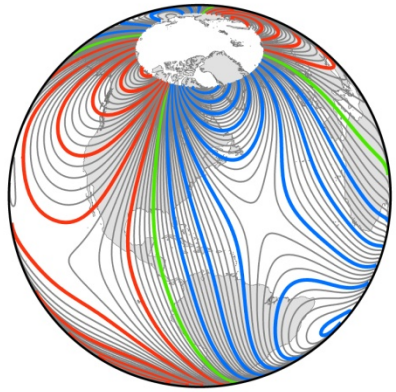
Quantifying the uncertainty in global geomagnetic models



- Global magnetic field reference models
  - WMM, IGRF & High Definition Geomagnetic Model
- Simple update of Williamson's magnetic error values
  - Breakdown by main, crustal and disturbance fields
  - Adjustments for non-Gaussian error distribution
- Detailed error analysis
  - Identify the primary factors contributing to the magnetic error

  → Accurate error model taking all relevant factors into account

Stefan Maus and Manoj Nair (NOAA/NGDC)
Shola Okewunmi (Chevron)

ISCWSA
Florence, Sep-23 2010

Geomagnetic reference models

World Magnetic Model (WMM)

- Government/Defense standard model with guaranteed technical/software support

International Geomagnetic Reference Field (IGRF)

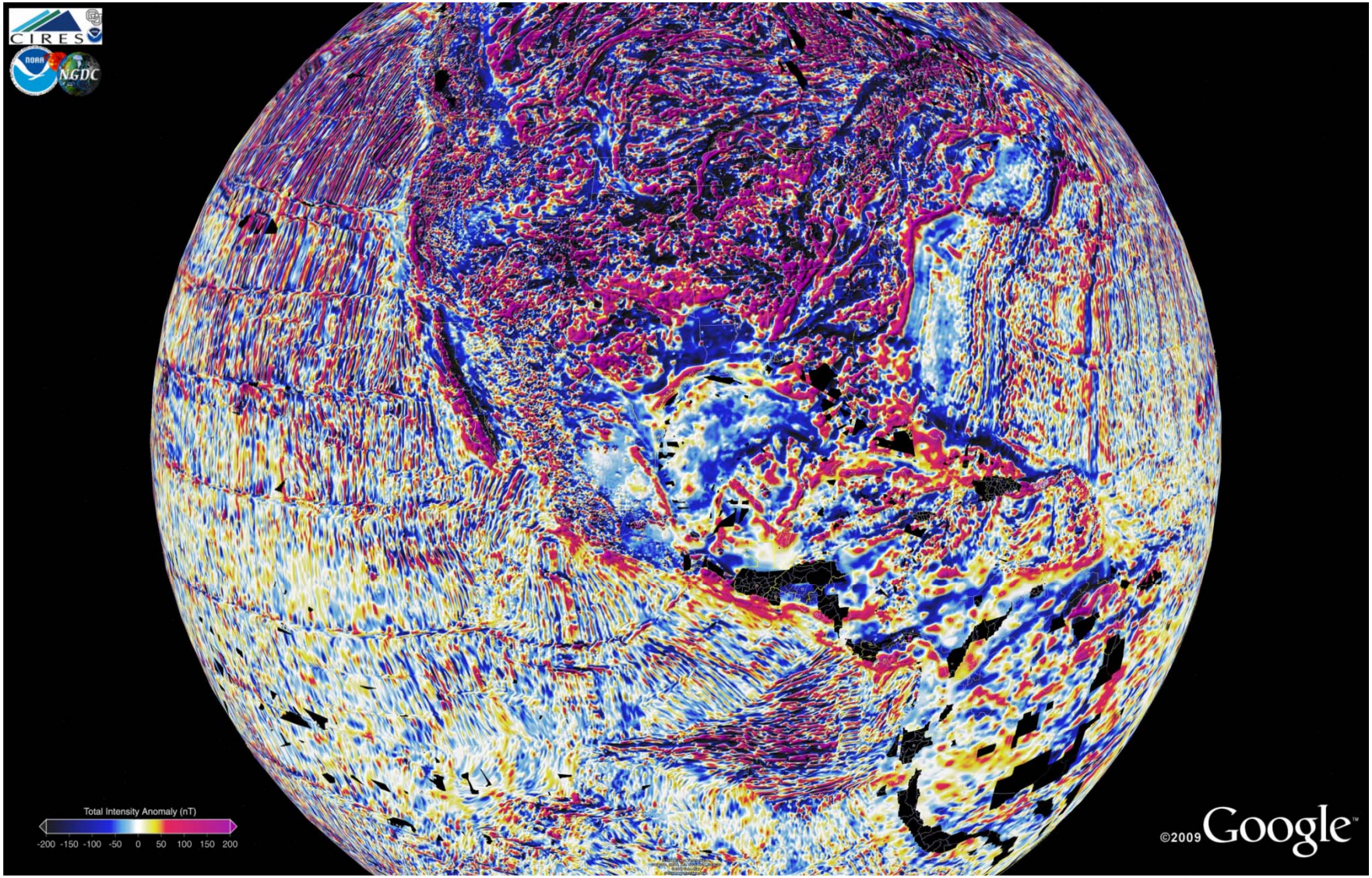
- Research Community model
- Includes retrospective updates back to 1900

NGDC plays a key role in producing, distributing and providing support for both the WMM and the IGRF

Earth Magnetic Anomaly Grid (EMAG2)

2-arc minute (4 km) resolution, 4km above ellipsoid

Compiled from airborne and marine and satellite magnetic measurements



High Definition Geomagnetic Model

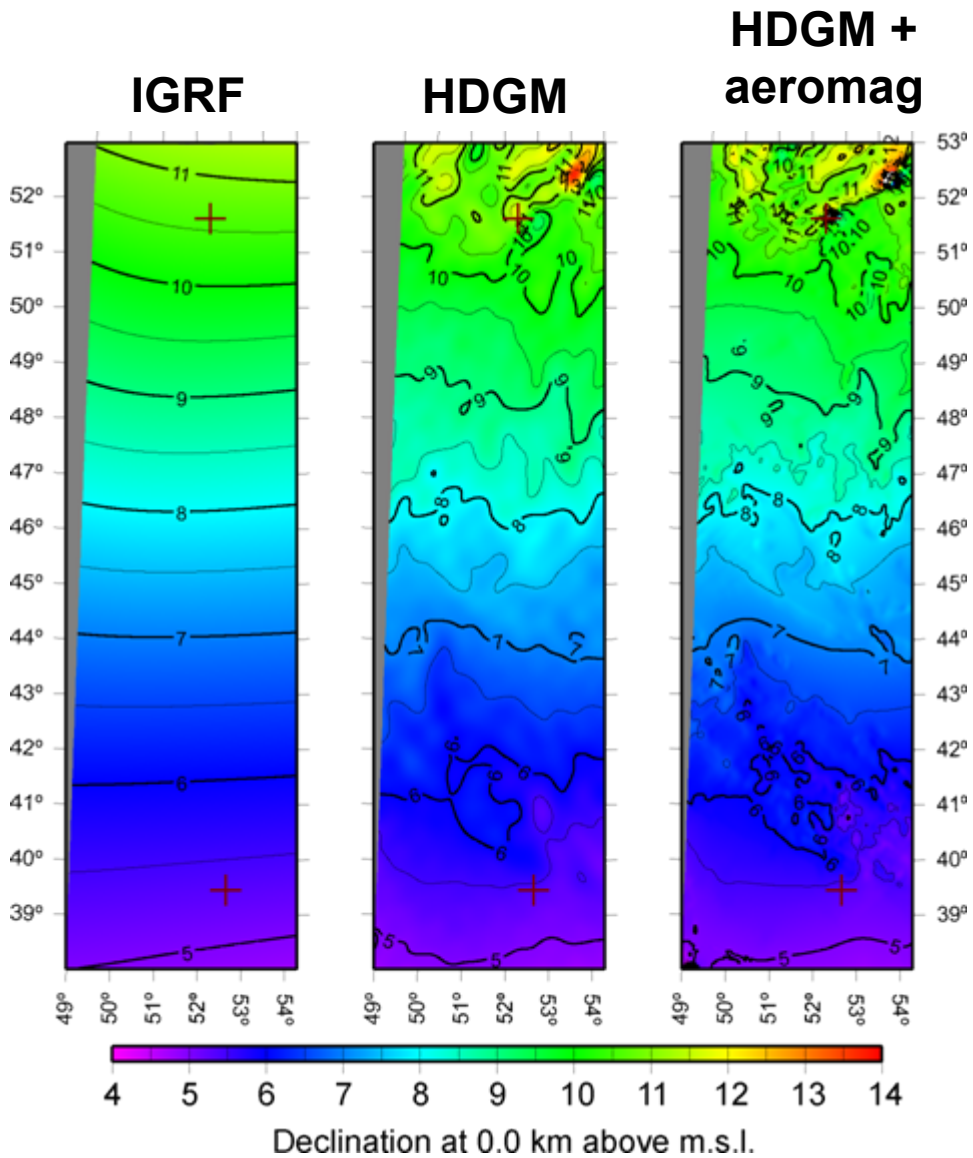
annually updated version of Enhanced Magnetic Model (EMM)

The HDGM model includes:

- **Main field**
- **Secular variation**
- **Crustal field to degree 720**
- **Stable external field**
- **Error model**

Annual model updates available each December 1st to members of a new University of Colorado Geomagnetism Research Consortium

For further details see: http://geomag.org/consortium



Error tables for IGRF and HDGM

Intention of this study:

Provide error estimates for IGRF and HDGM corresponding to BGGM error tables (Macmillan, McKay and Grindrod, SPE/IADC 119851)

~~Original plan: Reproduce BGGM tables for IGRF & HDGM~~

New plan is to provide 2 options:

1. Simple: values to plug into the ISCWSA-2000 error model
2. Accurate: Breakdown by the primary error factors

Methodology partly borrowed from *Macmillan et al.* study

Simple 1σ error table for Williamson 2000

		Total field	Dip	Declination
	Williamson 2000	130 nT	0.20º	0.36º + 5000ºnT/B_H
This study				
	Total ($\sqrt{\Sigma e^2}$)	141 nT	0.24º	0º + 6280 ºnT/B_H
	IGRF	114 nT	0.21º	0º + 5080 ºnT/B_H
	HDGM			

Simple 1σ error table

			Total field	Dip	Declination
	Williamson 2000		130 nT	0.20º	0.36º + 5000ºnT/B_H
This study	Main field	IGRF	34 nT	0.05º	1430 ºnT/B_H
		HDGM	11 nT	0.02º	440 ºnT/B_H
	Crustal field	IGRF	131 nT	0.19º	5830 ºnT/B_H
		HDGM	106 nT	0.15º	4730 ºnT/B_H
	Steady extern	IGRF	10 nT	0.03º	400 ºnT/B_H
		HDGM	2 nT	0.01º	100 ºnT/B_H
	Disturbance field		40 nT	0.14º	1800 ºnT/B_H
	Total ($\sqrt{\Sigma e^2}$)		141 nT	0.24º	0º + 6280 ºnT/B_H
	IGRF		114 nT	0.21º	0º + 5080 ºnT/B_H
		HDGM			

