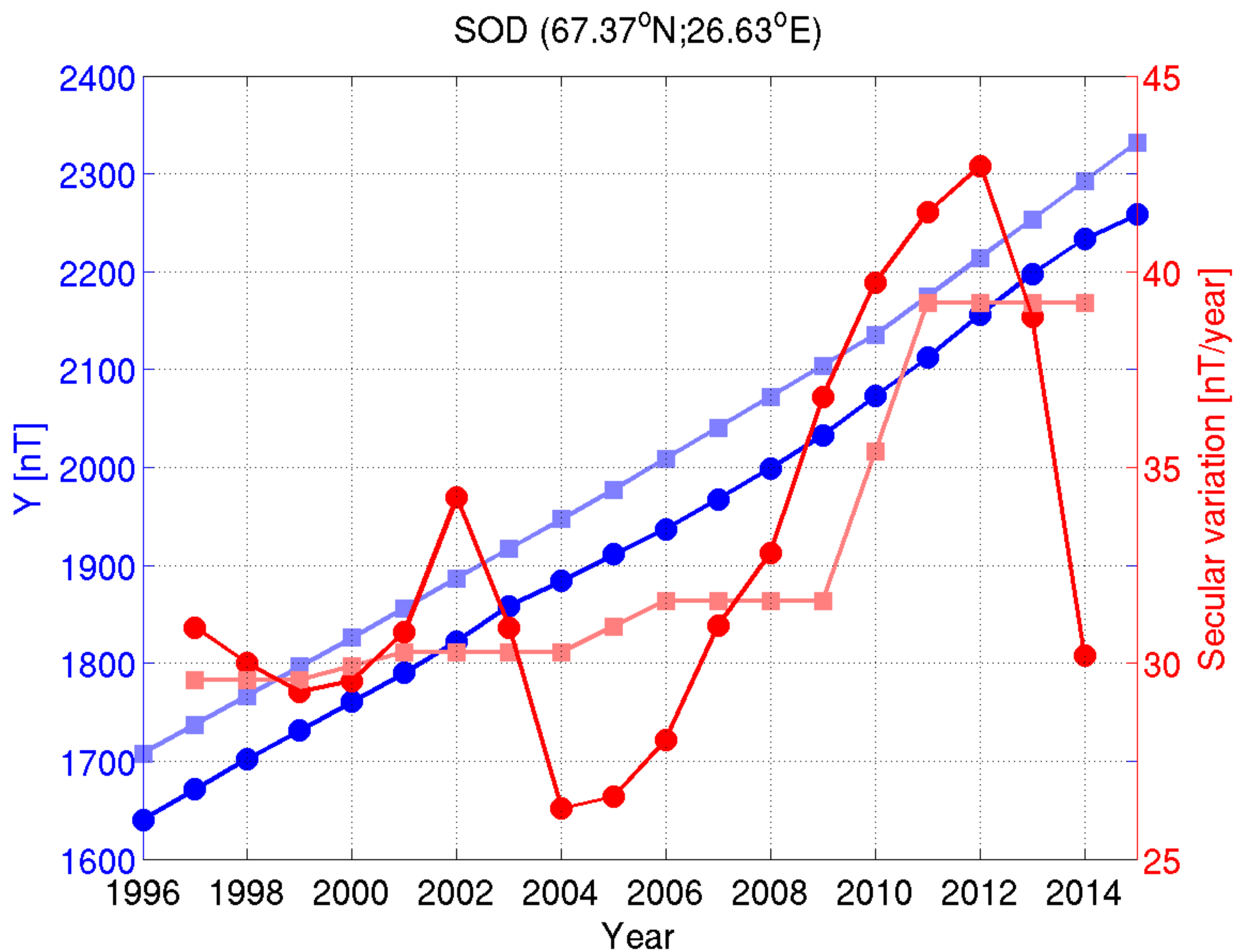


NUR (60.50°N;24.65°E)
x 10^4
1.51
1.5
1.49
1.48
1.47
1.46
1.45
1.44
H [nT]
1995
2000
2005
2010
2015
Year
5
0
-5
-10
-15
Secular variation [nT/year]

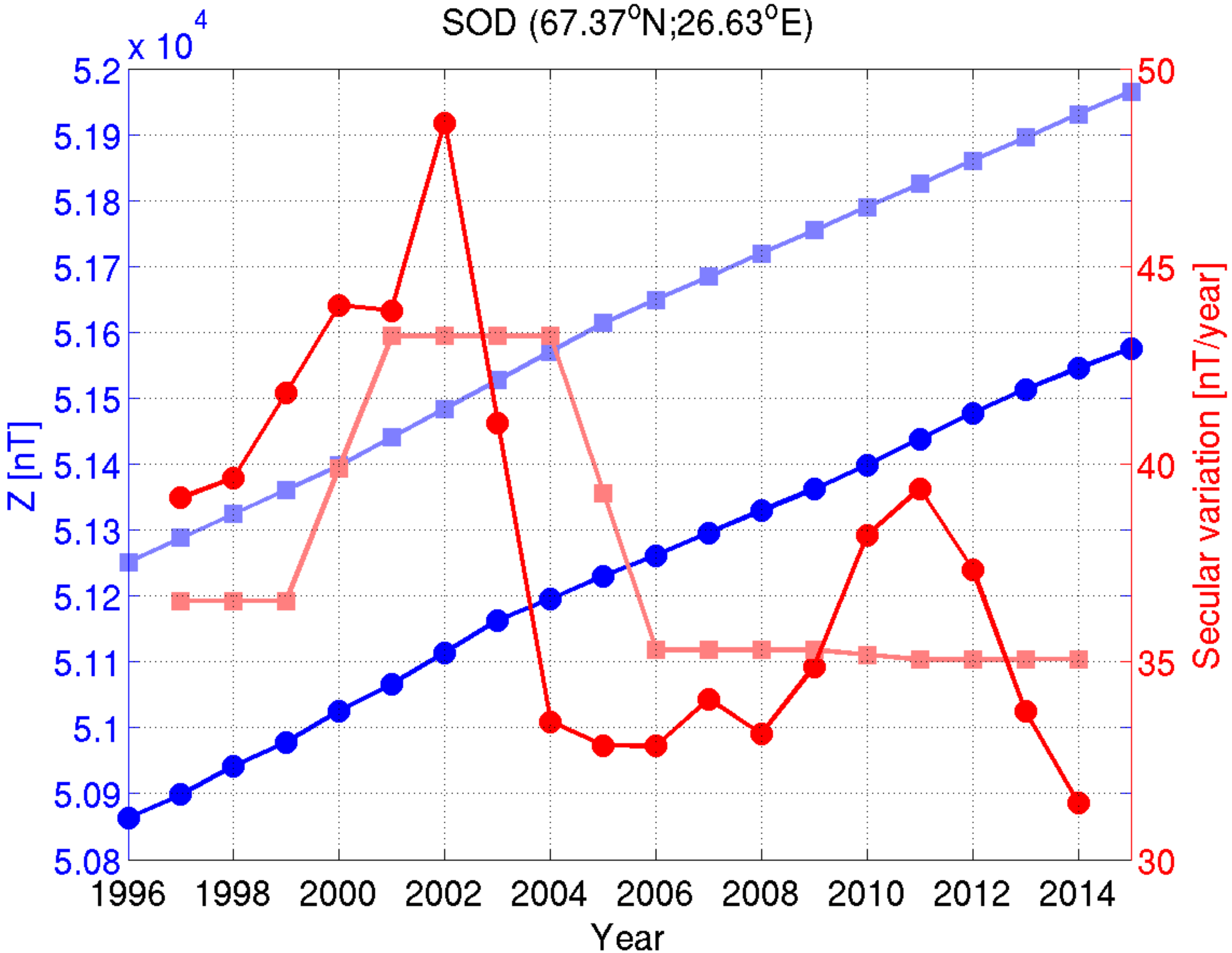

NUR (60.50°N;24.65°E)
D [°]
Secular variation [°/year]
Year
9
8.5
8
7.5
7
6.5
6
5.5
5
0.2
0.15
0.1
0.05
1995
2000
2005
2010
2015

