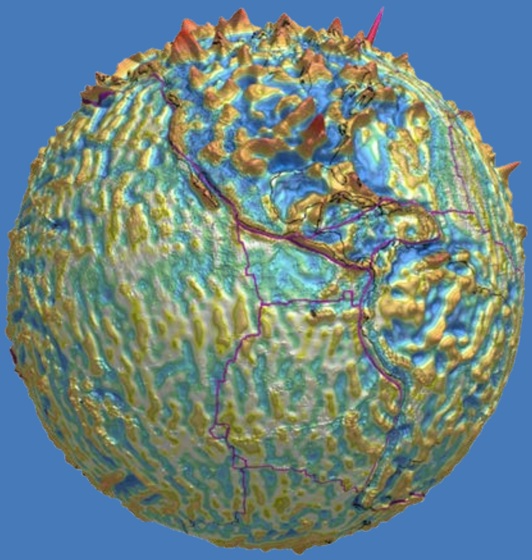
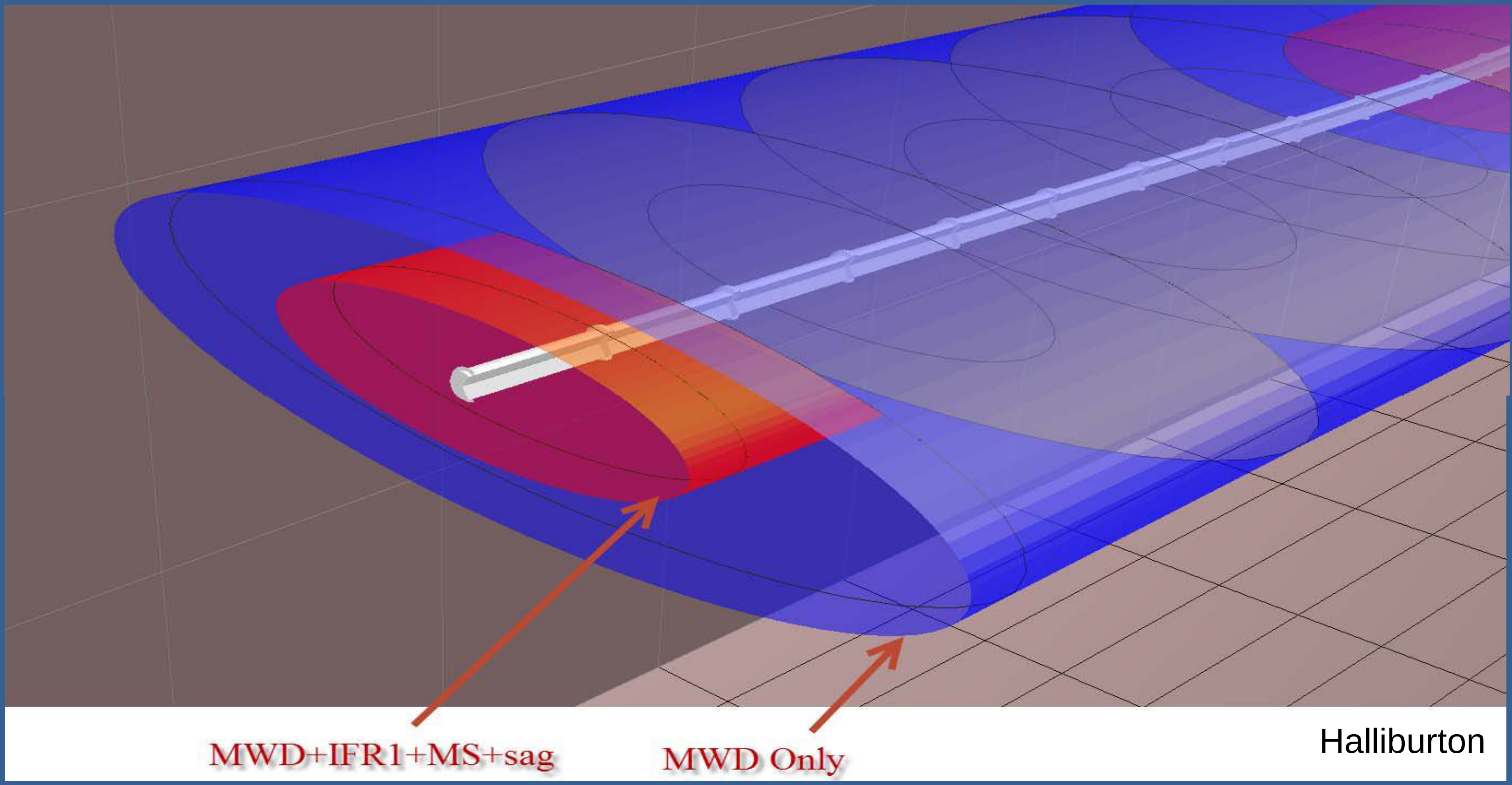
Managing Main & Crustal Magnetic Fields and New Developments in Global Magnetic Modeling



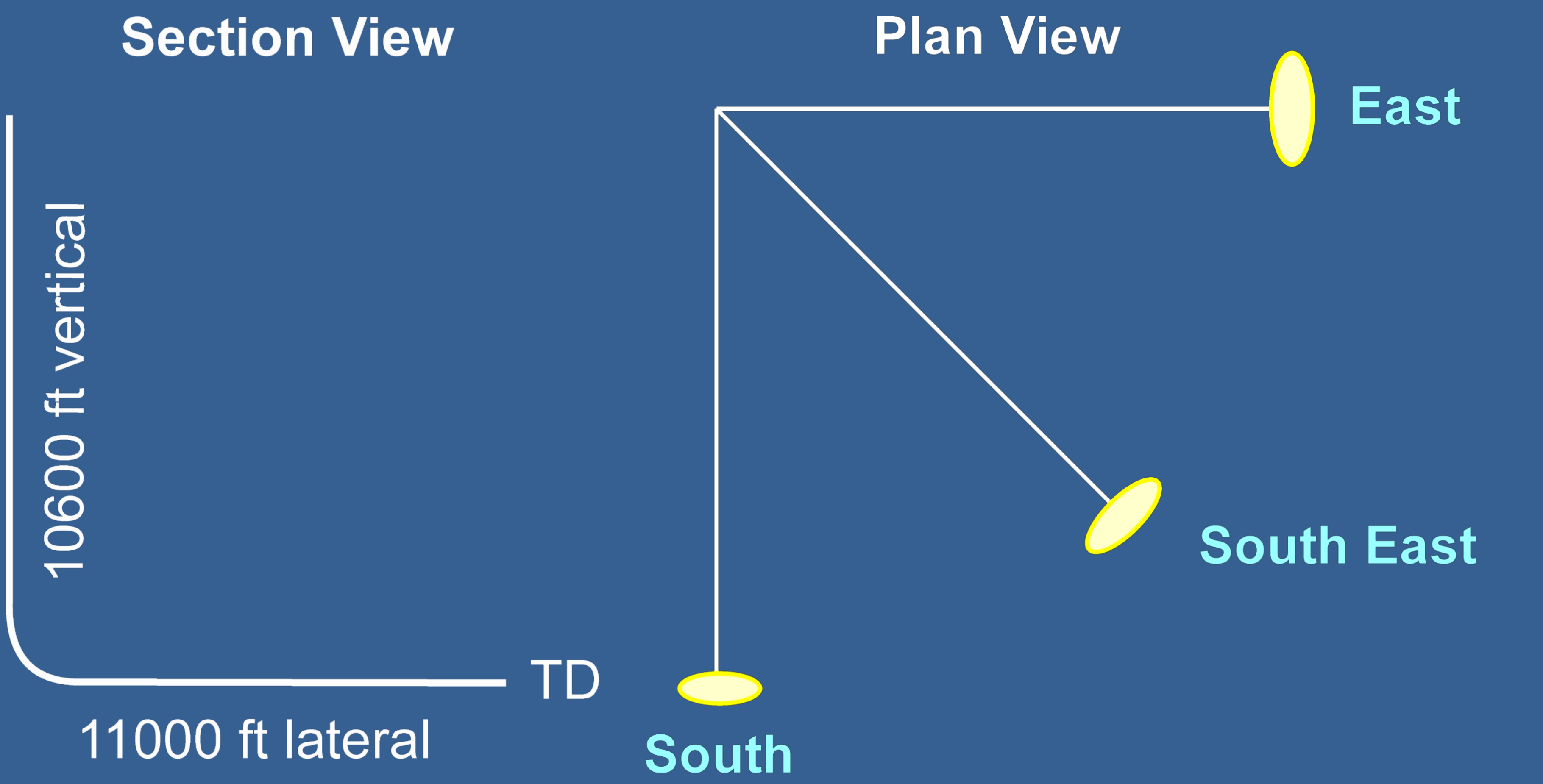
- Wellbore position uncertainty
- SD and HD geomagnetic models
- In-Field Referencing methods
  - Shortcomings of plane grid methods
  - Global ellipsoidal harmonic method
- Texas and Alberta aeromagnetic survey examples