Simple error table for 99.7 percentile

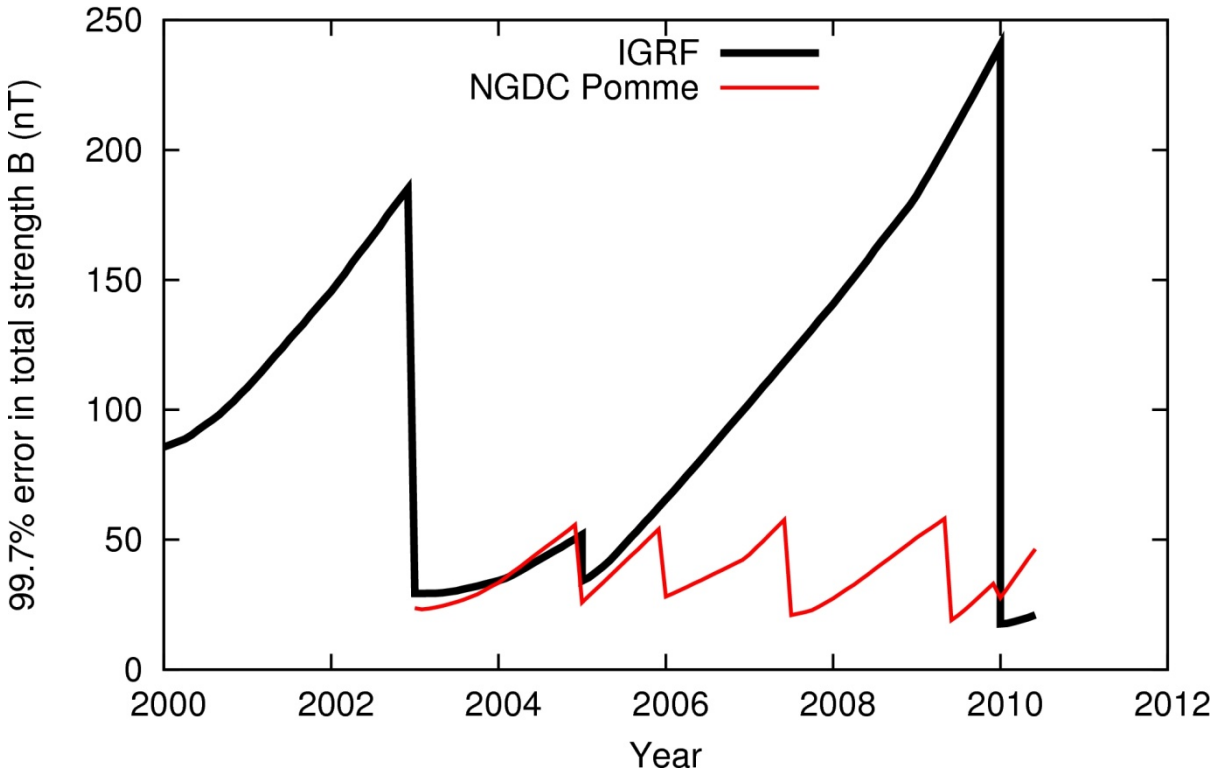
		Total field	Dip	Declination
	Williamson 2000 (3σ)	390 nT	0.60º	1.08º + 15000ºnT/B_H
This study				
	Total ($\sqrt{\Sigma e^2}$)	670 nT	1.33º	0º + 29 400 ºnT/B_H
	IGRF	550 nT	1.20º	0º + 24 200 ºnT/B_H
	HDGM			

Simple 99.7 percentile error table

			Total field	Dip	Declination
	Williamson 2000 (3σ)		390 nT	0.60º	1.08º + 15000ºnT/B_H
This study	Main field	IGRF	172 nT	0.26º	7 160 ºnT/B_H
		HDGM	46 nT	0.08º	1 820 ºnT/B_H
	Crustal field	IGRF	590 nT	0.86º	26 200 ºnT/B_H
		HDGM	477 nT	0.68º	21 300 ºnT/B_H
	Steady extern	IGRF	10 nT	0.03º	400 ºnT/B_H
		HDGM	2 nT	0.01º	100 ºnT/B_H
	Disturbance field		270 nT	0.98º	11 300 ºnT/B_H
	Total ($\sqrt{\Sigma e^2}$)*		670 nT	1.33º	0º + 29 400 ºnT/B_H
	IGRF		550 nT	1.20º	0º + 24 200 ºnT/B_H
		HDGM			

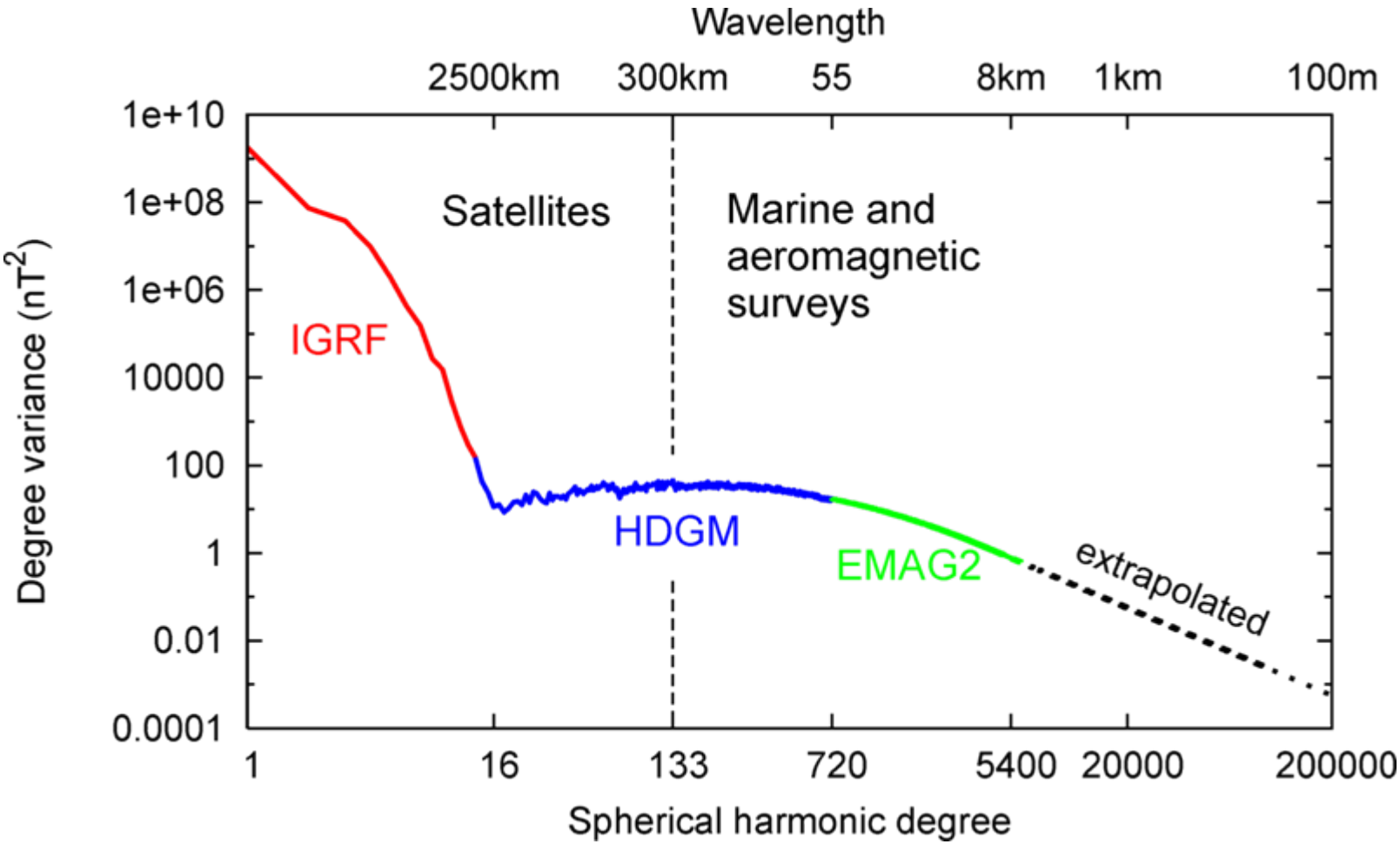
*Only approximately valid for non-Gaussian errors

Main field: 99.7% uncertainty in total field



- Past field known accurately, difficult to predict future
  → Models are accurate on their release date and deteriorate subsequently

Earth's Internal magnetic field degree variance



The area under the curve gives the total variance
$\langle \mathbf{B}^2 \rangle$ of the magnetic field vector **B**

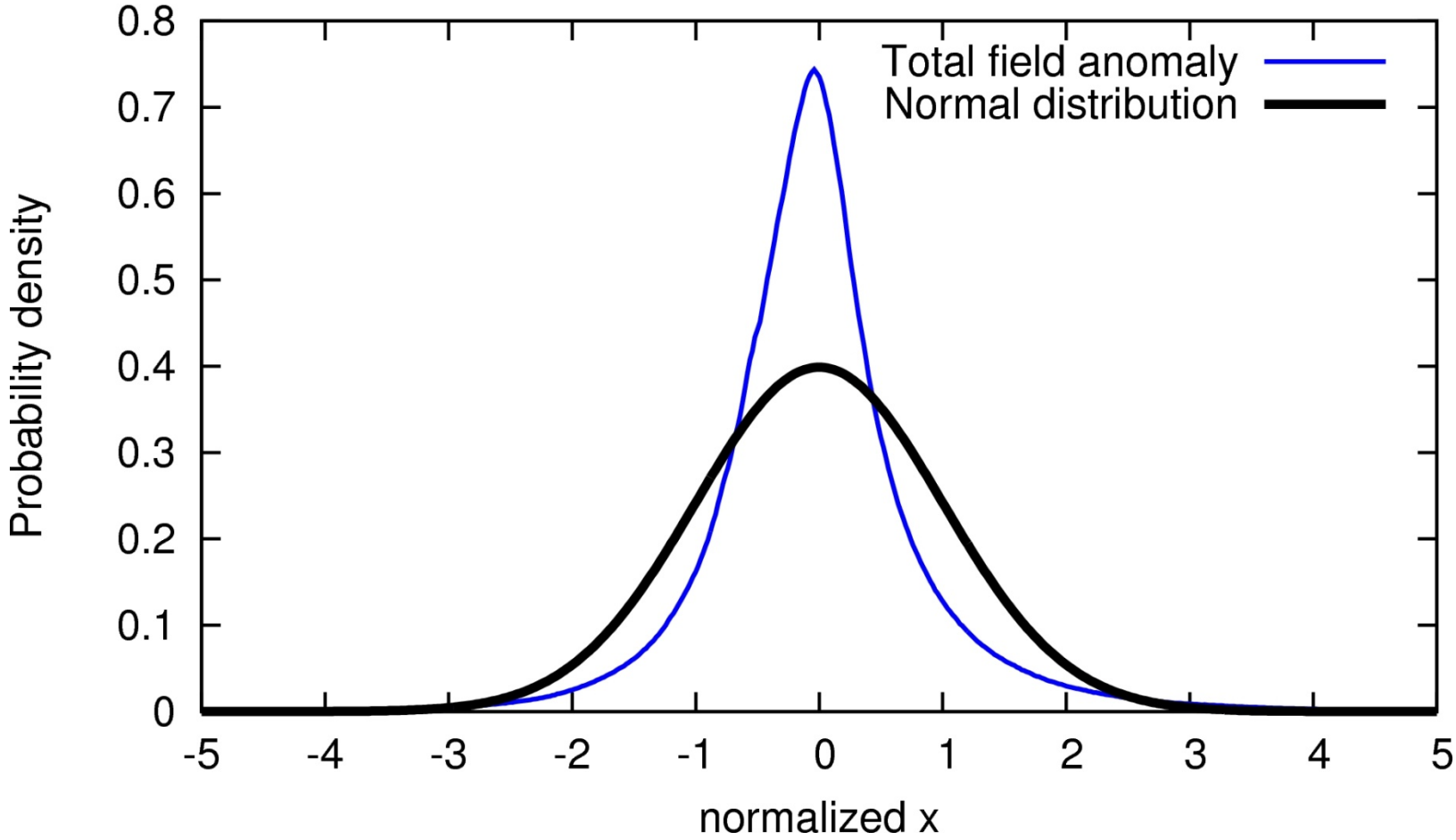
Crustal magnetic field omission error

	Model	Degree	Resolution	B	Dip	Declination
Omission error	IGRF	13	1500 km	131 nT	0.19°	5830 °nT/B_H
	Satellite	133	150 km	126 nT	0.18°	5580 °nT/B_H
	HDGM	720	28 km	97 nT	0.14°	4300 °nT/B_H
	Geomagnetic referencing requiring special processing:					
	EMAG2		4 km	41 nT	0.06°	1840 °nT/B_H
	Aeromag survey		1 km	22 nT	0.03°	960 °nT/B_H