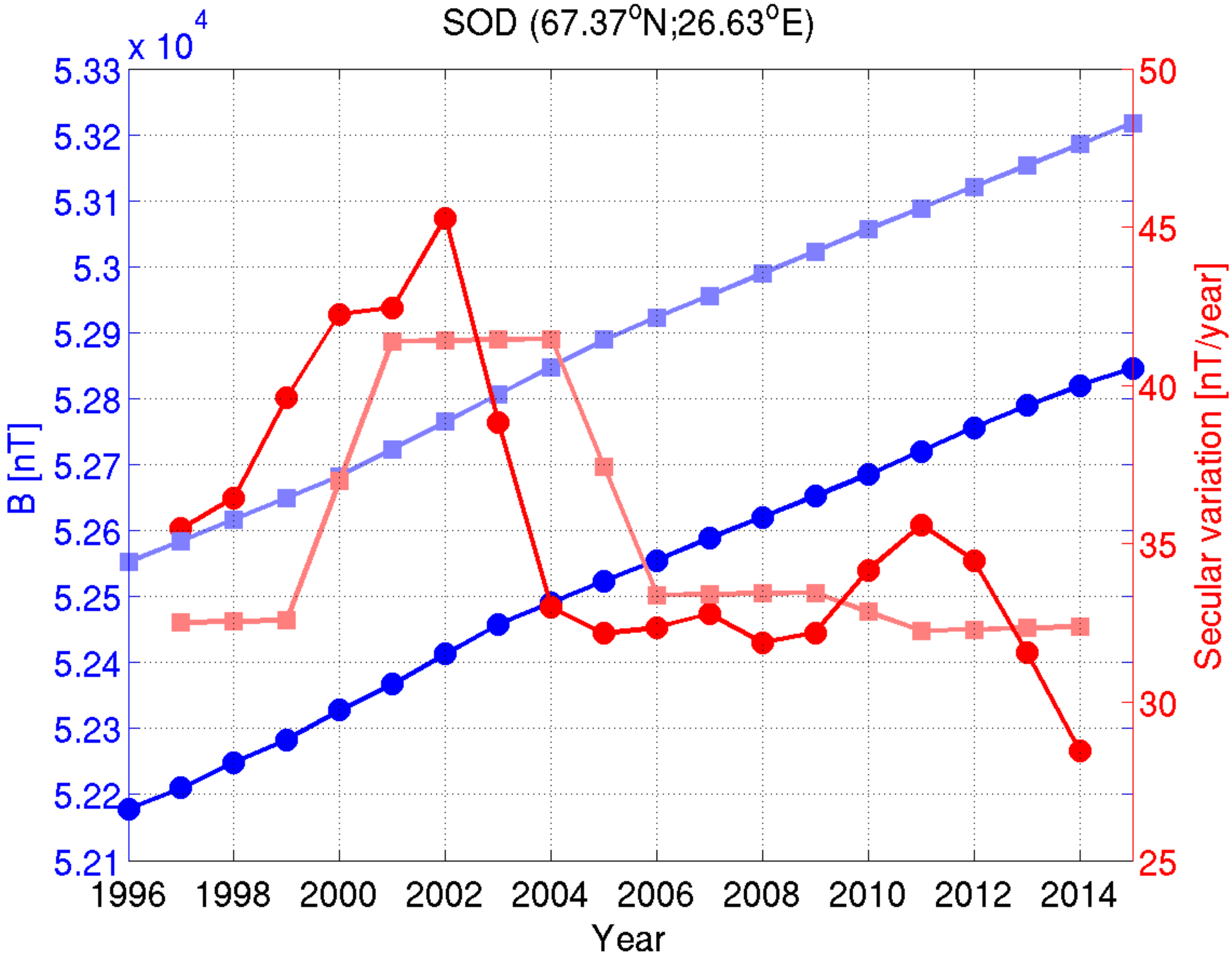

NUR (60.50°N;24.65°E)
73.9
73.8
73.7
73.6
73.5
73.4
73.3
73.2
73.1
73
I [°]
0.03
0.02
0.01
0
Secular variation [°/year]
1995
2000
2005
2010
2015
Year

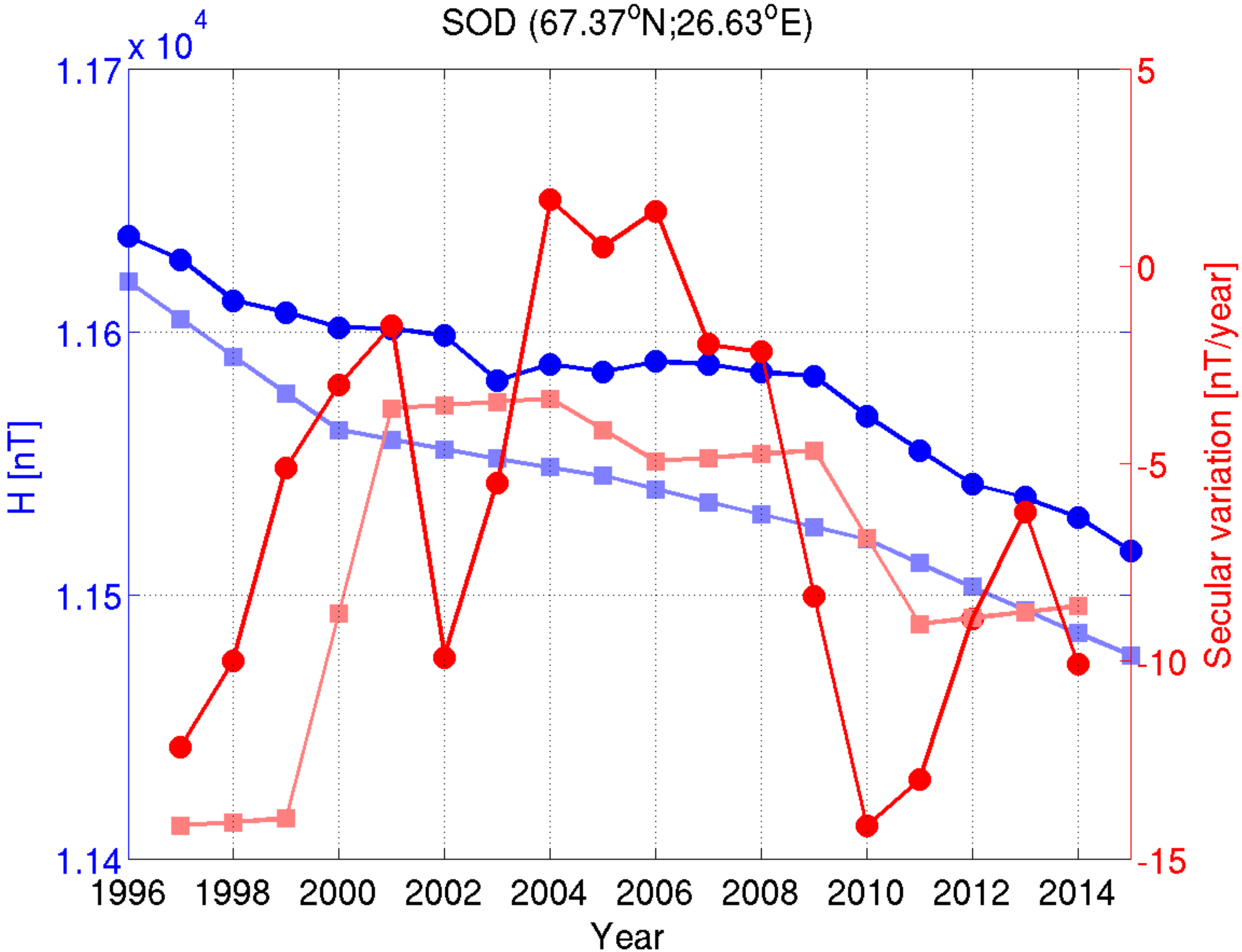

SOD (67.37°N;26.63°E)
x 10^4
1.16
1.15
1.14
1.13
1.12
X [nT]
0
-5
-10
-15
-20
-25
Secular variation [nT/year]
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
Year