Positional Uncertainty in MWD

- Largest source of lateral error: Magnetic field
- Accurate geomagnetic models and advanced corrections significantly reduce this error



Ellipses of Uncertainty Study



Uncertainties in Middle East

Lateral uncertainty at TD for well with 11,000 ft lateral section

Well Azim.	MWD+IGRF	**MWD**	MWD+HD	MWD +IFR1	MWD +IFR1+MS
	(ft)	**(ft)**	(ft)	(ft)	(ft)
E	370 (+7%)	**345**	325 (-6%)	289 (-16%)	145 (-58%)*
SE	329 (+10%)	**300**	277 (-8%)	233 (-22%)	134 (-55%)
S	266 (+16%)	**229**	199 (-13%)	131 (-43%)	117 (-49%)

*with limitations

Vertical Uncertainty at TD

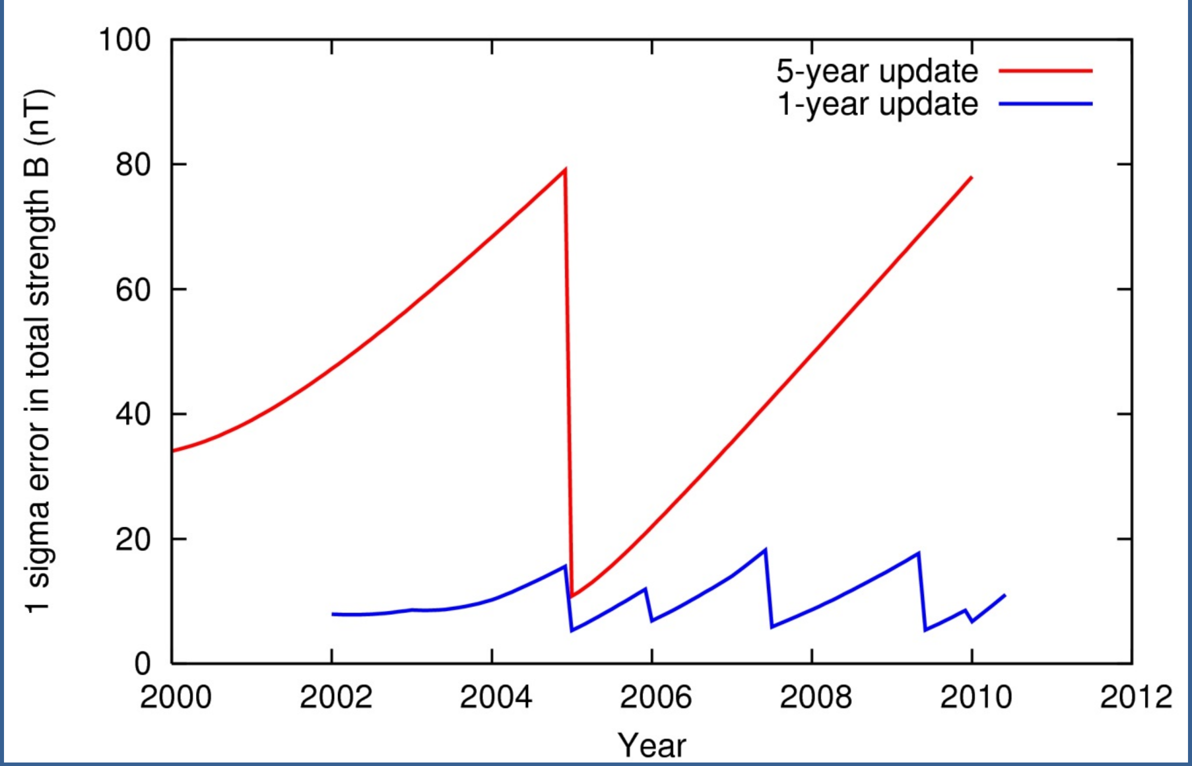
TVD	**MWD**	MWD+IFR1+SAG+MS
10600 ft	**119 ft**	71 ft (-40%)