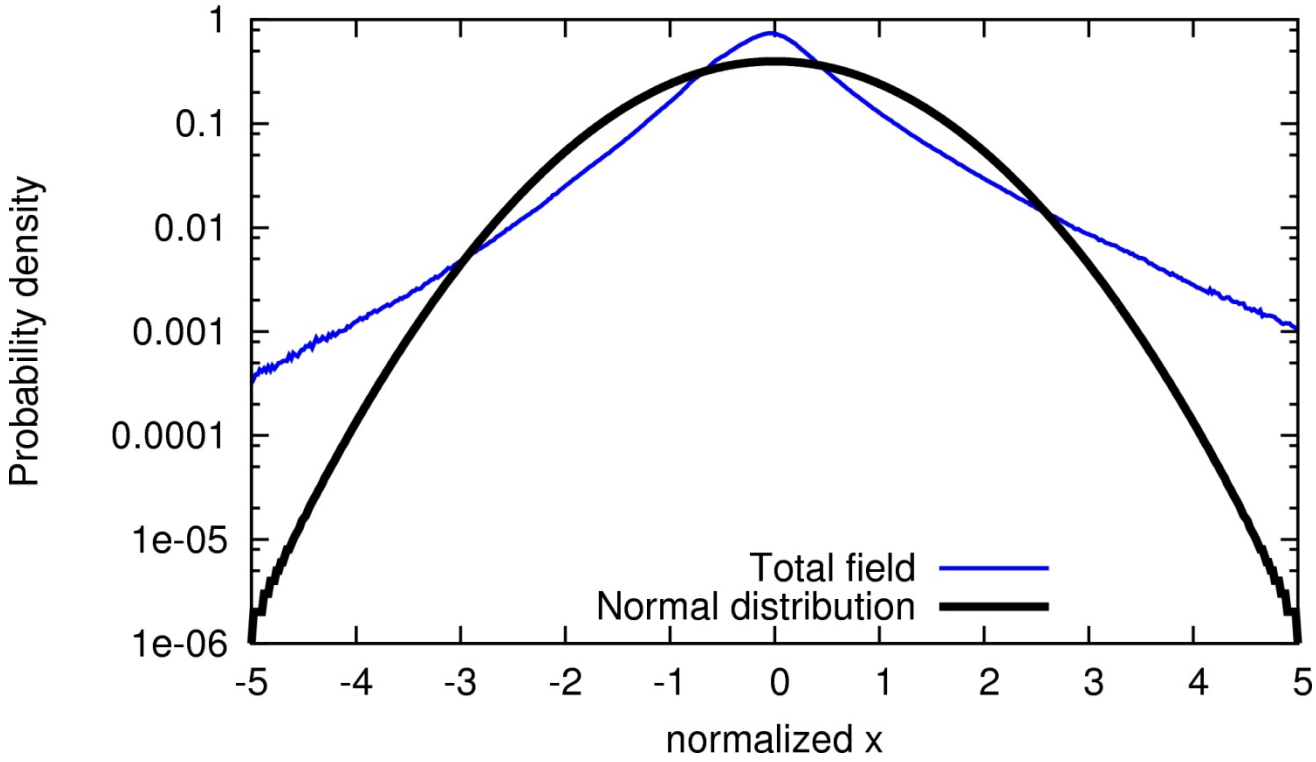
Crustal magnetic field error (1 σ)

	Model	Degree	Resolution	B	Dip	Declination
Omission error	IGRF	13	1500 km	131 nT	0.19°	5830 °nT/B_H
	Satellite	133	150 km	126 nT	0.18°	5580 °nT/B_H
	HDGM	720	28 km	97 nT	0.14°	4300 °nT/B_H
HDGM accounts for roughly 75% of crustal power to degree 720:						
Total error	HDGM	720	28 km	106 nT	0.15°	4730 °nT/B_H
Geomagnetic referencing requiring special processing:						
Omission error	EMAG2		4 km	41 nT	0.06°	1840 °nT/B_H
	Aeromag survey		1 km	22 nT	0.03°	960 °nT/B_H

Crustal error distribution standardized to σ=1 from Earth Magnetic Anomaly Grid EMAG2

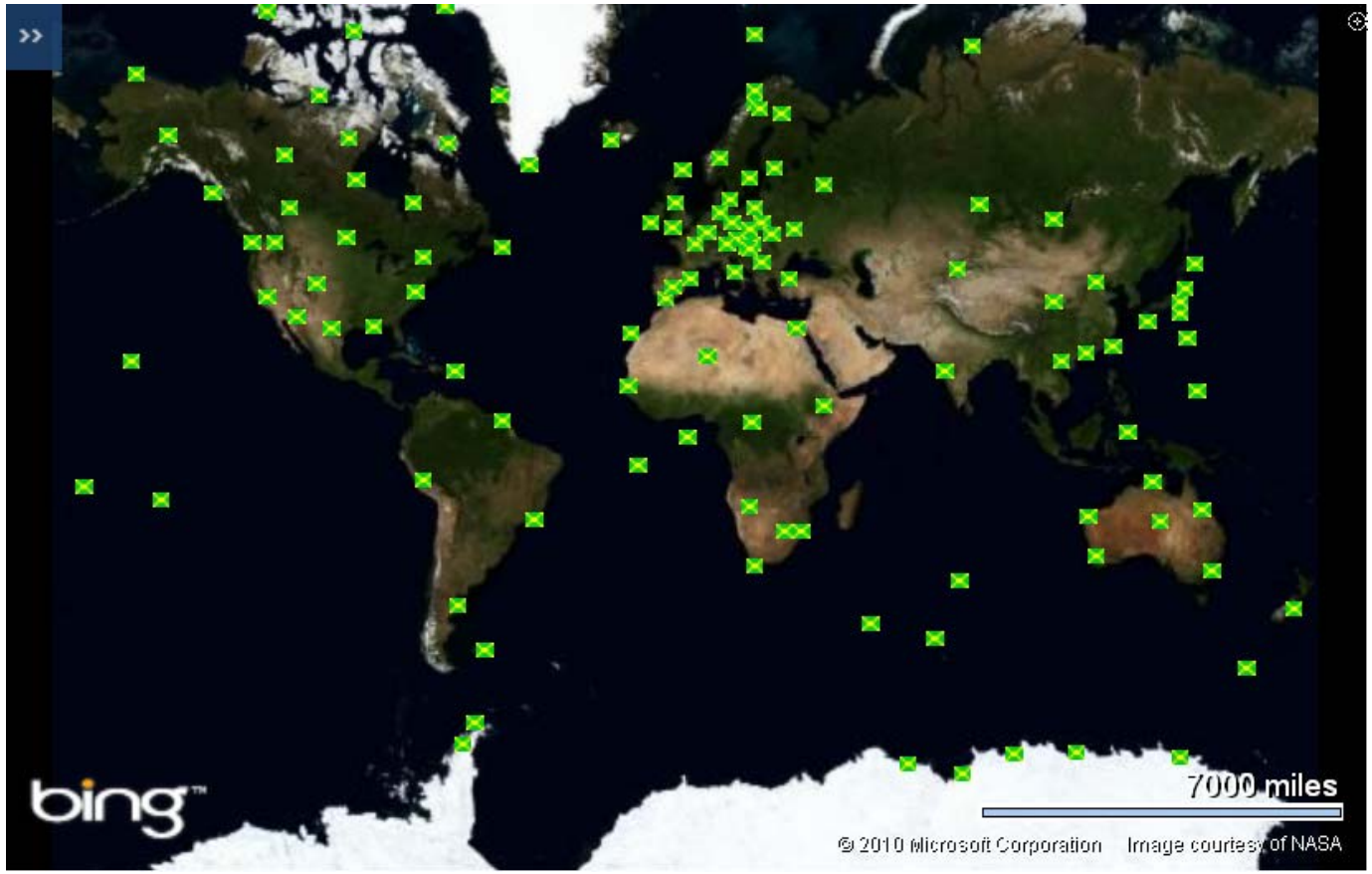


Crustal error distribution standardized to σ=1 logarithmic scale



	68.3%		95.4%		99.7%	
Normal	1 σ		2 σ		3 σ	
	σ	Offset	σ	Offset	σ	Offset
Crustal B	0.66	-34%	1.92	-4%	4.54	51%