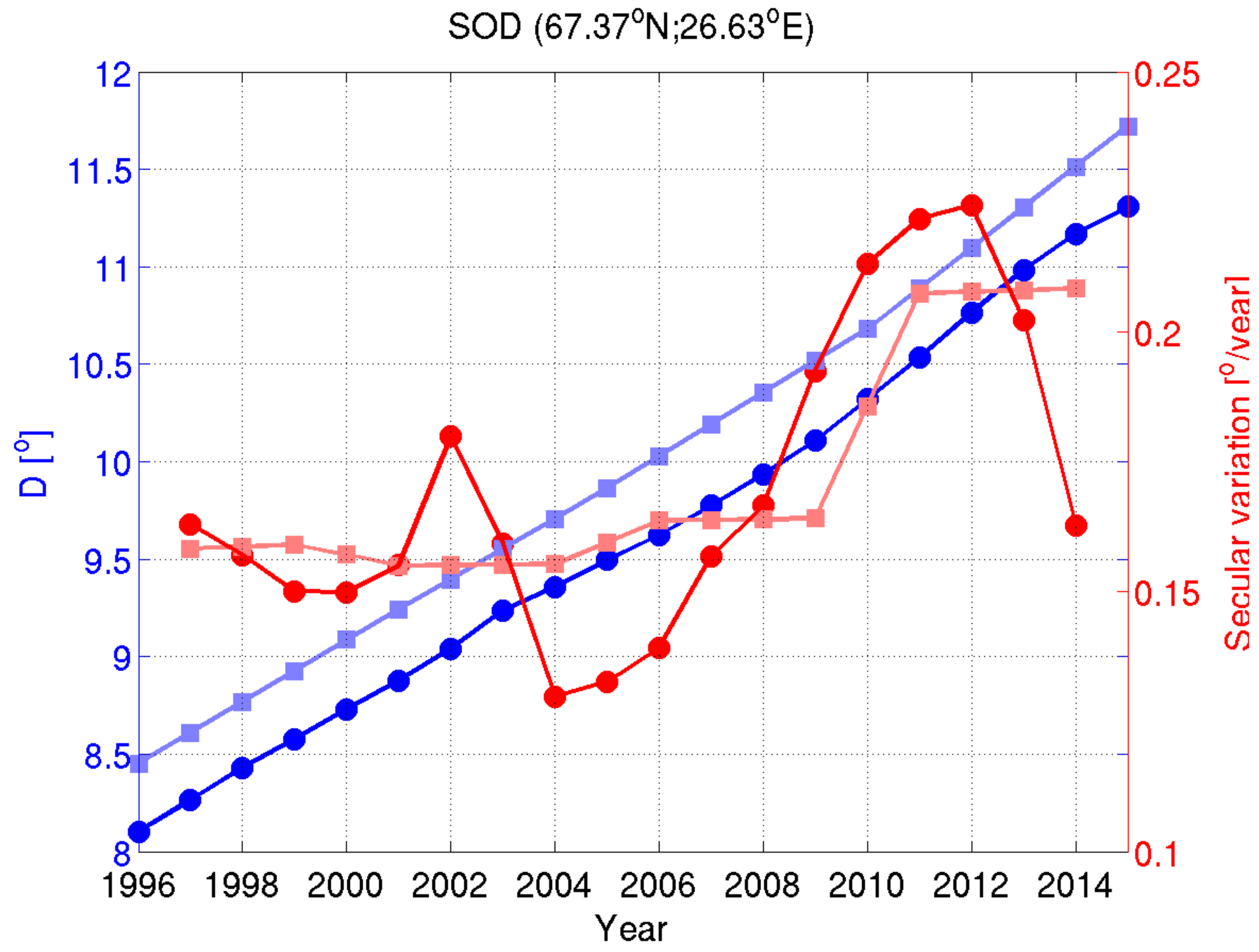


SOD (67.37°N;26.63°E)
Y [nT]
Secular variation [nT/year]
Year
2400
2300
2200
2100
2000
1900
1800
1700
1600
45
40
35
30
25
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014