3D Ellipsoids given for 95% confidence interval = 2.79 sigma

Error model: ISCWSA OWSG 2014

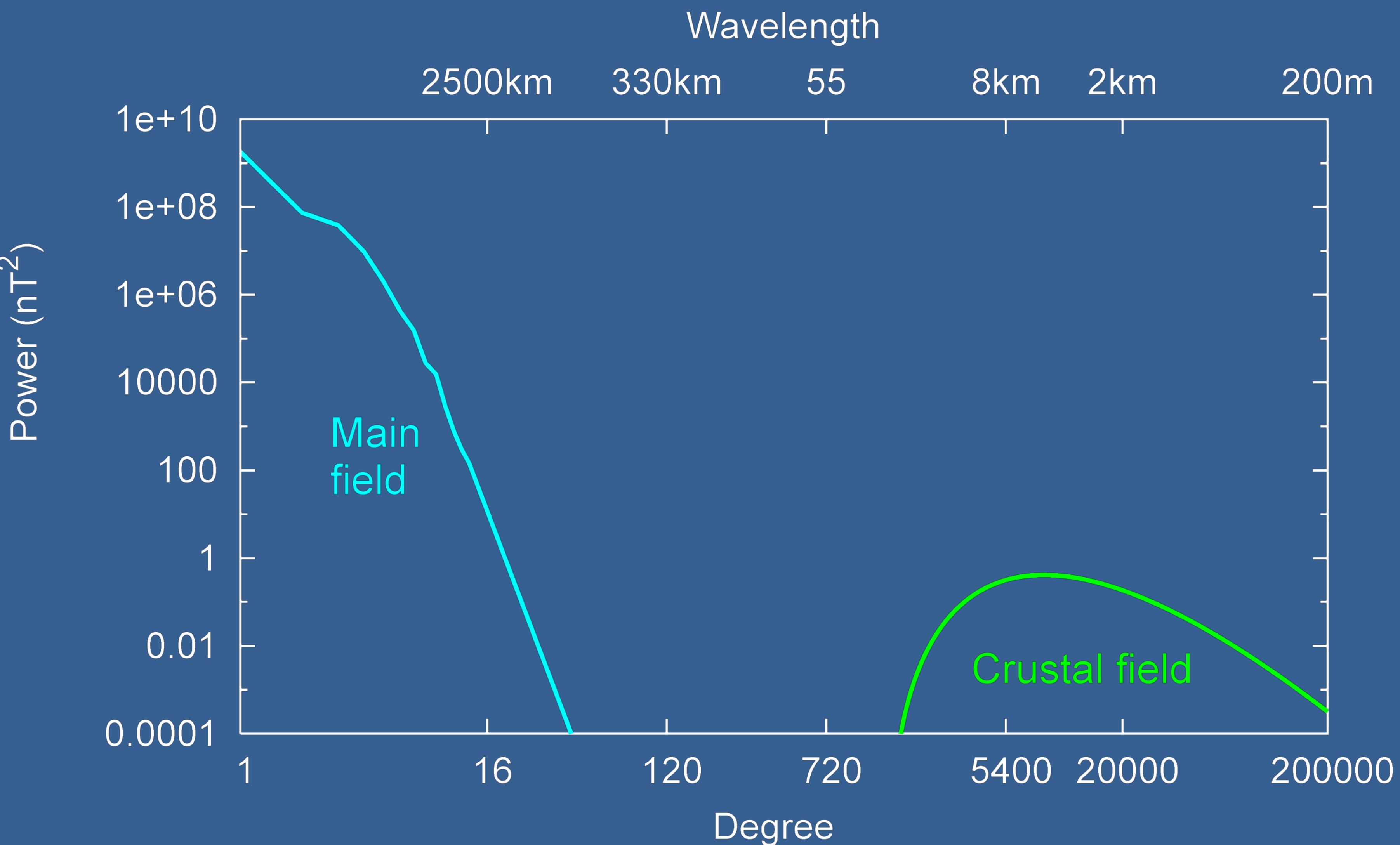
Main Field Commission Error

Only shown is the commission error of the main field.
This does not include errors from omitting the crustal field.

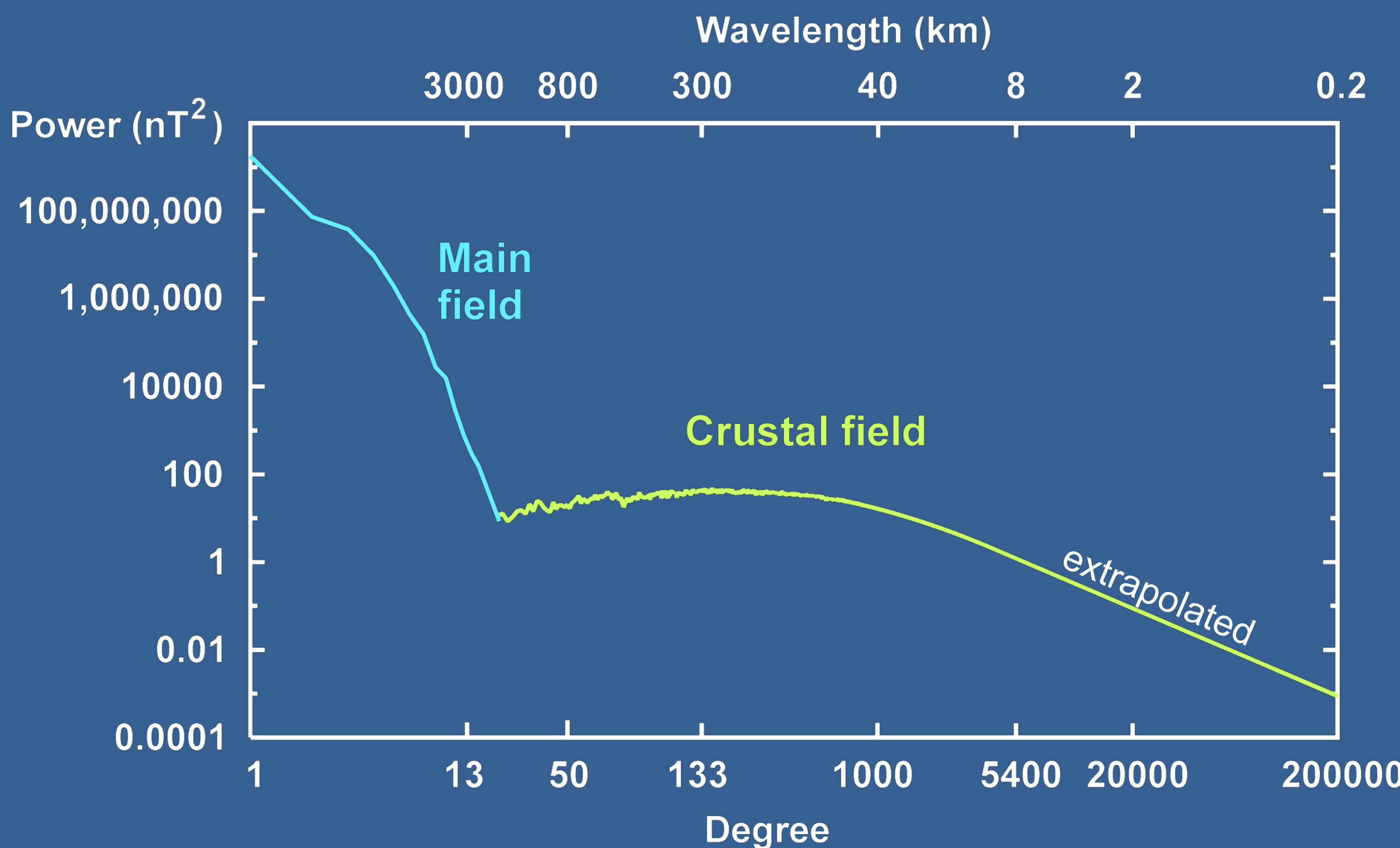


This demonstrates the importance of using annually updated models

Crustal Anomalies: The Old View



Geomagnetic Power Spectrum



Representing the magnetic field

- Magnetic field vector represented as gradient of a potential

$$\boldsymbol{B} = -\boldsymbol{\nabla} V$$

- Potential satisfies LaPlace's differential equation:

$$\boldsymbol{\nabla}^2 V = 0$$

- Harmonic functions satisfy LaPlace's equation
  - Sphere: Spherical harmonics
  - Ellipsoid: Ellipsoidal harmonics
  - Plane: Harmonic waves

Spherical harmonic Models

$$\mathbf{B} = -\nabla V$$

Spherical harmonic expansion of potential *V*

$$V(\lambda,\psi,r,t) = a\sum_{n=1}^{N}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n+1}\left(g_n^m(t)\cos m\lambda + h_n^m(t)\sin m\lambda\right)\mathrm{P}_n^m(\sin\psi)$$