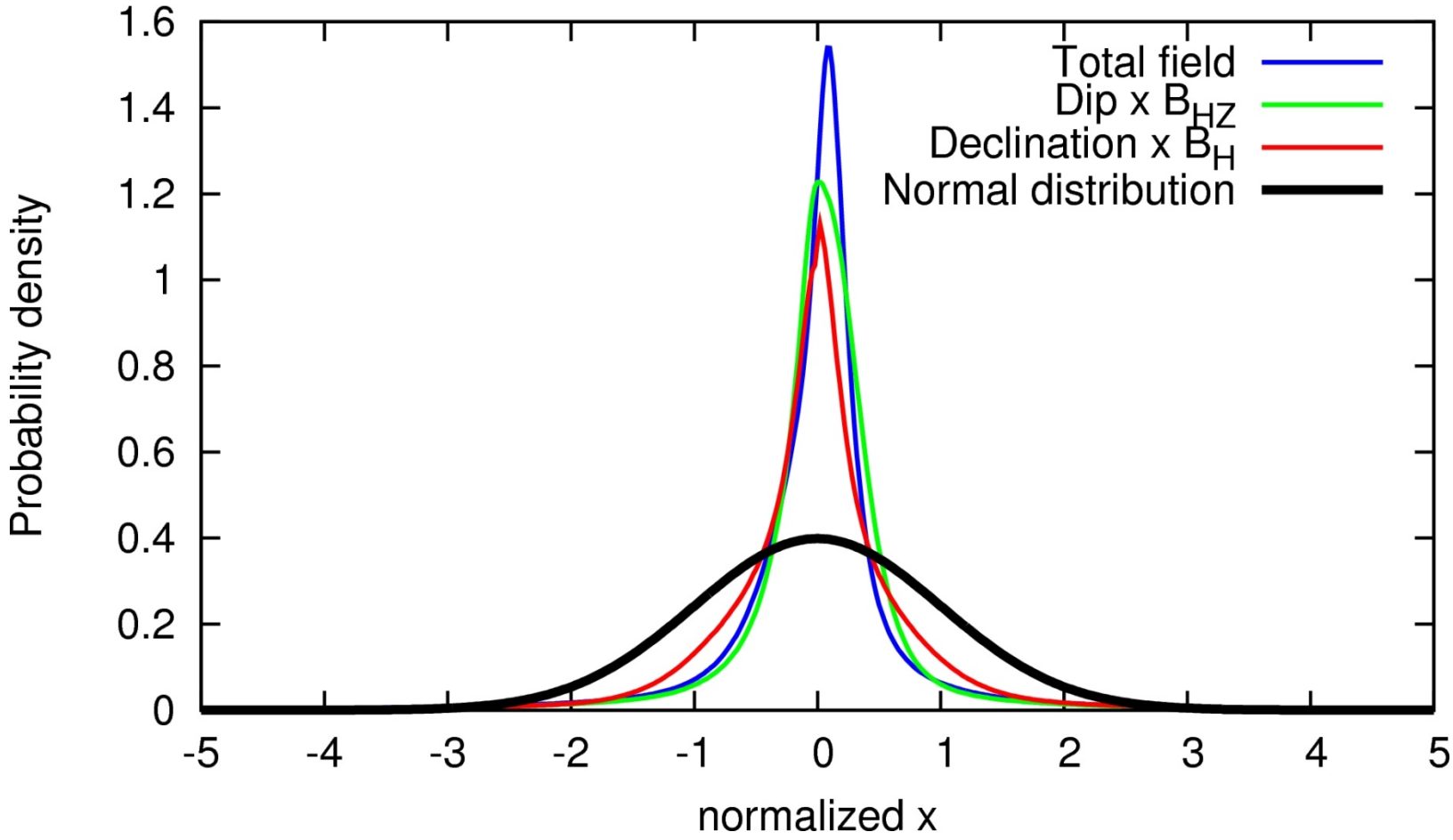
Disturbance field contribution estimated using magnetic observatory minute values



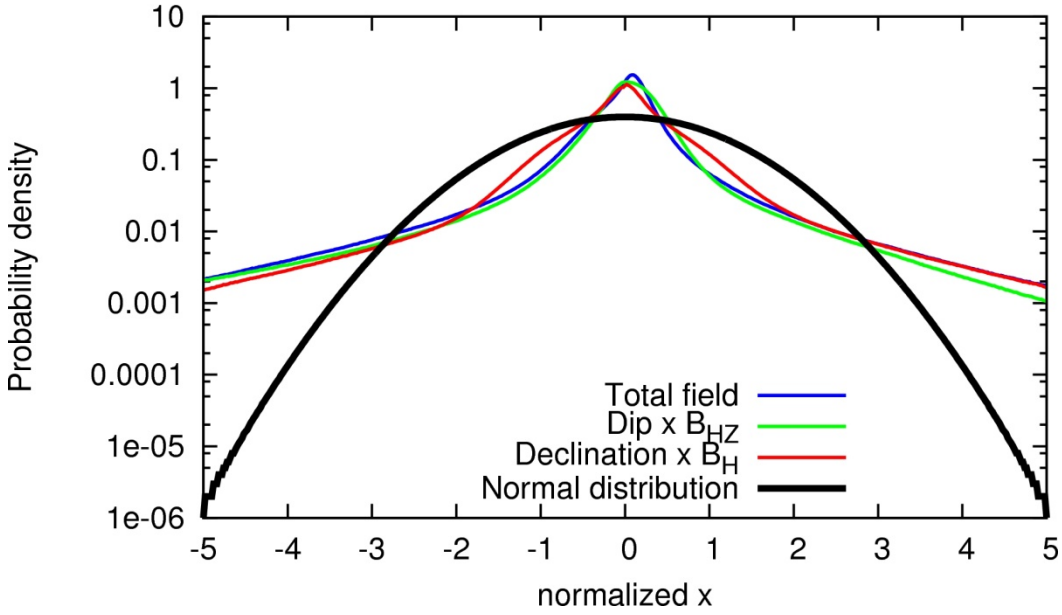
http://spidr.ngdc.noaa.gov/spidr

Data from 1995 to 2006, covering one full solar cycle

Disturbance field error distribution

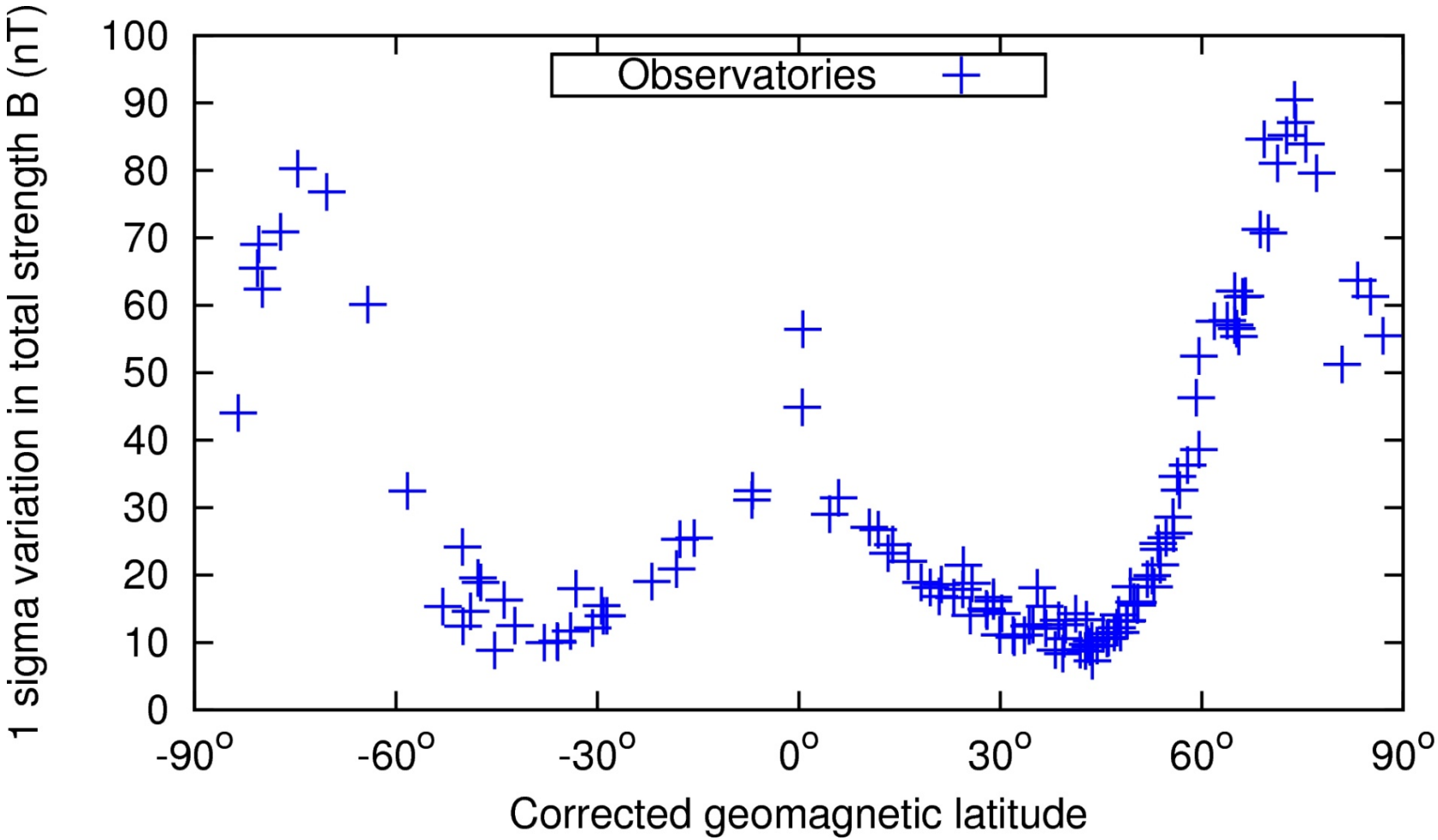


Disturbance field error distribution logarithmic scale

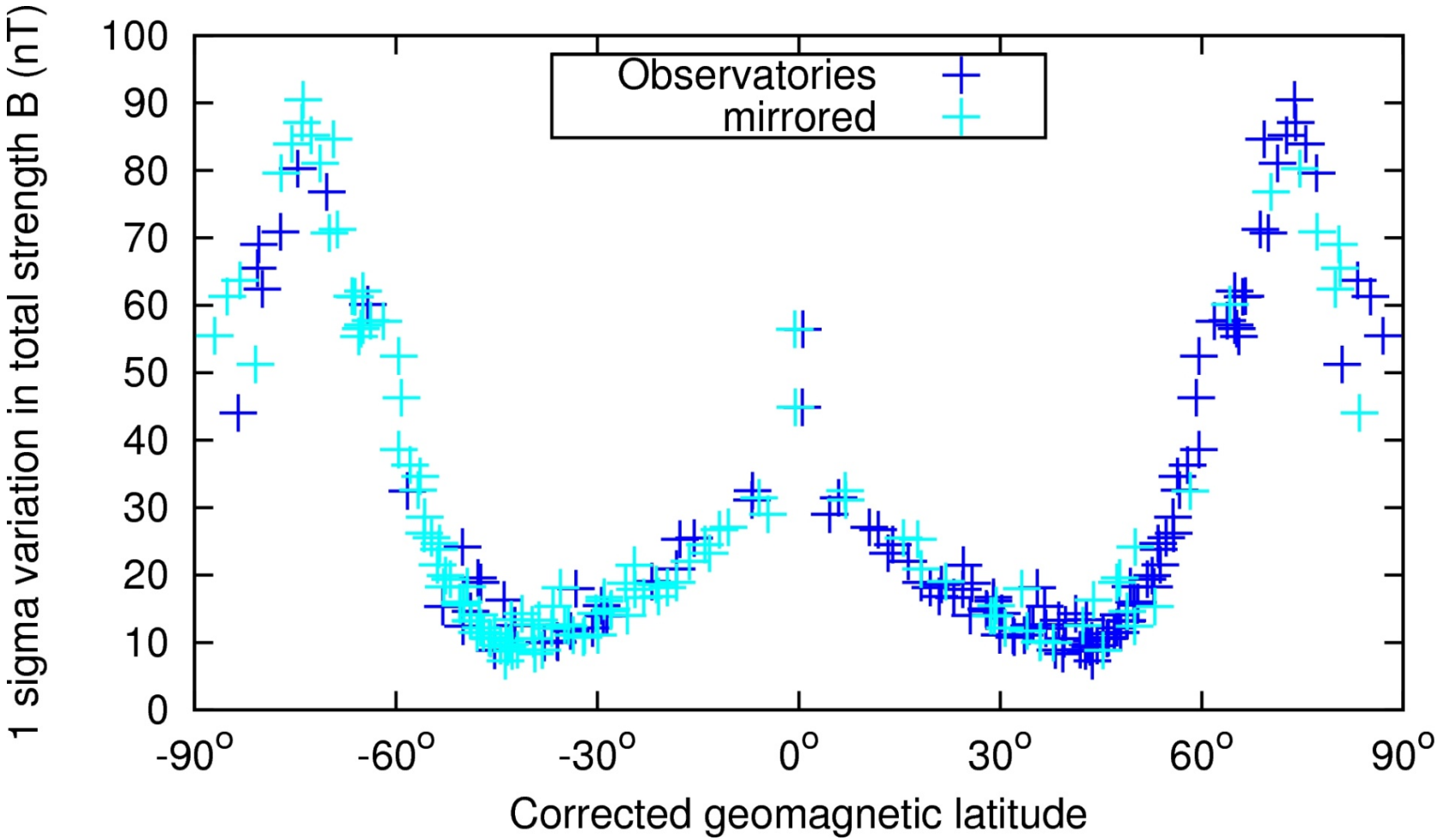


	68.3%		95.4%		99.7%	
	σ	Offset	σ	Offset	σ	Offset
B	0.4	-60%	1.96	-2%	6.68	113%
Dip	0.4	-60%	1.74	-13%	7.04	135%
Declination	0.56	-44%	1.82	-9%	6.28	110%