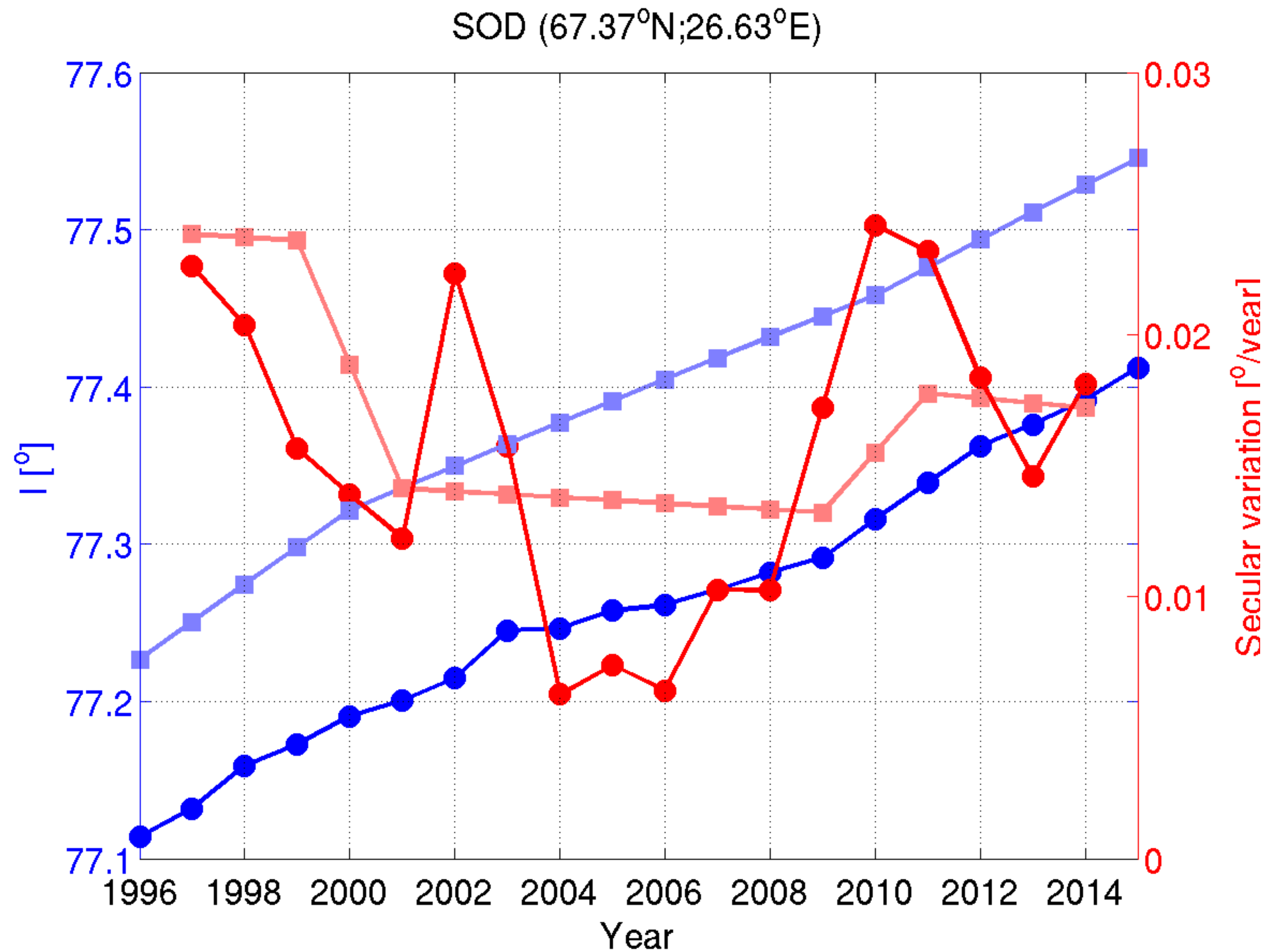

SOD (67.37°N;26.63°E)
x 10^4
5.2
5.19
5.18
5.17
5.16
5.15
5.14
5.13
5.12
5.11
5.1
5.09
5.08
Z [nT]
50
45
40
35
30
Secular variation [nT/year]
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
Year


SOD (67.37°N;26.63°E)
x 10^4
B [nT]
Secular variation [nT/year]
Year
5.33
5.32
5.31
5.3
5.29
5.28
5.27
5.26
5.25
5.24
5.23
5.22
5.21
50
45
40
35
30
25
1996 1998 2000 2002 2004 2006 2008 2010 2012 2014


SOD (67.37°N;26.63°E)
x 10^4
1.17
1.16
1.15
1.14
H [nT]
5
0
-5
-10
-15
Secular variation [nT/year]
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
Year



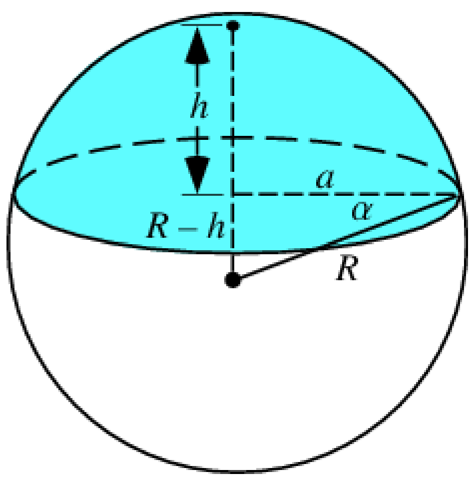
SOD (67.37°N;26.63°E)
D [°]
Secular variation [°/year]
Year
12
11.5
11
10.5
10
9.5
9
8.5
8
0.25
0.2
0.15
0.1
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014


SOD (67.37°N;26.63°E)
77.6
77.5
77.4
77.3
77.2
77.1
I [°]
0.03
0.02
0.01
0
Secular variation [°/year]
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
Year

Regional modeling of the magnetic field

Spherical cap harmonic analysis

- Spherical cap harmonics [HAINES, 1985, 1990] have been widely used for regional modeling of the magnetic field.
- Application of the global spherical harmonic analysis to a limited spherical cap surface.
- A spherical cap is a portion of a sphere cut off by a plane. If the plane passes through the center of the sphere, so that the height of the cap is equal to the radius of the sphere, the spherical cap is called a hemisphere.



The potential function can be represented as

$$V(r,\theta,\varphi,t)=R_E\sum_{k=0}^{k_{max}}\sum_{m=0}^{k}\left(\frac{R_E}{r}\right)^{n_k(m)+1}\left(G_k^m(t)\cos m\varphi+H_k^m(t)\sin m\varphi\right)P_{n_k(m)}^m(\cos\theta)$$

r radius
R_E Earth radius
θ co-latitude
θ_0 cap half-angle
φ longitude
t time
$n_k(m)$ degree of the spherial cap harmonic
m order
k index
k_{max} maximum index of the spherical cap harmonic expansion
G, H coefficients
$P_{n^k(m)}^m(\cos\theta)$ Schmidt semi-normalized associated Legendre function of the first kind

$n_k(m)$ is chosen so that

$$\frac{dP_{n_k(m)}^m(\cos\theta_0)}{d\theta}=0 \text{ when } k-m \text{ is even}$$