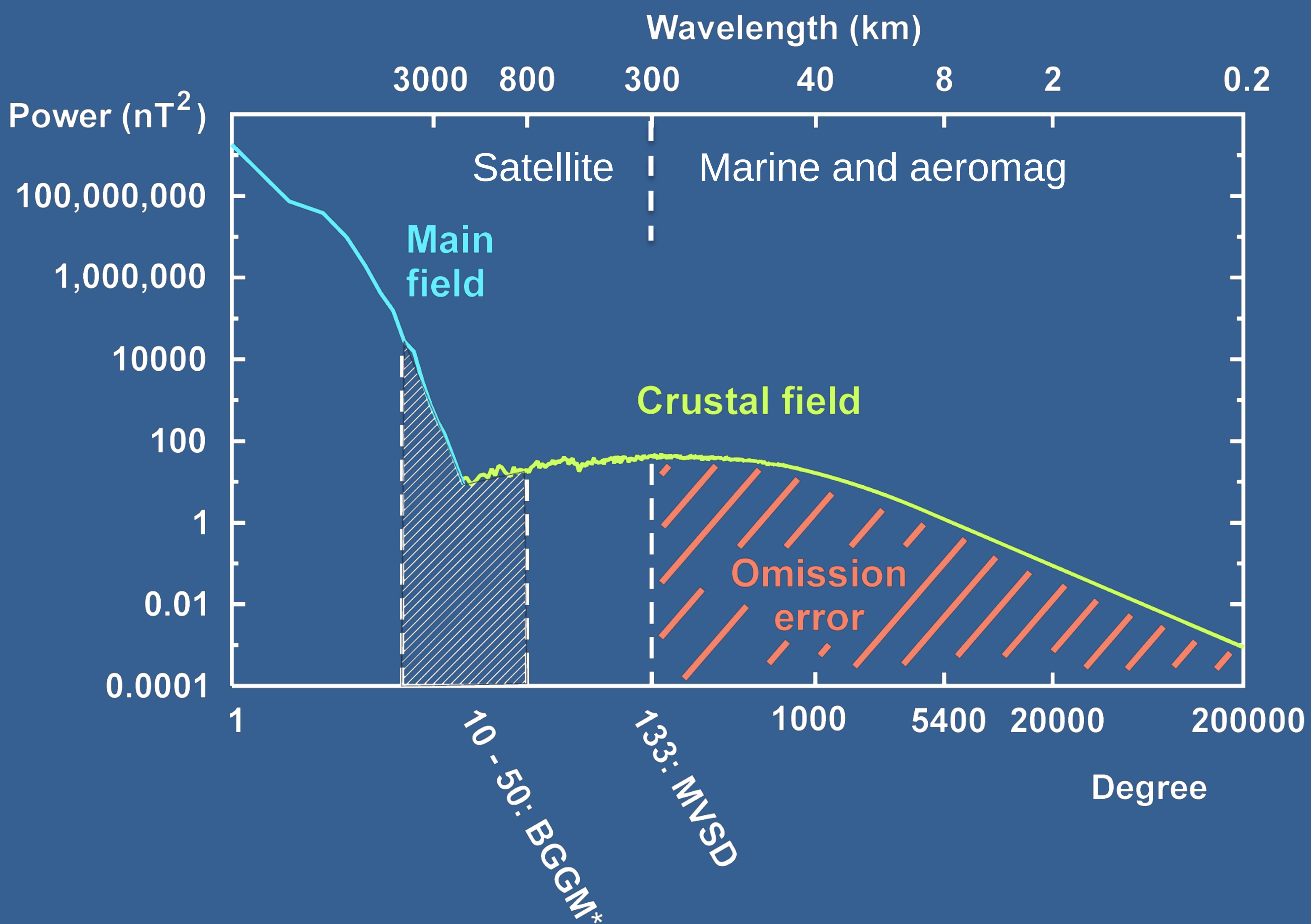
N = Degree of the model

a = Geomagnetic reference radius (6371.2 km)

$g_n^m(t)$ and $h_n^m(t)$: Model coefficients

$\mathrm{P}_n^m(\sin\psi)$: Associated Legendre functions

Standard Definition Models (MWD)

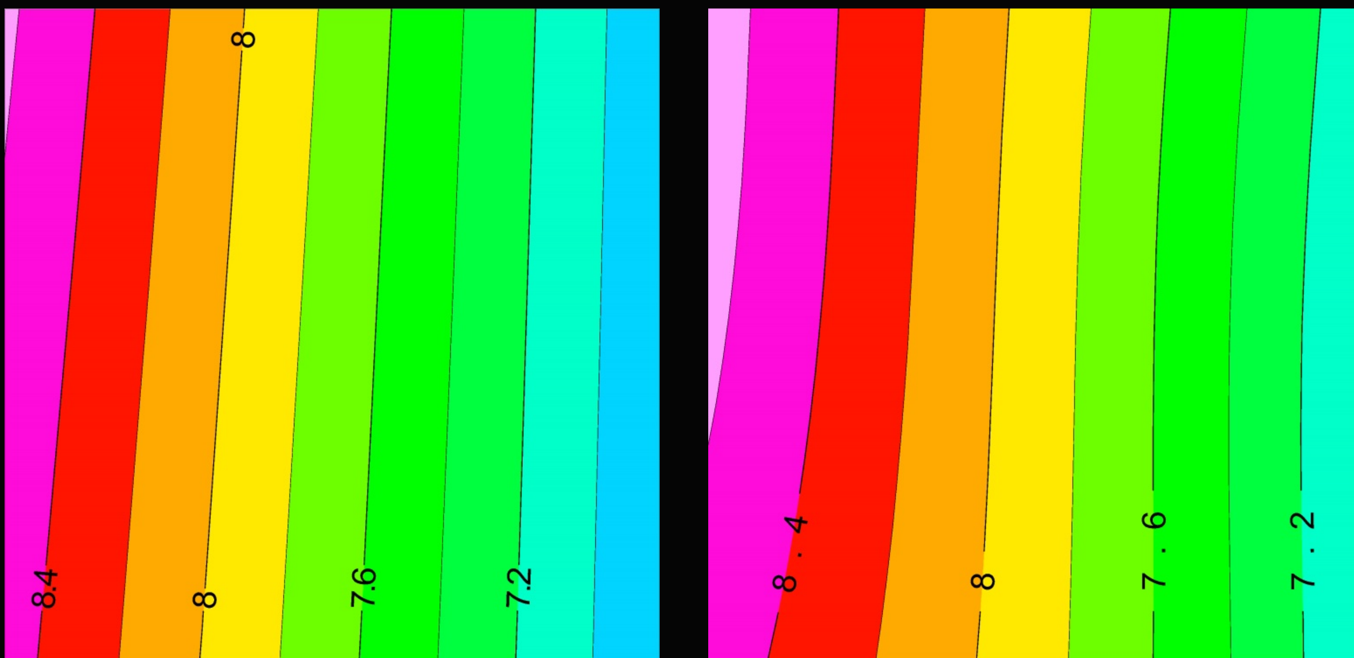


*Degree of BGGM depends on evaluation date

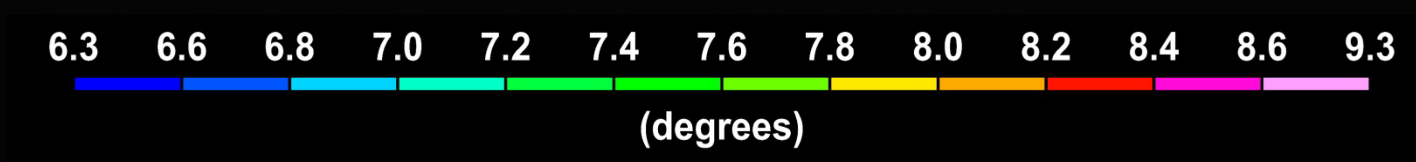
Declination Comparison (Bakken)

Main Field

MVSD



50 mi x 50 mi



SD models: Spherical harmonic expansion of potential

$$V(\lambda,\psi,r)=a\sum_{n=1}^{N}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n+1}\left(g_n^m\cos m\lambda+h_n^m\sin m\lambda\right)\mathrm{P}_n^m(\sin\psi)$$