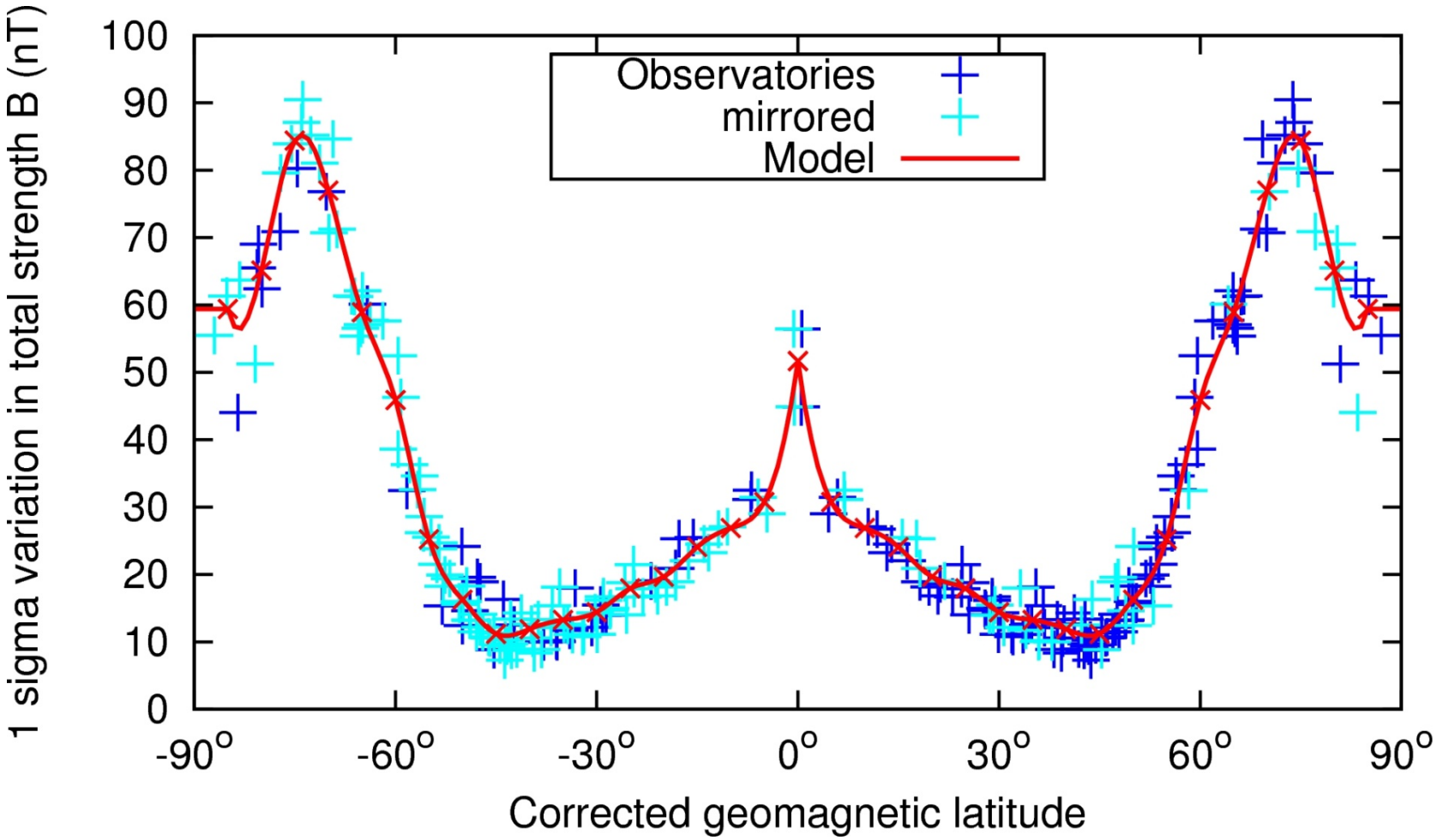
Disturbance field variation in total field (B) by corrected geomagnetic latitude



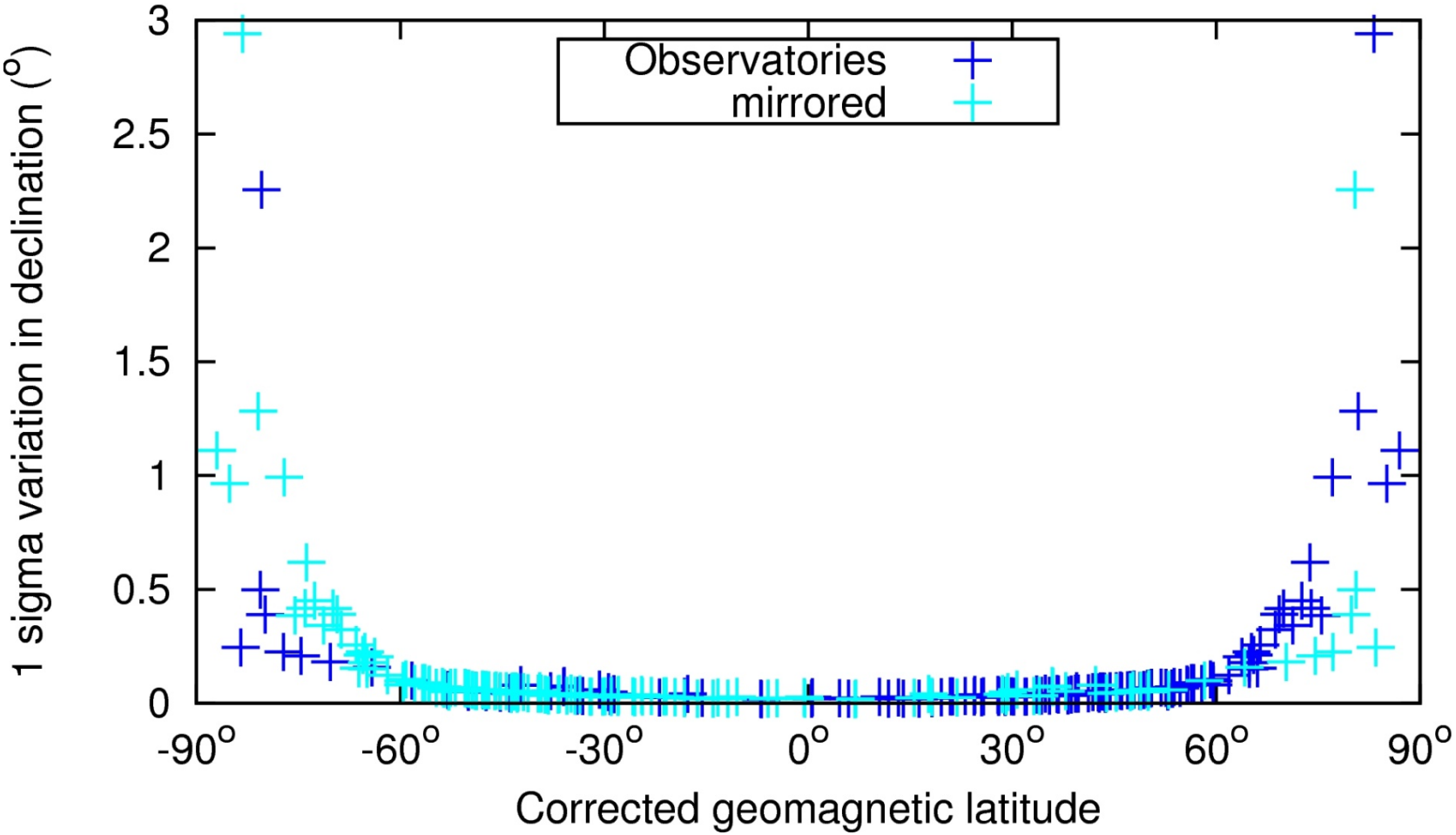
Disturbance field variation in total field (B)



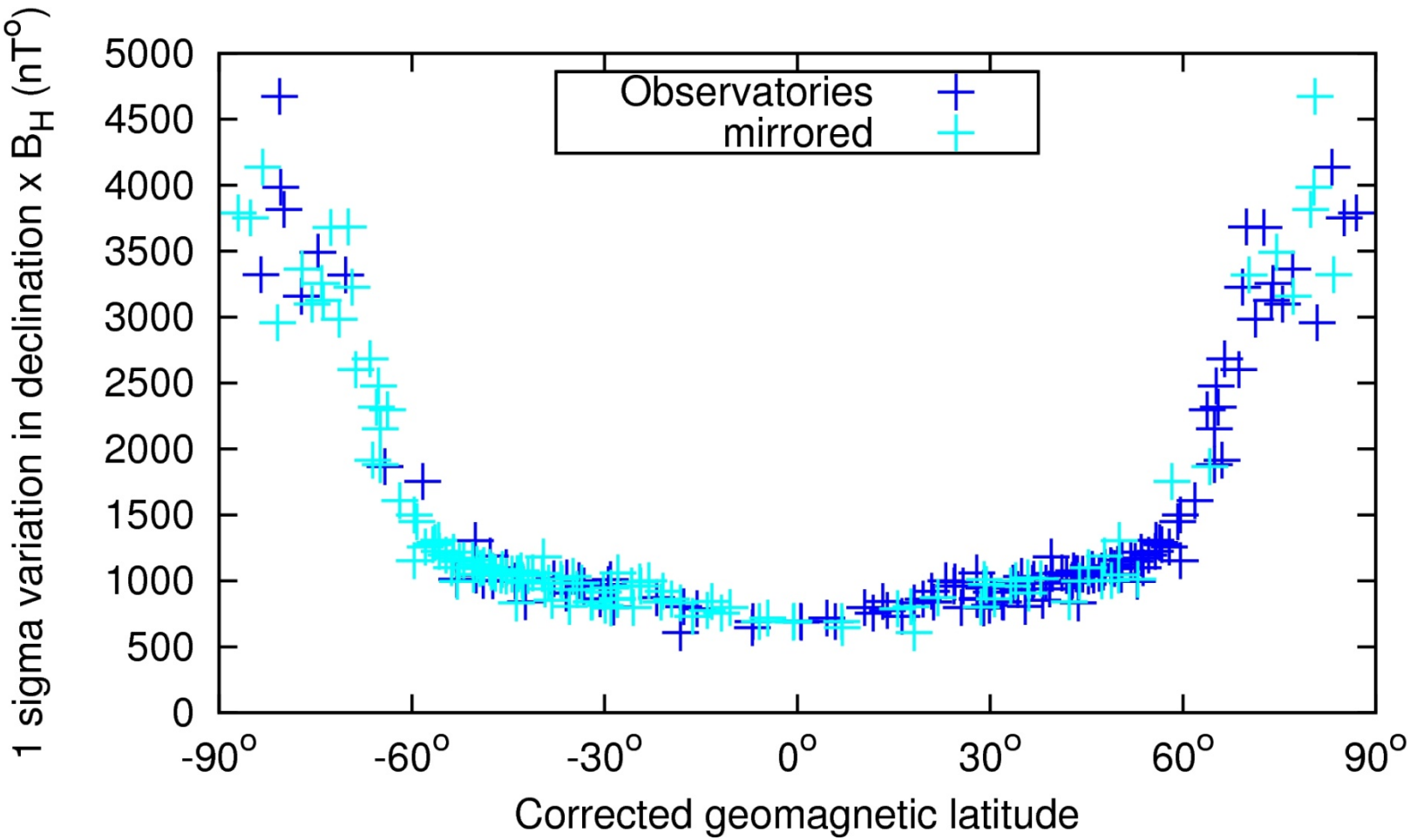
Disturbance field variation in total field (B)