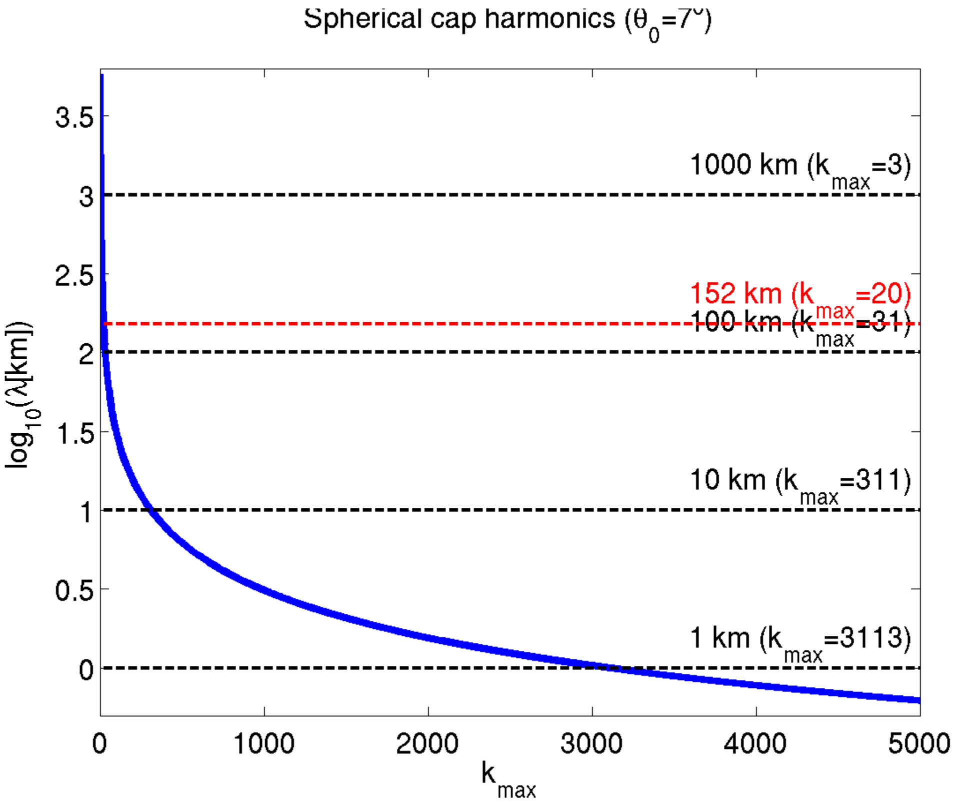
and

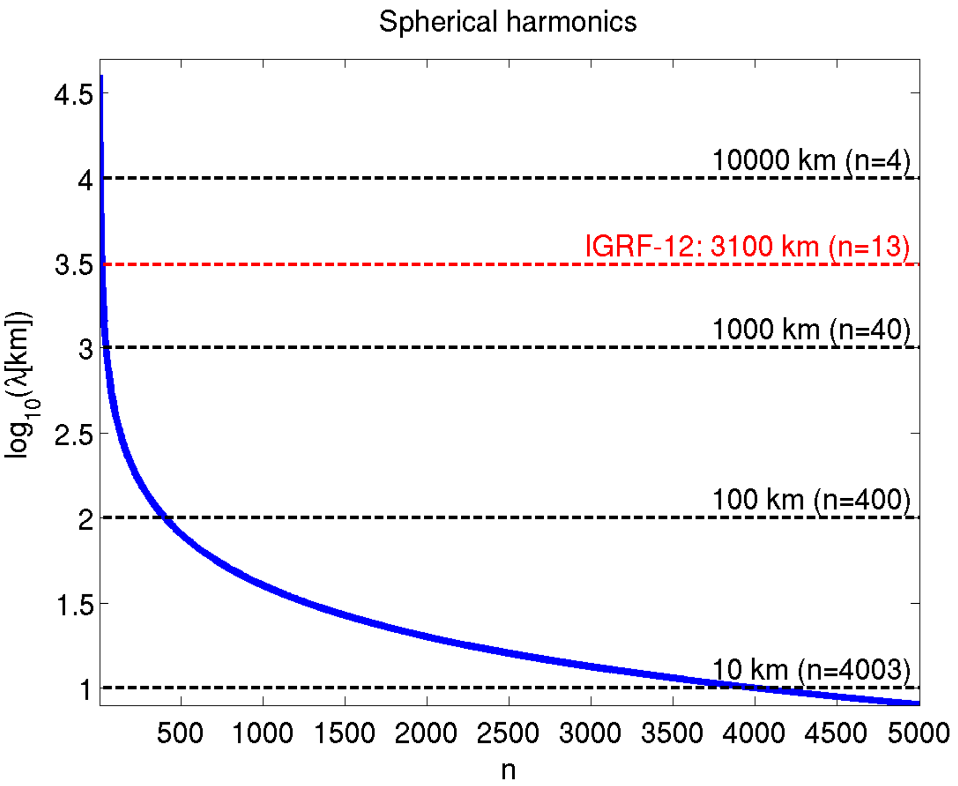
$$P_{n_k(m)}^m(\cos\theta_0)=0 \text{ when } k-m \text{ is odd}$$

- The most significant difference of the spherical cap harmonic expansion compared to the spherical harmonic expansion is that the degree is no longer an integer. Thus, a spherical cap harmonic function does not have the same kind of a physical interpretation as a spherical harmonic function where degree n corresponds to a magnetic multipole.

- The shortest wavelength that can be described by a spherical cap harmonic expansion is:

$$\lambda = \frac{2\pi R_E}{\dfrac{k_{max}+0.5}{\theta_0/90^o}+0.5}$$





Magnetic maps of Finland

Spherical cap harmonic model of the anomalous magnetic field in Finland

- The observations cover a limited area.
- The main field is generated by the geodynamo in the Earth's liquid outer core. Its contribution, as given by the IGRF model, is subtracted from the measured magnetic field. The remnant or anomalous magnetic field is generated by magnetized rocks in the crust and upper mantle.
  - A magnetic anomaly is a local variation in the Earth's magnetic field resulting from variations in the chemistry or magnetism of the rocks.
  - An anomaly is a local contribution to the magnetic field. Therefore, the main field must be subtracted from the measured field. Usually the IGRF is used for this purpose.
- A spherical cap surface (for example), inside of which the spherical cap harmonic model for the anomalous magnetic field is calculated, is chosen such that it covers the area under examination.
  - For Finland, a spherical cap centered at 63°N, 24°E with a radius $\theta_0 = 7^\circ$ has been used. Such a surface covers the entire Finland.
  - Maximum degree of $k_{max} = 20$ then produces 72 statistically significant coefficients out of the 441 possible ones.
  - The shortest wavelength described by the model is 160 km.

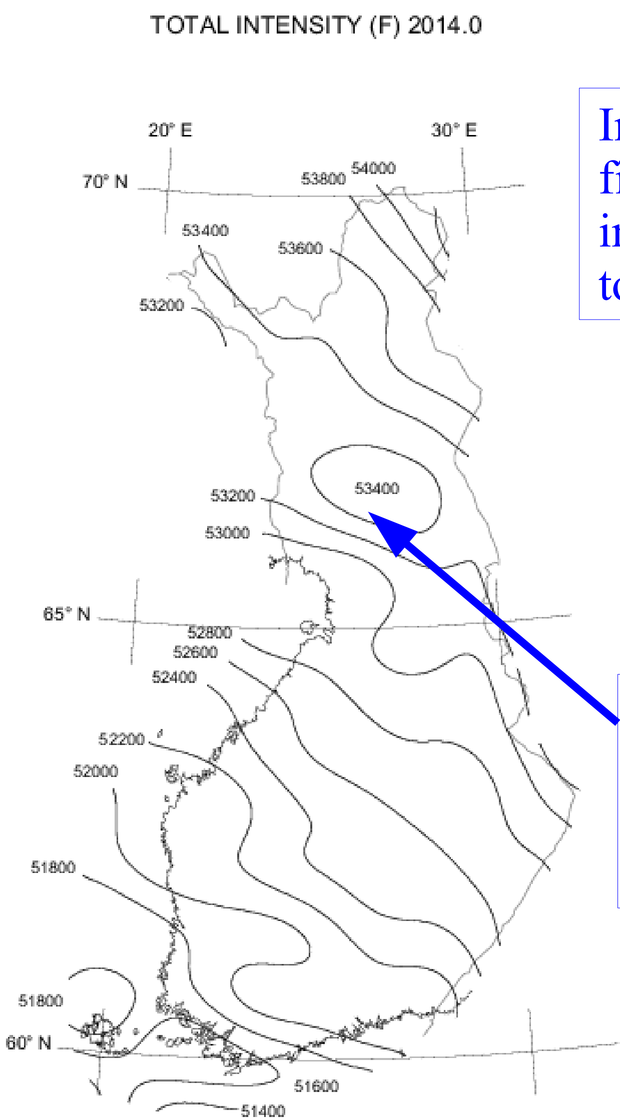
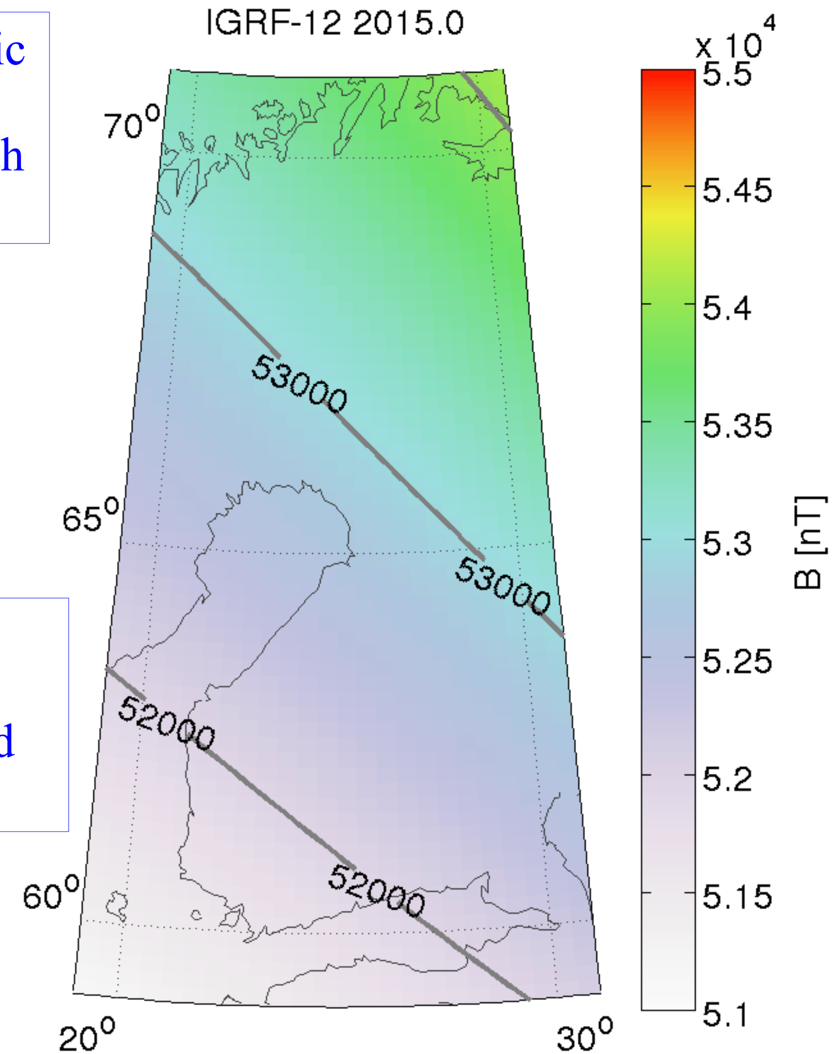


Figure 14: Total intensity F 2014.0 in nT

In Finland, magnetic field intensity increases from south to north.