High Definition models: Ellipsoidal harmonic expansion

$$V(\lambda,\beta,u)=a\sum_{n=1}^{N}\sum_{m=0}^{n}\frac{Q_n^m(i\frac{u}{E})}{Q_n^m(i\frac{b}{E})}\left(g_n^m\cos m\lambda+h_n^m\sin m\lambda\right)\mathrm{P}_n^m(\sin\beta)$$

u = semi-minor axis of confocal ellipsoid at location

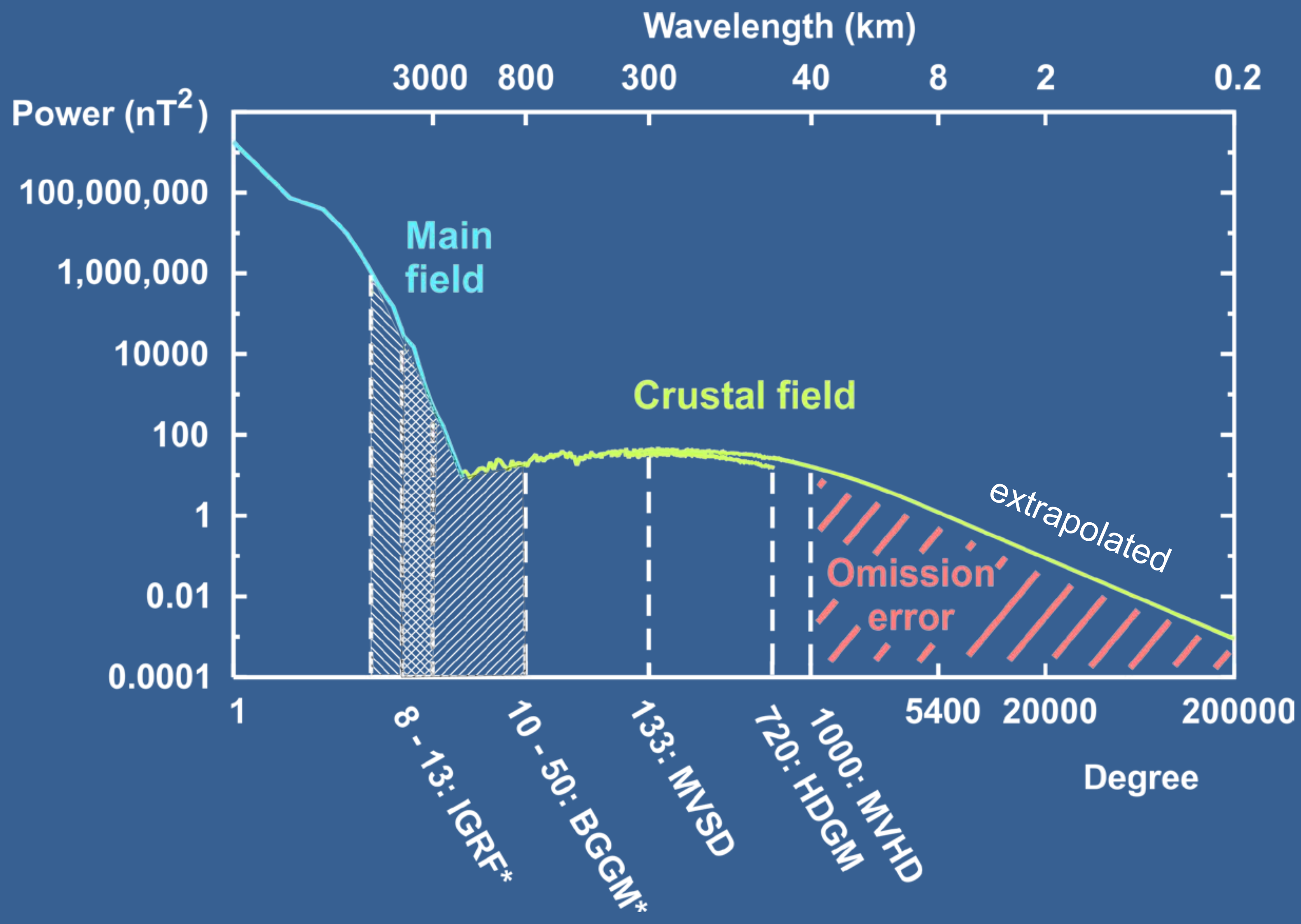
b = semi-minor axis of WGS84 ellipsoid

E = distance of foci from Earth center

β = reduced latitude

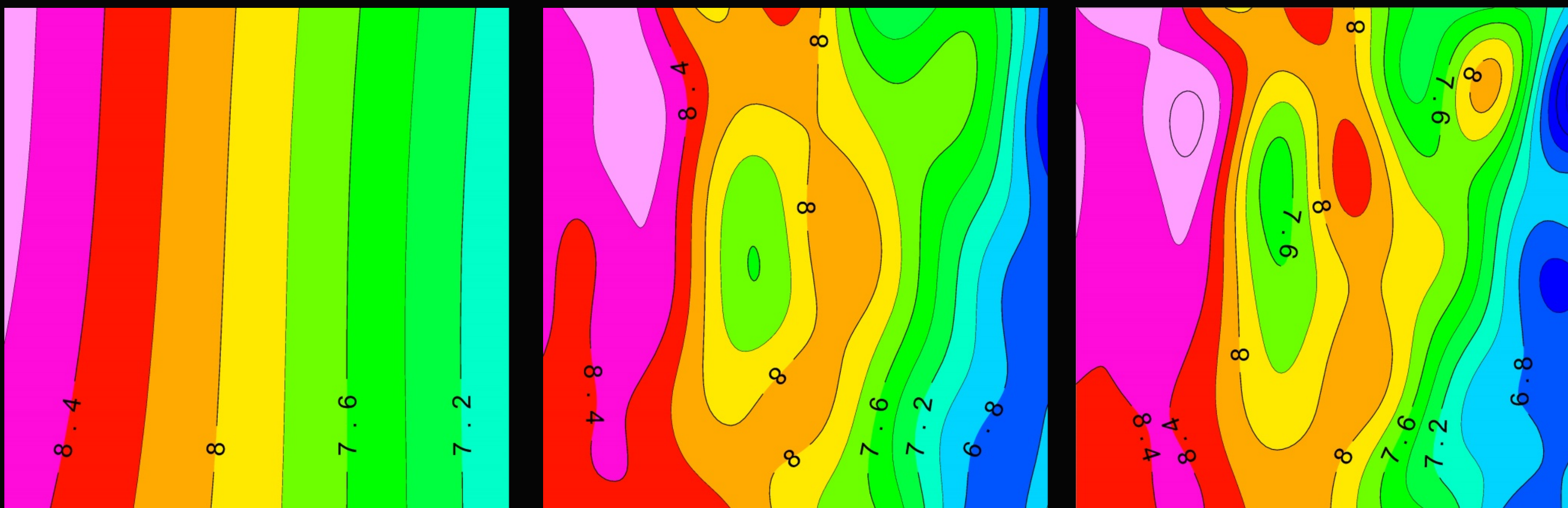
Q_{nm} = Associated Legendre functions of the second kind

High Definition Models (MWD+HD)