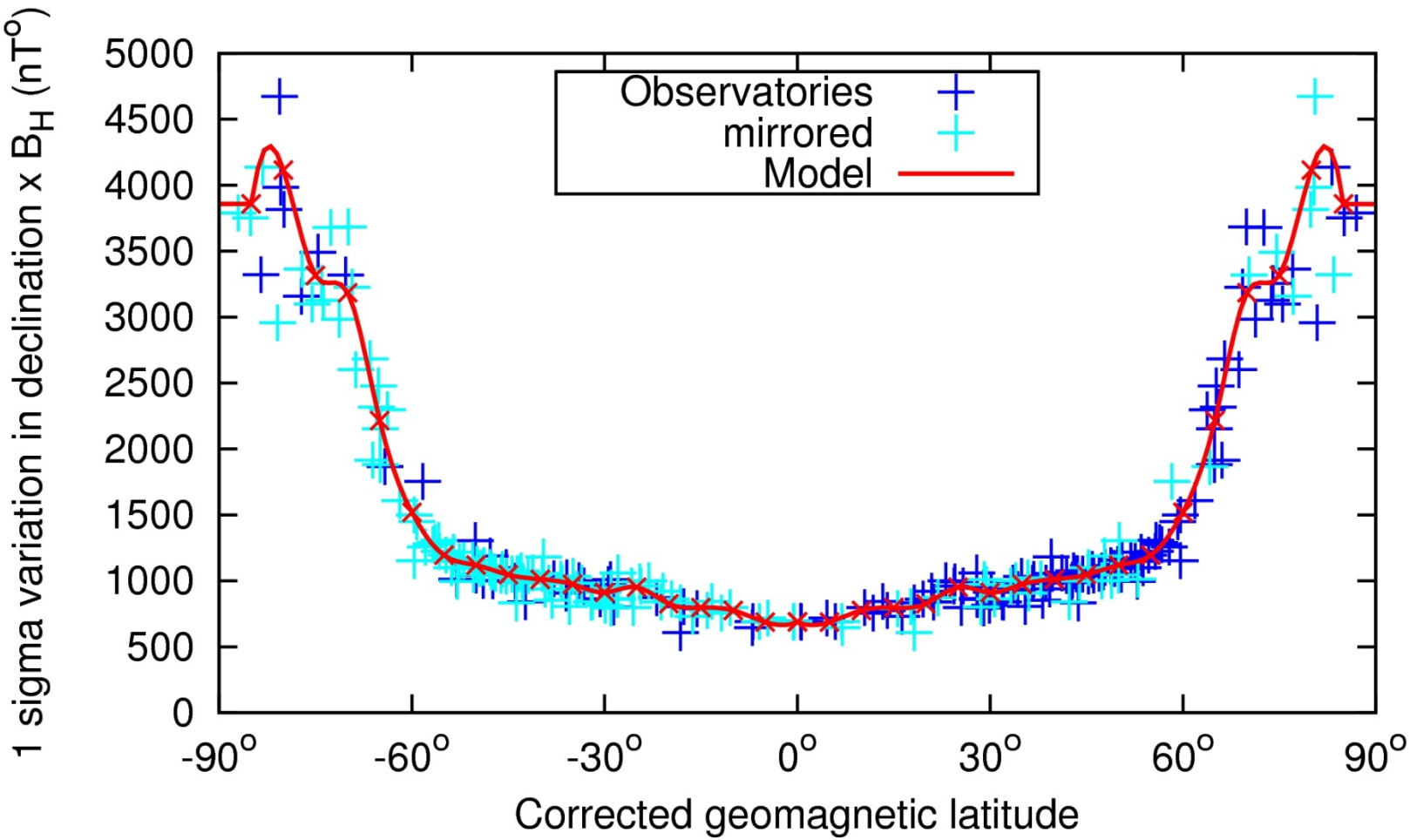
Disturbance field variation in declination



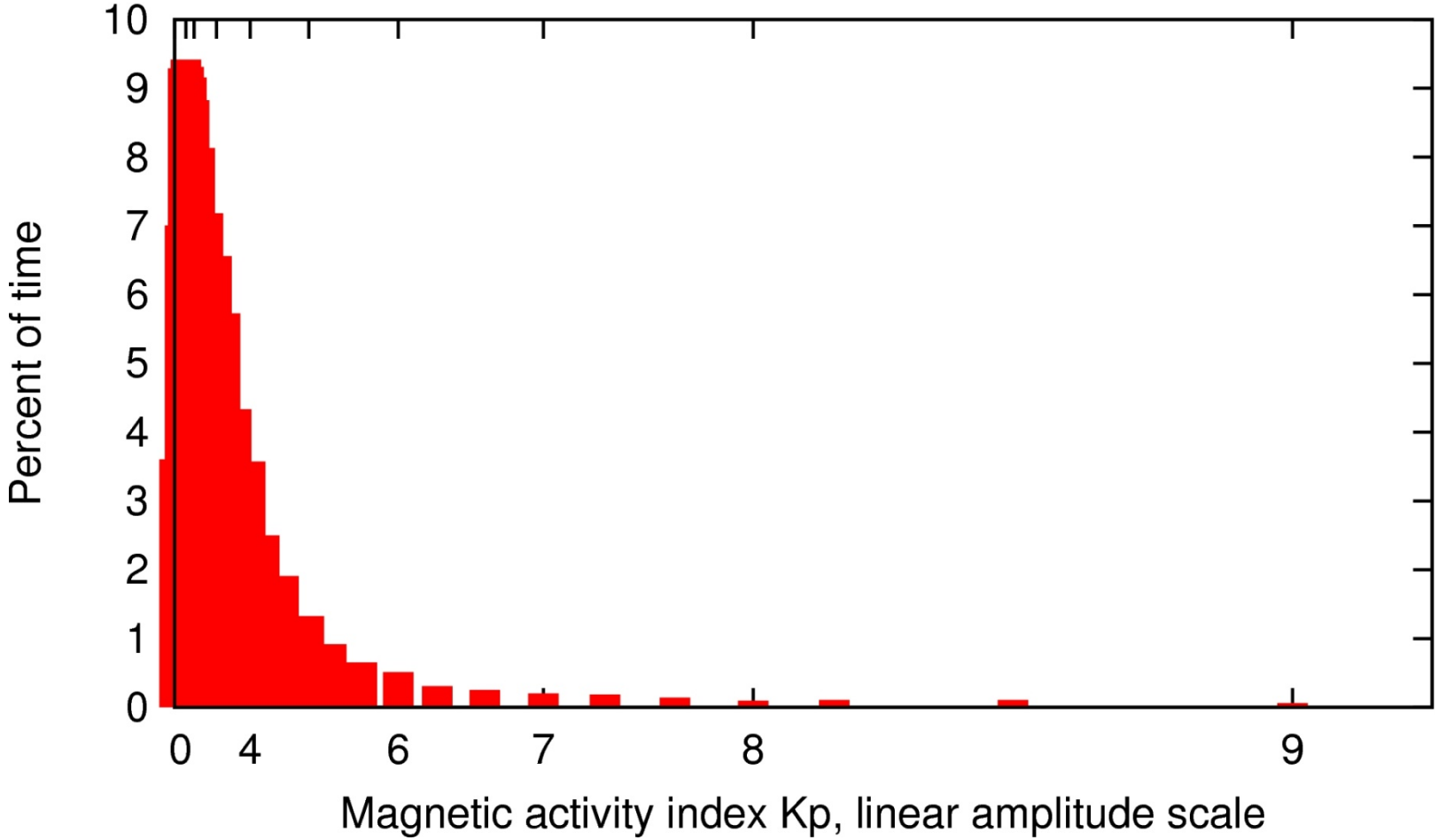
Disturbance field variation in declination x B_H



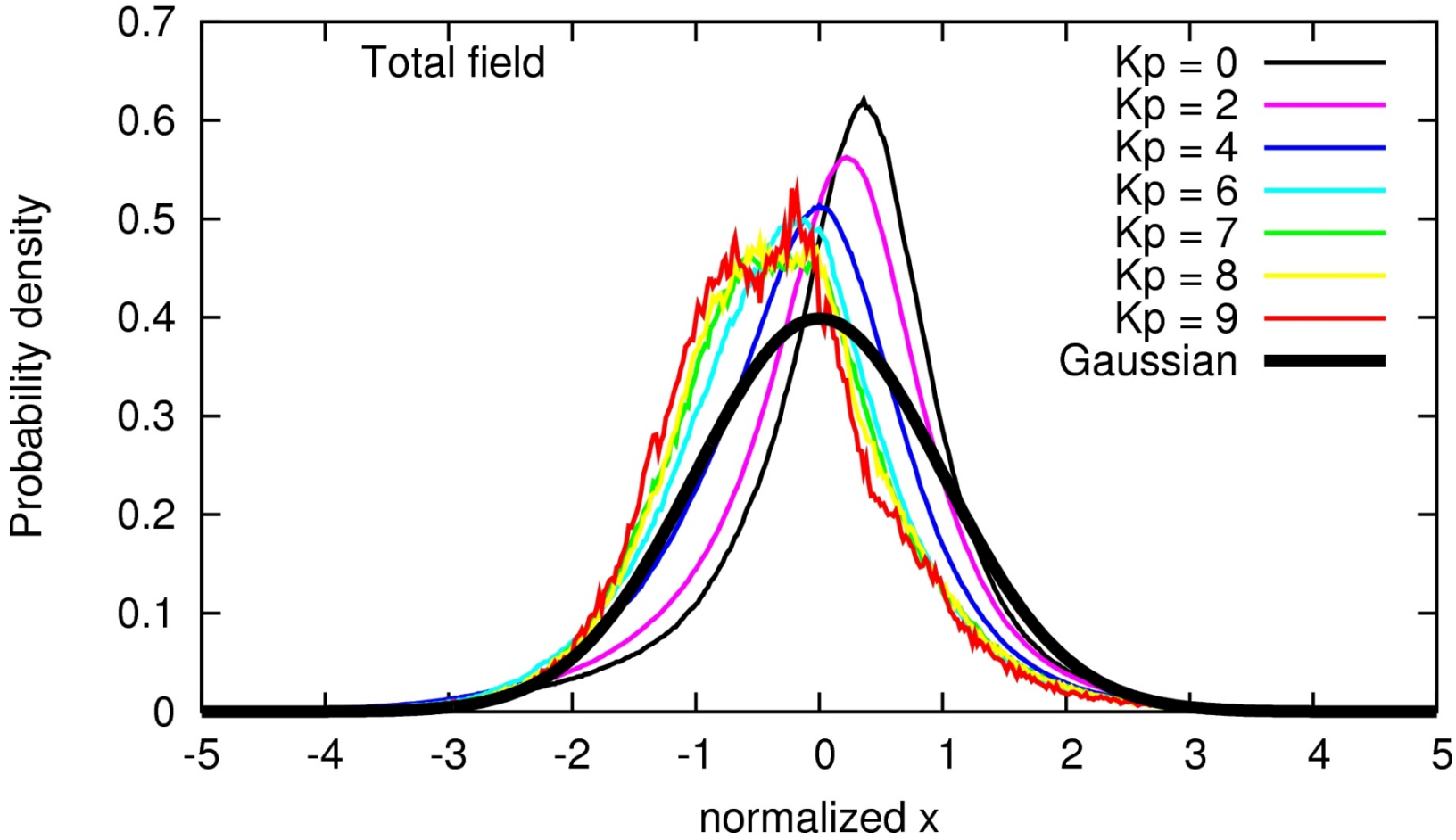
Disturbance field variation in declination x B_H