Extension of the Kiruna magnetic anomaly, centered at 67ºN,20ºE.



Pajunpää, K., and Häkkinen, L., Nurmijärvi Geophysical Observatory Magnetic Results 2013, Finnish Meteorological Institute Reports 2014:4. http://hdl.handle.net/10138/45151

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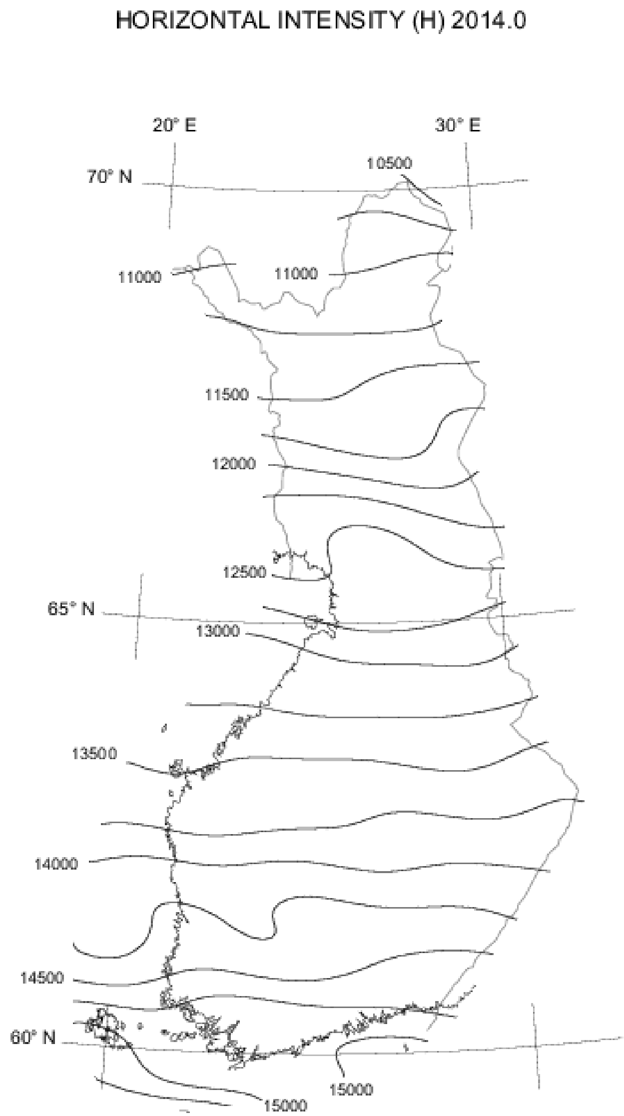
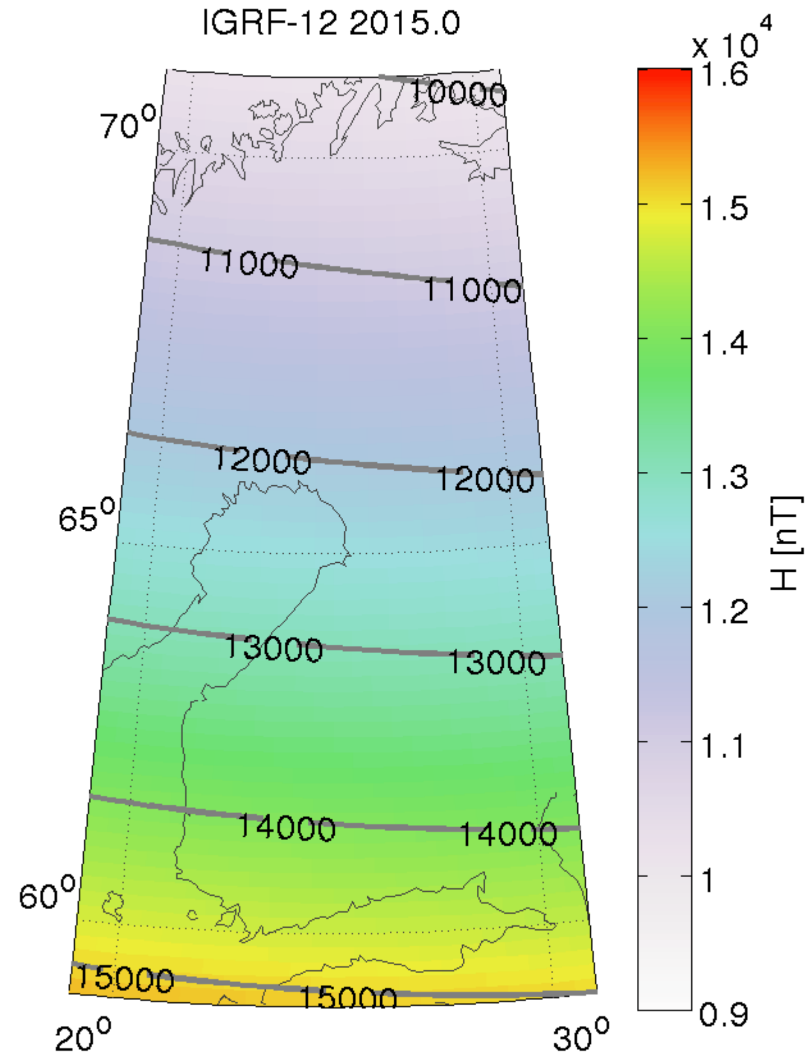