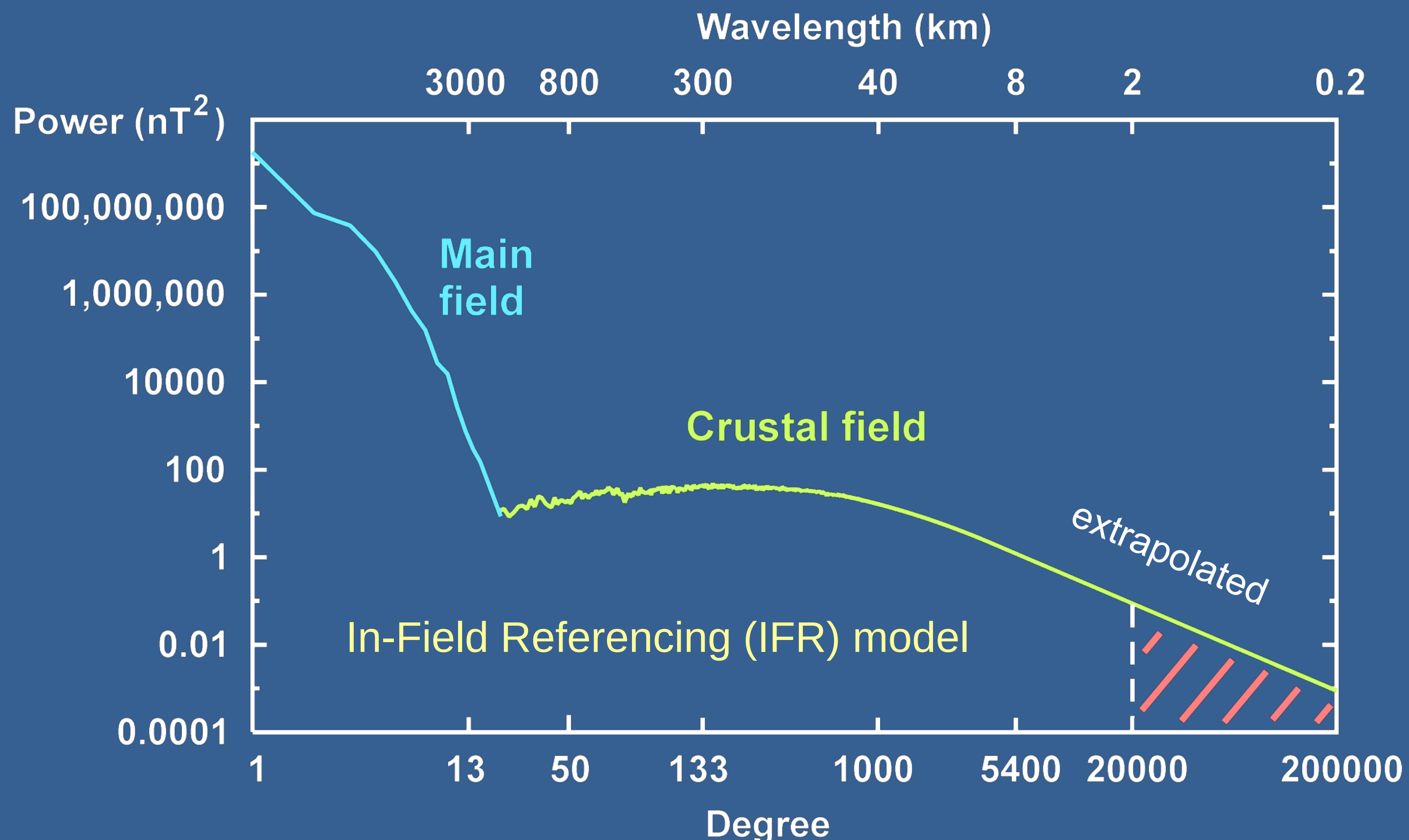
Declination Comparison (Bakken)

MVSD HDGM MVHD



Increasing resolution and accuracy

In-Field Referencing (MWD+IFR)



IFR models combine local marine or airborne magnetic total field measurements with global satellite magnetic data

Solving for the IFR Model

- Magnetic field vector $\boldsymbol{B} = -\boldsymbol{\nabla} V$

- Aeromag surveys measure the total field F, which is the derivative of the potential in the direction of the magnetic field:

$$\mathrm{F} = -\boldsymbol{\nabla} V \cdot \boldsymbol{b}$$

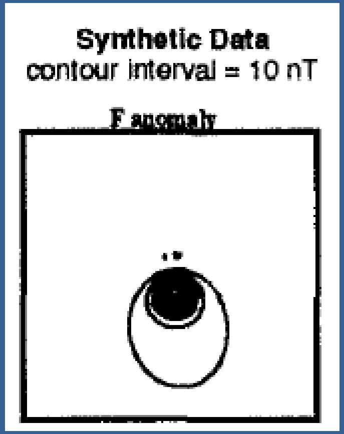
- For a local IFR model, this is not enough information to solve LaPlace's differential equation:

$$\boldsymbol{\nabla}^2 V = 0$$

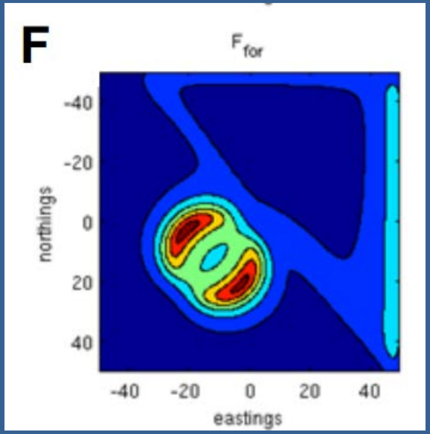
- For a unique solution, have to specify boundary conditions!

Methods Using a Plane Grid

- FFT method (e.g. Dean 1958; Russel, Shiells and Kerridge, SPE 30452, 1995)
- Equivalent source method (Dampney, 1969; Macmillan & Billingham, ISCWSA-40, 2014)
- Both techniques assume that all anomalies are completely contained within the local grid
  - Equivalent to assuming V = 0 on the boundary