Histogram of magnetic activity (Kp index)



Error distributions standardized to σ=1 by magnetic latitude (CGM) and activity (Kp)



Prudhoe Bay example (148.7 W, 70.3N)
Declination error (2σ)

	Survey #	Main field error	Crustal field error	Disturbance field error	Total error	Updated Willmsn (simple)
Past	1					
	40					
	80					
	120					
Today	150					
Tomorrow	160					
Future	180+					

Prudhoe Bay example (148.7 W, 70.3N) Declination error (2σ)

Using simple error model:

Magnetic horizontal strength (B_H): 19 100 nT

Magnetic reference model: HDGM

	Survey #	Main field error	Crustal field error	Disturbance field error (simple)	Total error (accurate)	Updated Willmsn (simple)
Past	1	0.04º	0.50º	0.19º		0.53º
	40	0.04º	0.50º	0.19º		0.53º
	80	0.04º	0.50º	0.19º		0.53º
	120	0.04º	0.50º	0.19º		0.53º
Today	150	0.04º	0.50º	0.19º		0.53º
Tomorrow	160	0.04º	0.50º	0.19º		0.53º
Future	180+	0.04º	0.50º	0.19º		0.53º

Prudhoe Bay example (148.7 W, 70.3N) Declination error (2σ)

Using accurate error model:

Corrected geomagnetic latitude (CGM): 70.4º

Magnetic horizontal strength (B_H): 19 100 nT

Magnetic vertical strength (B_Z): 50 000 nT

Magnetic reference model: HDGM

	Survey #	Main field error	Crustal field error	Disturbance field error (accurate)	Total error (accurate)	Updated Willmsn (simple)
Past	1	0.04º	0.50º			0.53º
	40	0.04º	0.50º			0.53º
	80	0.04º	0.50º			0.53º
	120	0.04º	0.50º			0.53º
Today	150	0.04º	0.50º			0.53º
Tomorrow	160	0.04º	0.50º			0.53º
Future	180+	0.04º	0.50º	0.34º	0.61º	0.53º

Prudhoe Bay example (148.7 W, 70.3N) Declination error (2σ)

Using accurate error model:

Corrected geomagnetic latitude (CGM): 70.4º

Magnetic horizontal strength (B_H): 19 100 nT

Magnetic vertical strength (B_Z): 50 000 nT

Magnetic reference model: HDGM

	Survey #	Main field error	Crustal field error	Disturbance field error (accurate)	Total error (accurate)	Updated Willmsn (simple)
Past	1	0.04º	0.50º	0.12º (Kp=0)	0.52º	0.53º
	40	0.04º	0.50º	0.26º (Kp=2)	0.56º	0.53º
	80	0.04º	0.50º	2.04º (Kp=9)	2.10º	0.53º
	120	0.04º	0.50º	0.80º (Kp=6)	0.94º	0.53º
Today	150	0.04º	0.50º			0.53º
Tomorrow	160	0.04º	0.50º			0.53º
Future	180+	0.04º	0.50º	0.34º	0.61º	0.53º

Prudhoe Bay example (148.7 W, 70.3N) Declination error (2σ)

Using accurate error model:

Corrected geomagnetic latitude (CGM): 70.4º

Magnetic horizontal strength (B_H): 19 100 nT

Magnetic vertical strength (B_Z): 50 000 nT

Magnetic reference model: HDGM

	Survey #	Main field error	Crustal field error	Disturbance field error (accurate)	Total error (accurate)	Updated Willmsn (simple)
Past	1	0.04º	0.50º	0.12º (Kp=0)	0.52º	0.53º
	40	0.04º	0.50º	0.26º (Kp=2)	0.56º	0.53º
	80	0.04º	0.50º	2.04º (Kp=9)	2.10º	0.53º
	120	0.04º	0.50º	0.80º (Kp=6)	0.94º	0.53º
Today	150	0.04º	0.50º	0.18º (Kp=1)	0.53º	0.53º
Tomorrow	160	0.04º	0.50º	0.26º (Kp<2)	0.56º	0.53º
Future	180+	0.04º	0.50º	0.34º	0.61º	0.53º

Summary

Simple error tables for IGRF and HDGM

- Compatible with the ISCWSA-2000 error model
- Breakdown by Main, Crustal and Disturbance field
- Percentiles accounting for non-Gaussian distribution

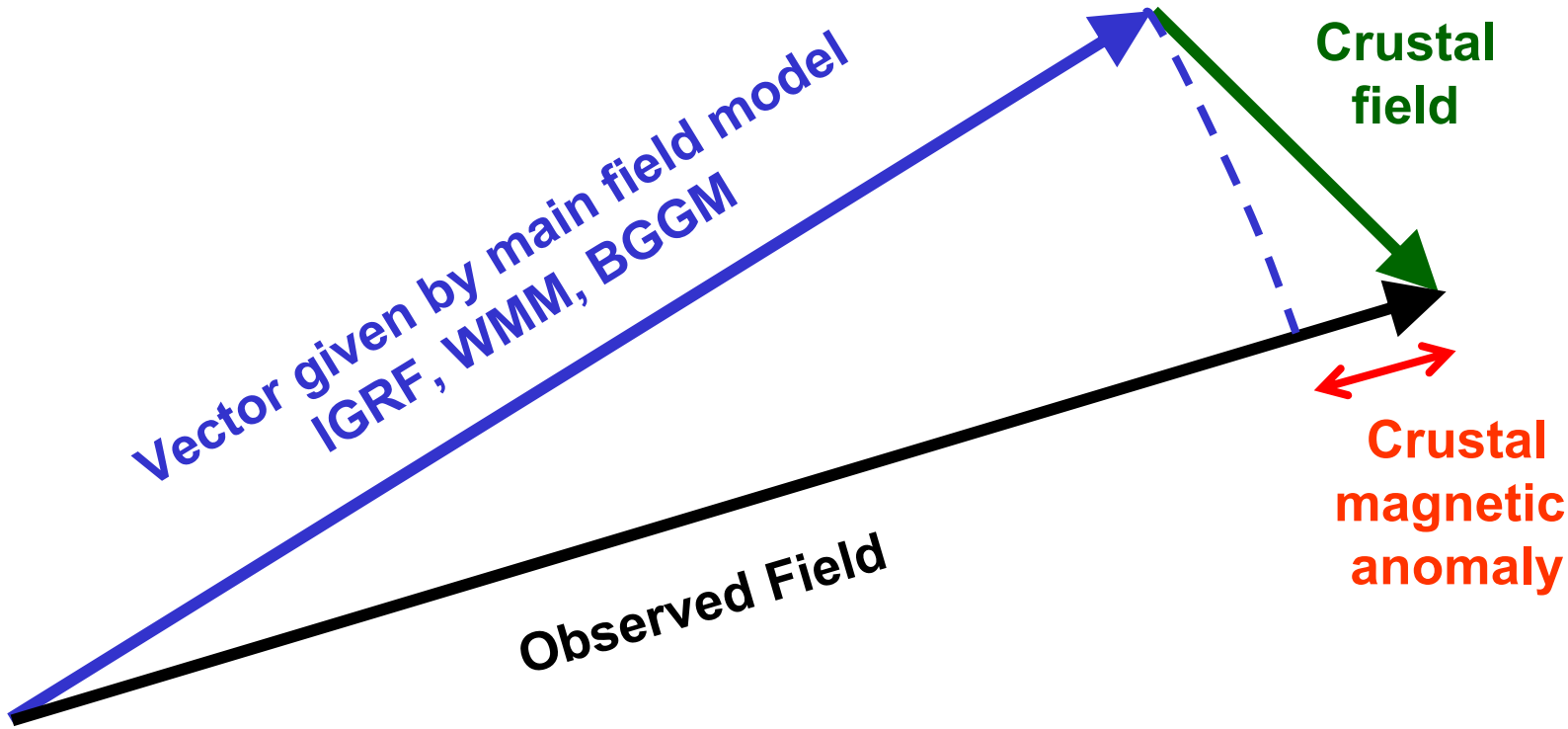
Accurate error model accounting for further factors

- Main field: time since last model update (for IGRF!)
- Crustal field: degree of the model
- Disturbance field: Magnetic latitude and activity (Kp)