Figure 15: Horizontal intensity H 2014.0 in nT



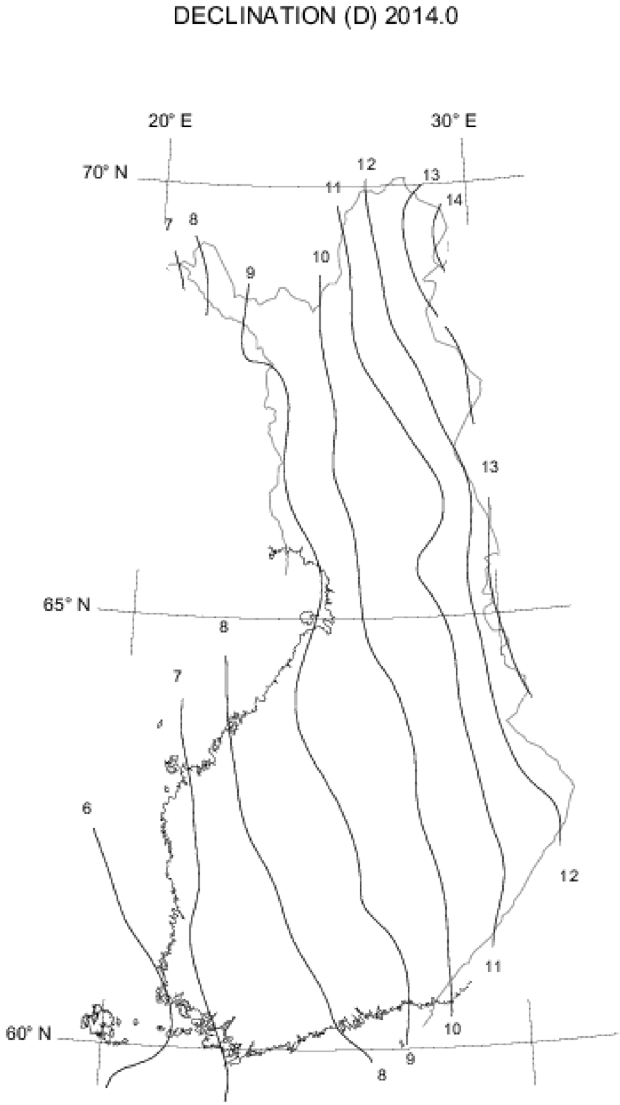
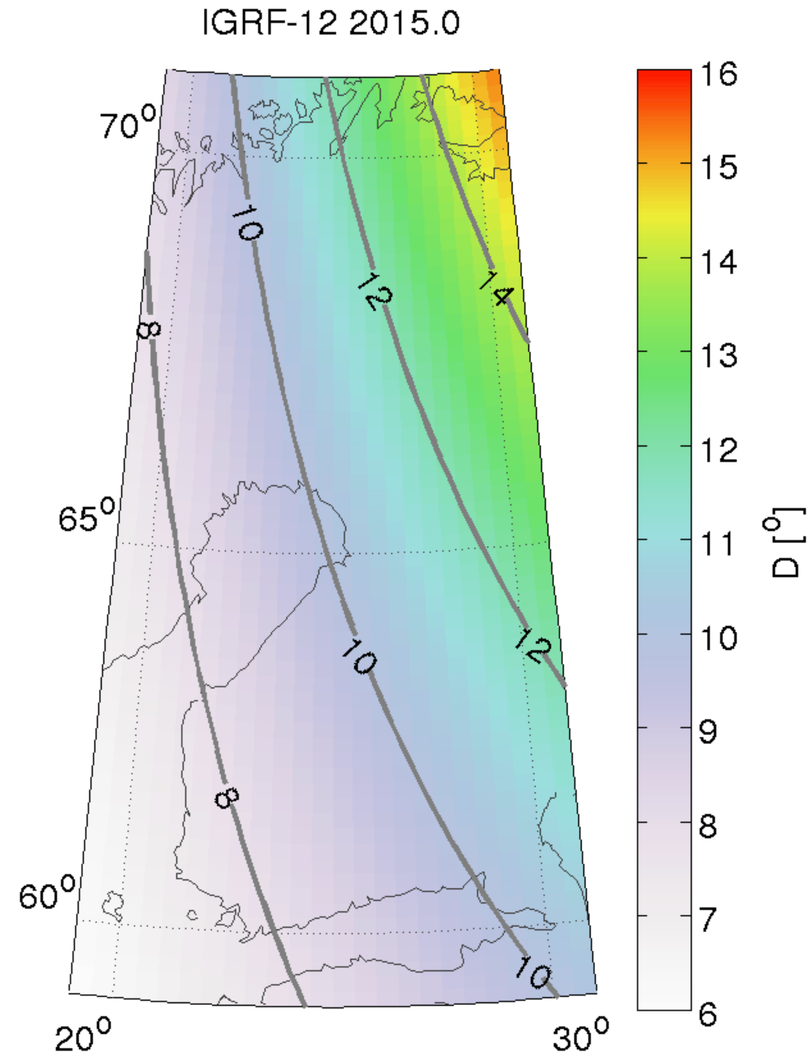


Figure 16: Declination D 2014.0 in degrees



In Finland, D increases from southwest to northeast.

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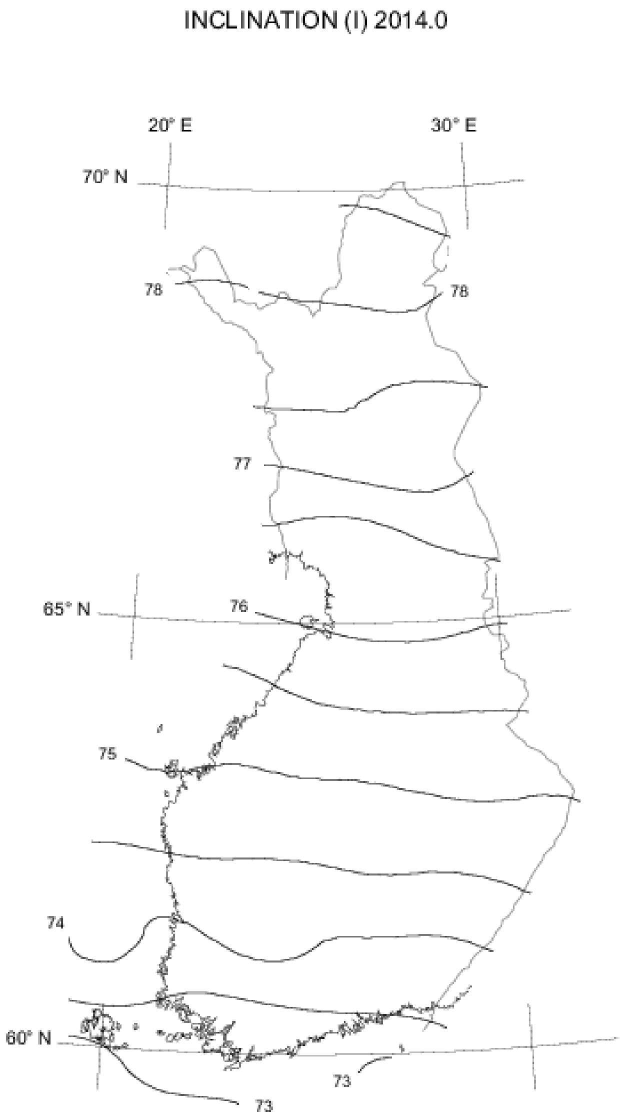
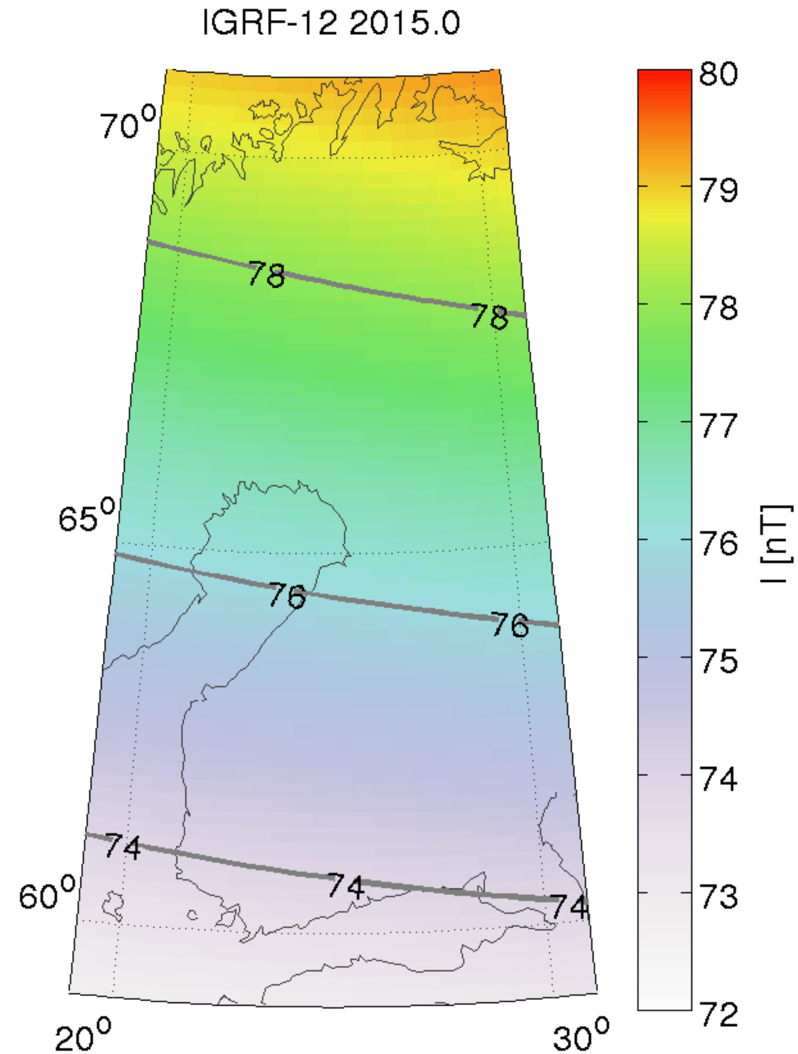