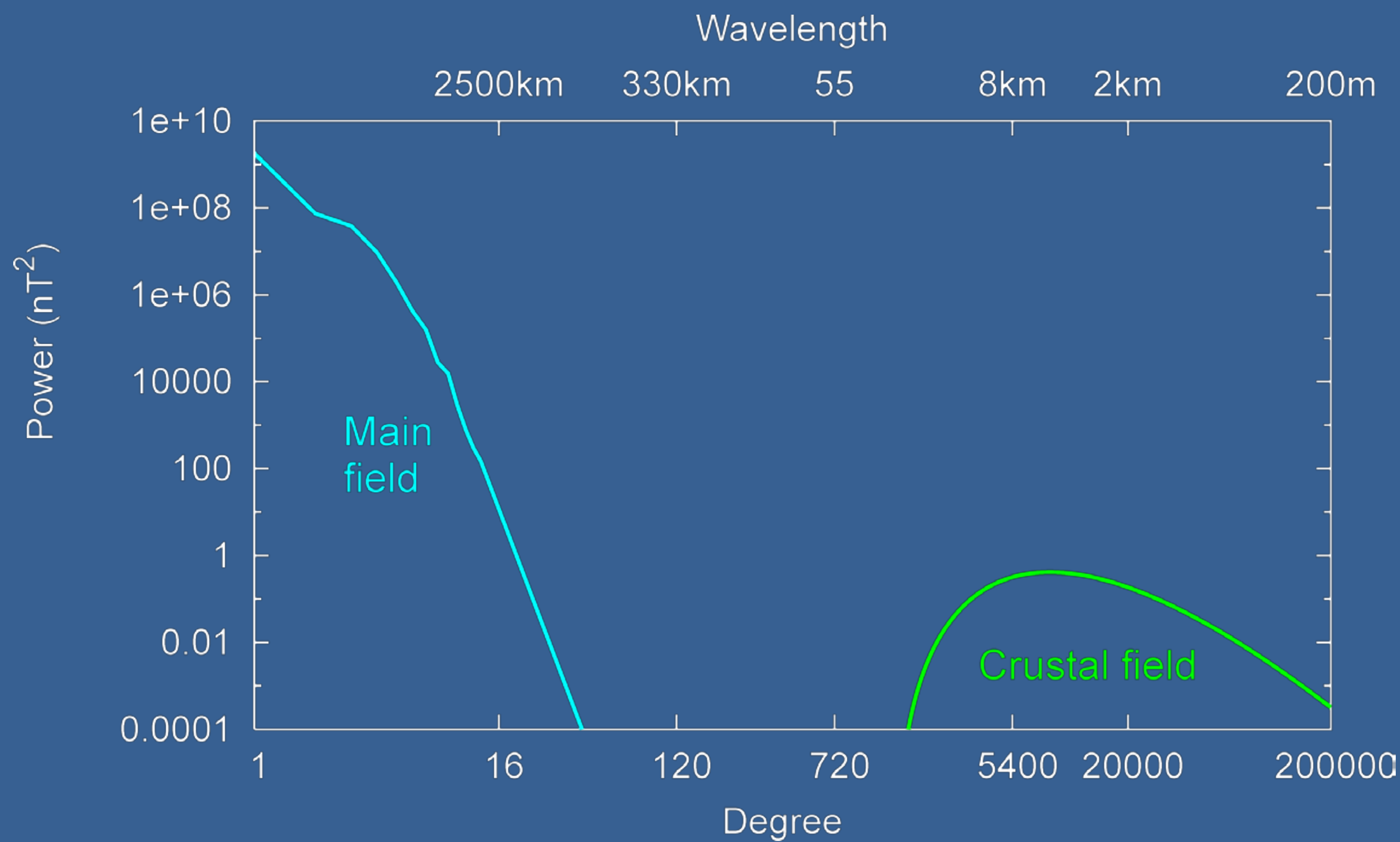


Russel, Shiells and Kerridge, SPE 30452, 1995



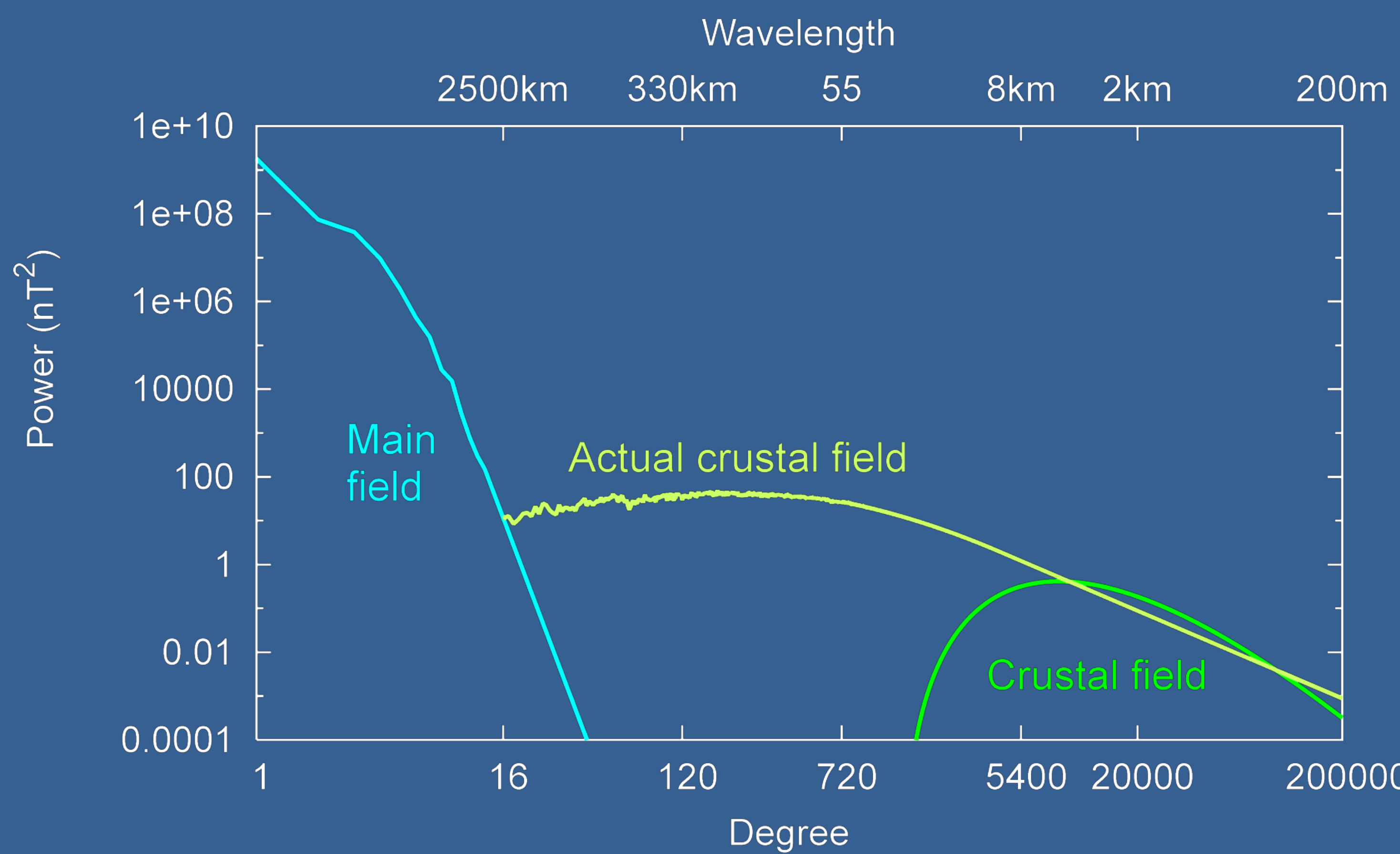
Macmillan & Billingham, ISCWSA-40, 2014

Assumption of Plane Grid Methods



- Grid methods assume that all anomalies are confined to the local grid.
- This implies that there are no wavelengths longer than the grid size.