Acknowledgement of satellite and observatory data providers

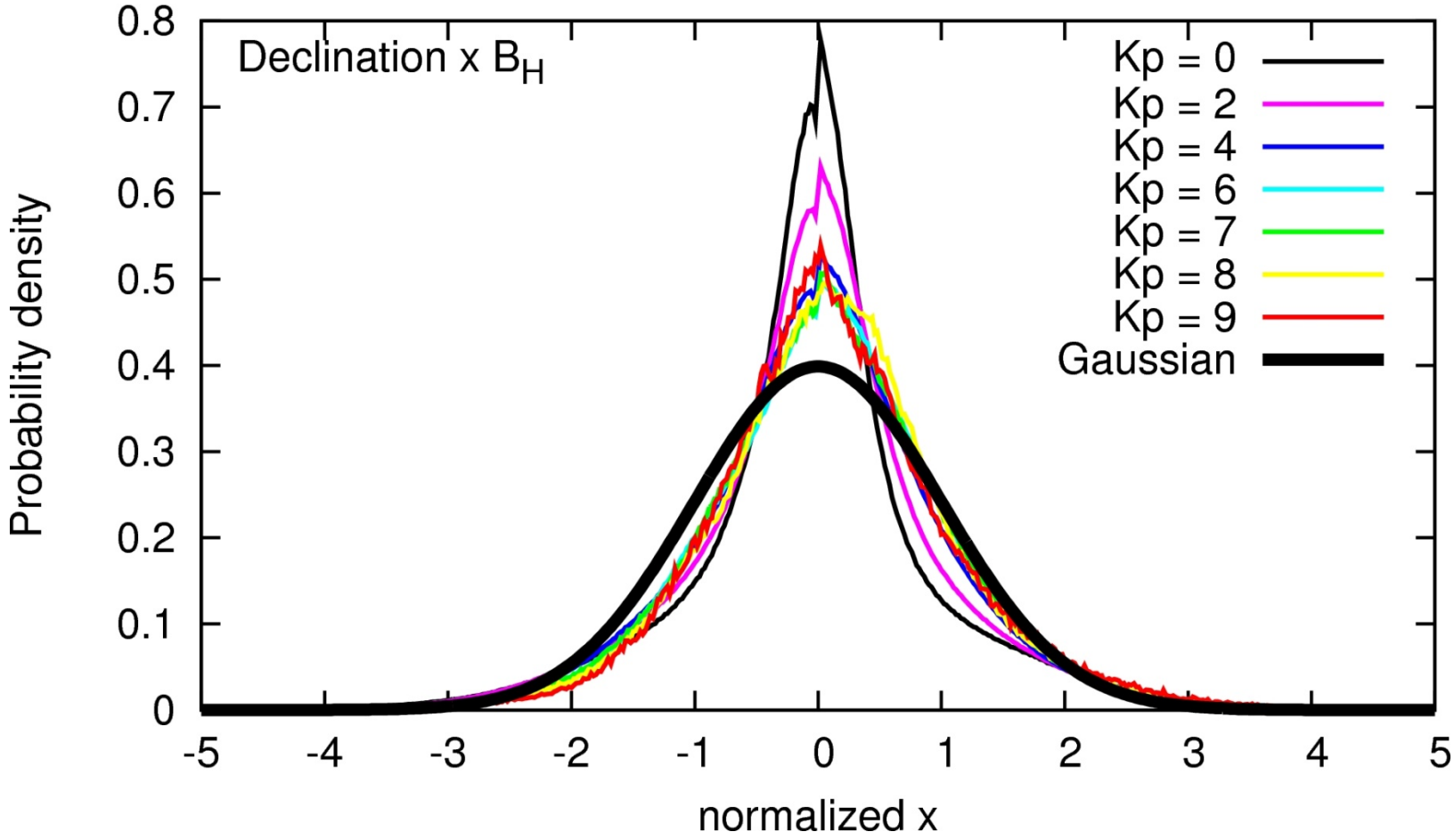
Presentation available at: http://geomag.org/ISCWSA

What is displayed in a crustal magnetic anomaly map?

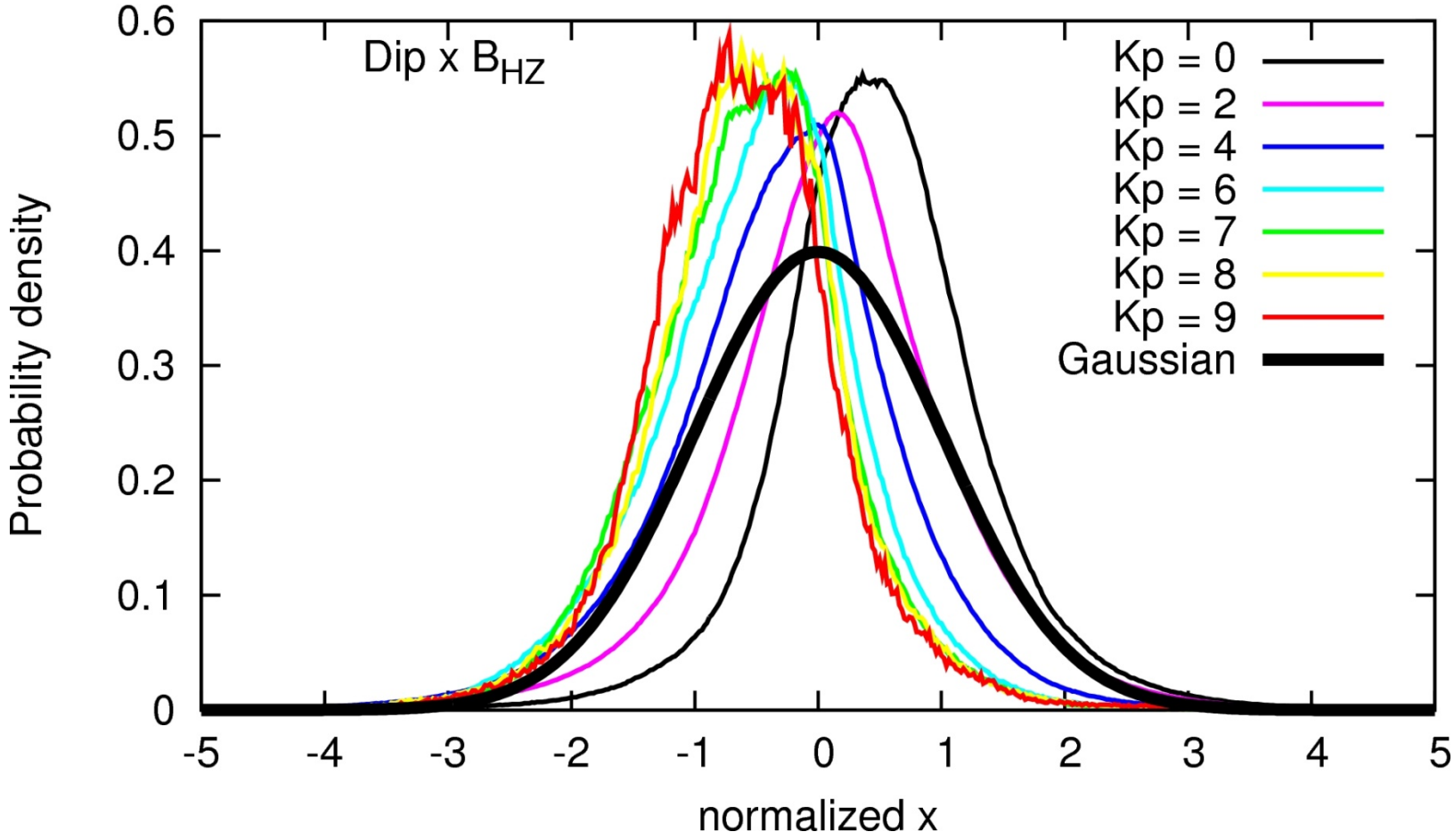


→ **Knowing the main field and the crustal anomaly does not provide the direction and dip of the field. This requires further special processing (In-Field Referencing).**

Error distributions standardized to σ=1 by magnetic latitude (CGM) and activity (Kp)



Error distributions standardized to σ=1 by magnetic latitude (CGM) and activity (Kp)



Prudhoe Bay example (148.7 W, 70.3N) Declination error (99.7%)

Using accurate error model:

Corrected geomagnetic latitude (CGM): 70.4º

Magnetic horizontal strength (B_H): 19 100 nT

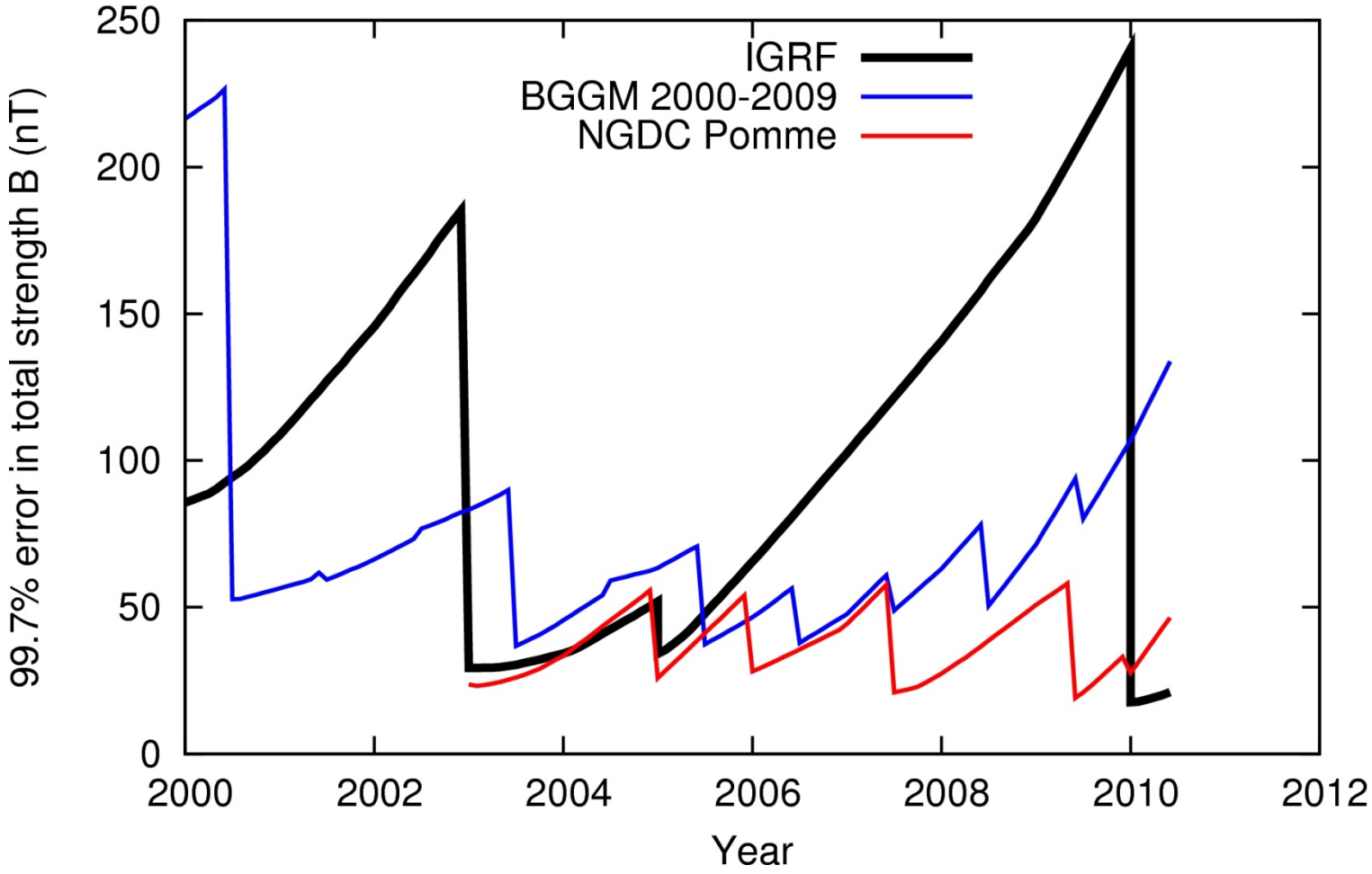
Magnetic vertical strength (B_Z): 50 000 nT

Magnetic reference model: HDGM

	Survey #	Main field error	Crustal field error	Disturbance field error (accurate)	Total error (accurate)	Updated Willmsn (simple)
Past	1	0.10º	1.12º	0.27º (Kp=0)	1.16º	1.27º
	40	0.10º	1.12º	0.55º (Kp=2)	1.25º	1.27º
	80	0.10º	1.12º	4.41º (Kp=9)	4.55º	1.27º
	120	0.10º	1.12º	1.74º (Kp=6)	2.07º	1.27º
Today	150	0.10º	1.12º	0.39º (Kp=1)	1.19º	1.27º
Tomorrow	160	0.10º	1.12º	0.55º (Kp<2)	1.25º	1.27º
Future	180+	0.10º	1.12º	0.91º	1.45º	1.27º

Main field: 99.7% error in total field

against BGGM 2010



Models are accurate on their release date and deteriorate subsequently