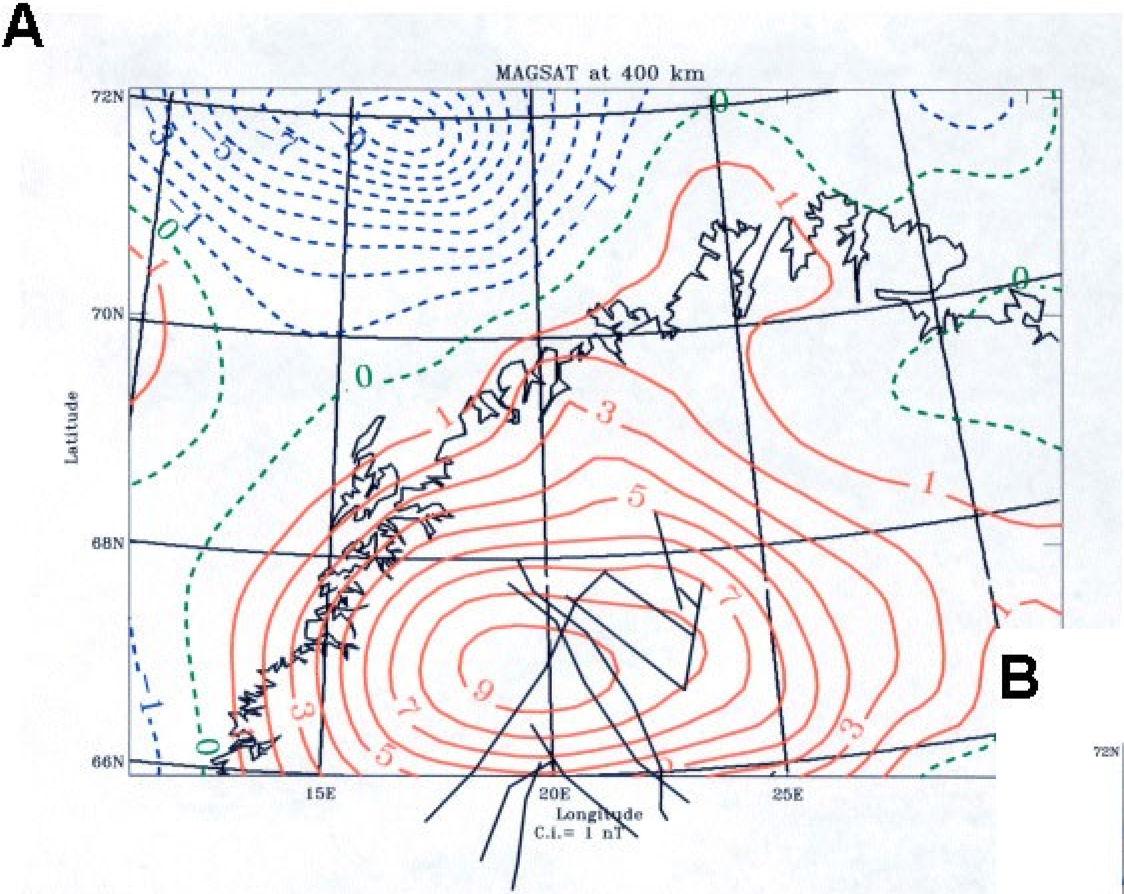
Figure 17: Inclination I 2014.0 in degrees



Kiruna magnetic anomaly

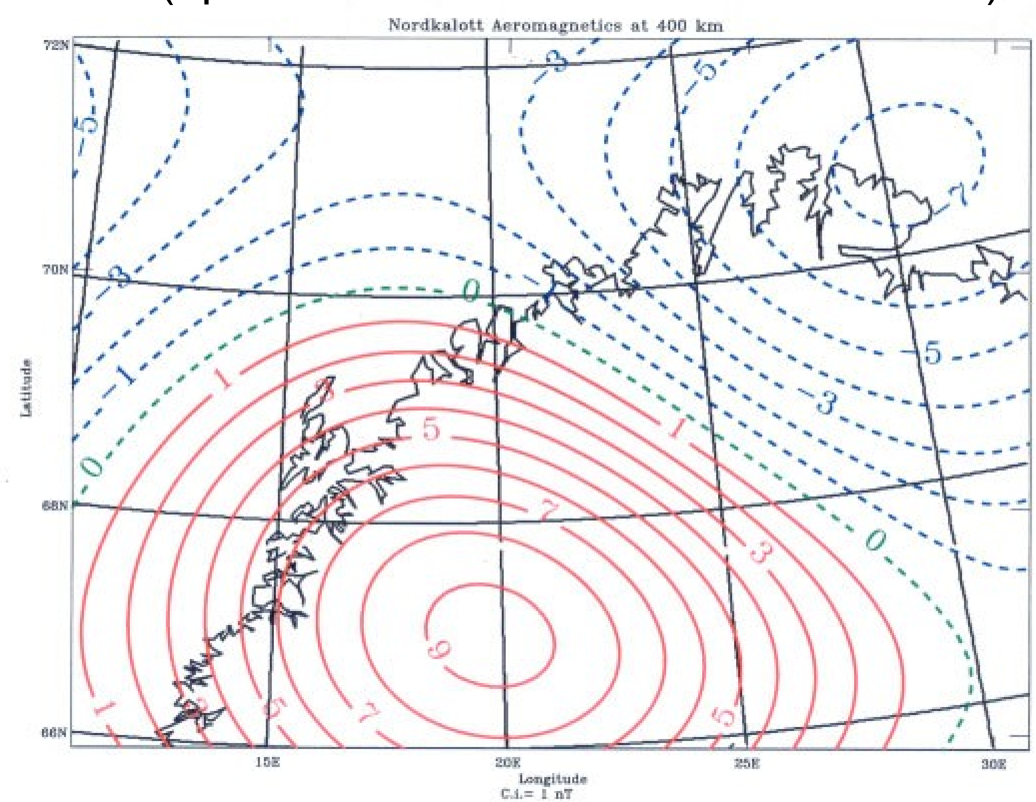
- One of the major magnetic anomalies.
- Centered in Kiruna, Sweden at 67ºN; 20ºE.
- Modeling suggests that the anomaly is associated with a 20 x 40 x 70 km block of strongly magnetized material at the depth of 20 km.
- The largest and most modern underground iron ore mine in the world is also located in Kiruna.
- The maximum magnetic field strength is
  - 40 000 nT on the ground
  - 6000 nT at 3 km altitude (aeromagnetic measurements, Korhonen et al., 1999)
  - 10 nT at 400 km altitude (MAGSAT measurements, Taylor et al., 1992)

A



B

(upward continued to MAGSAT altitude)



http://core2.gsfc.nasa.gov/terr_mag/kiruna.html