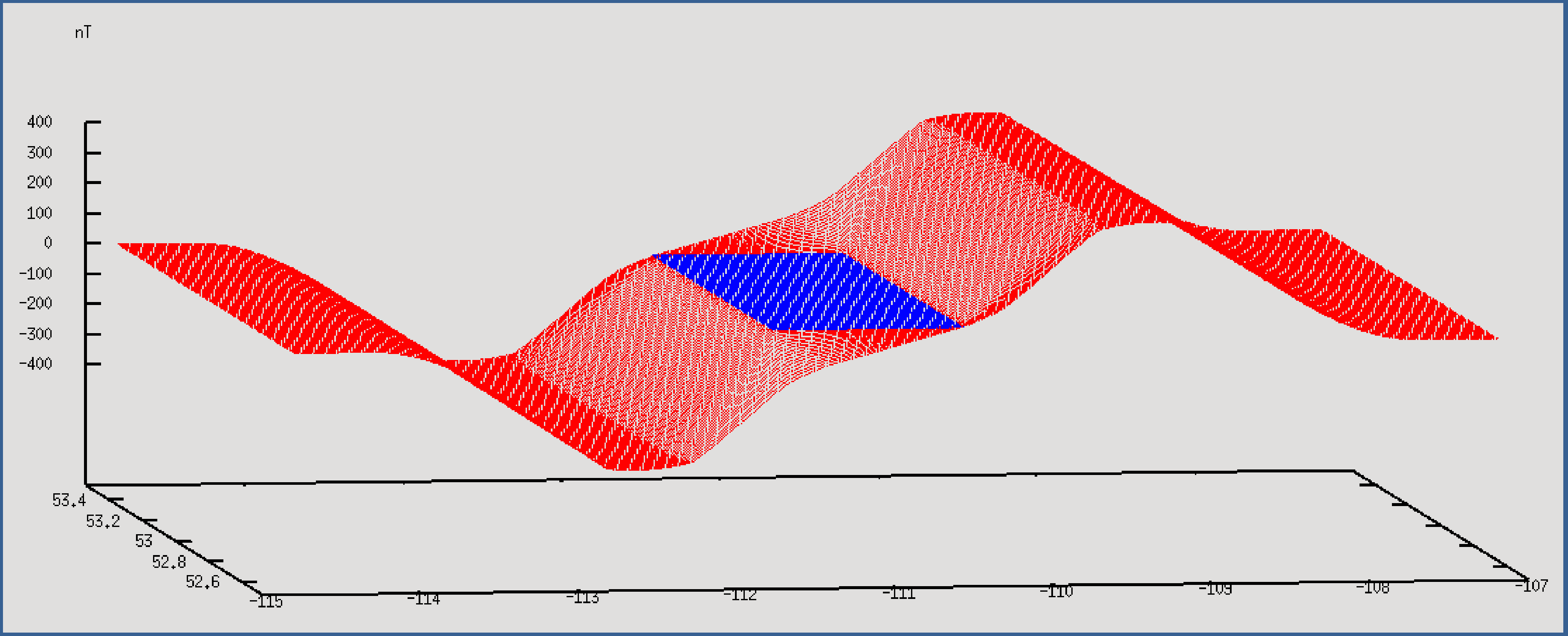
Assumption of Plane Grid Methods



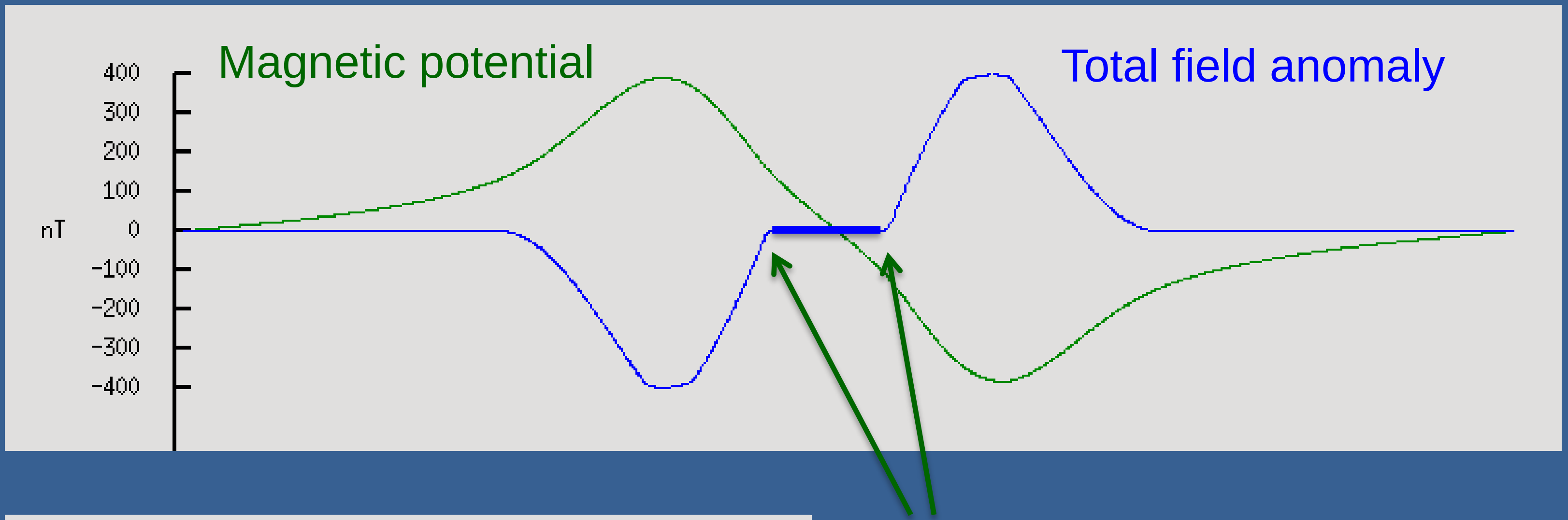
In reality, the crustal field has significant power at long wavelengths
At those wavelengths, the plane approximation is no longer valid

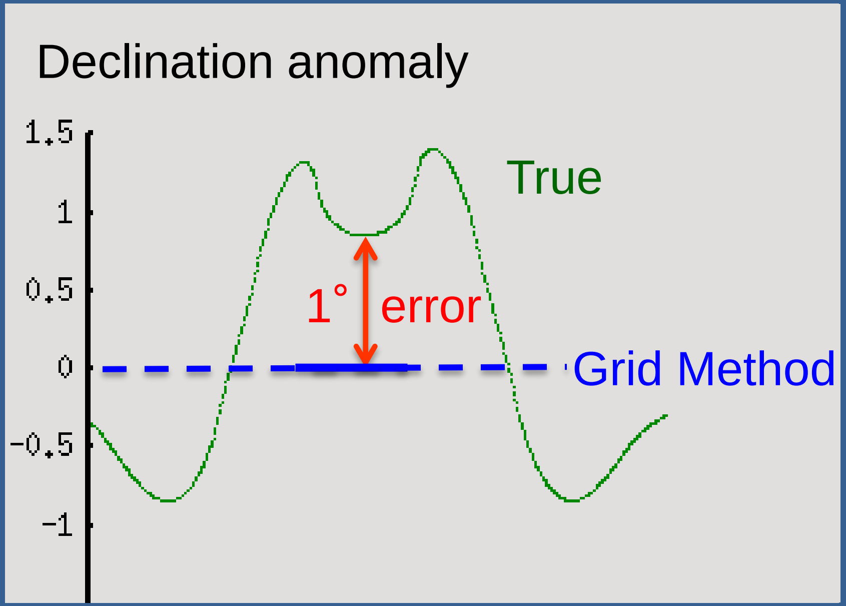
Synthetic Example

- Use 80 km x 80 km grid (shown in blue)
- To make it simple, assume that dF = 0 on the grid
- Surrounded by a long-wavelength 400 nT anomaly



Plane Grid Method Error





Mathematical reason for error: Grid method assumes that the potential is zero on the grid boundary

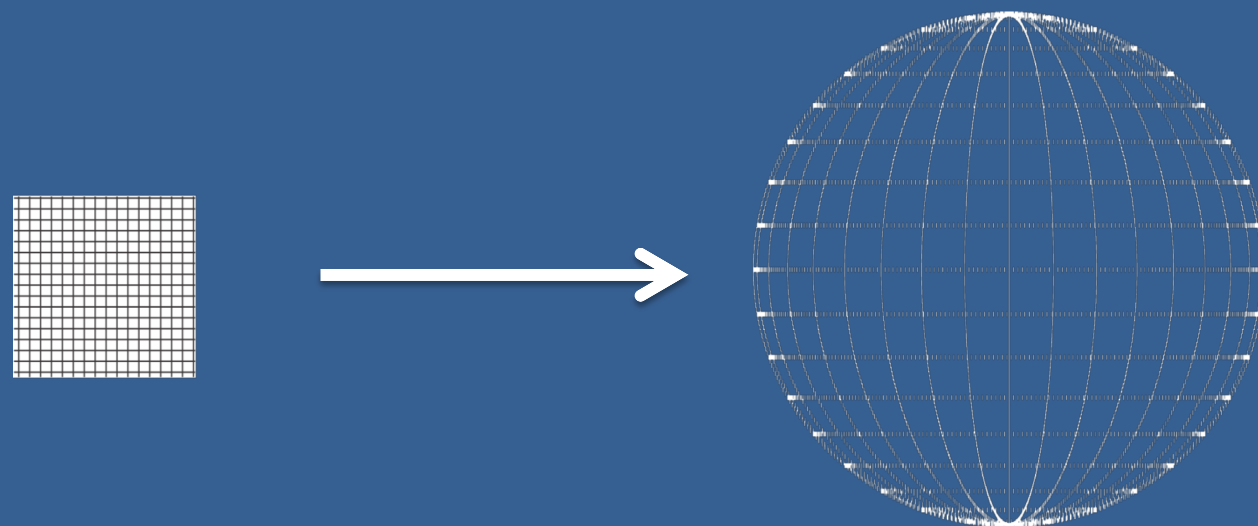
Any method used to solve LaPlace's equation on a grid without specifying boundary conditions will give incorrect results

Accurate IFR Solution

Problem: Magnetic potential not known on boundary

Solution: Eliminate the boundary

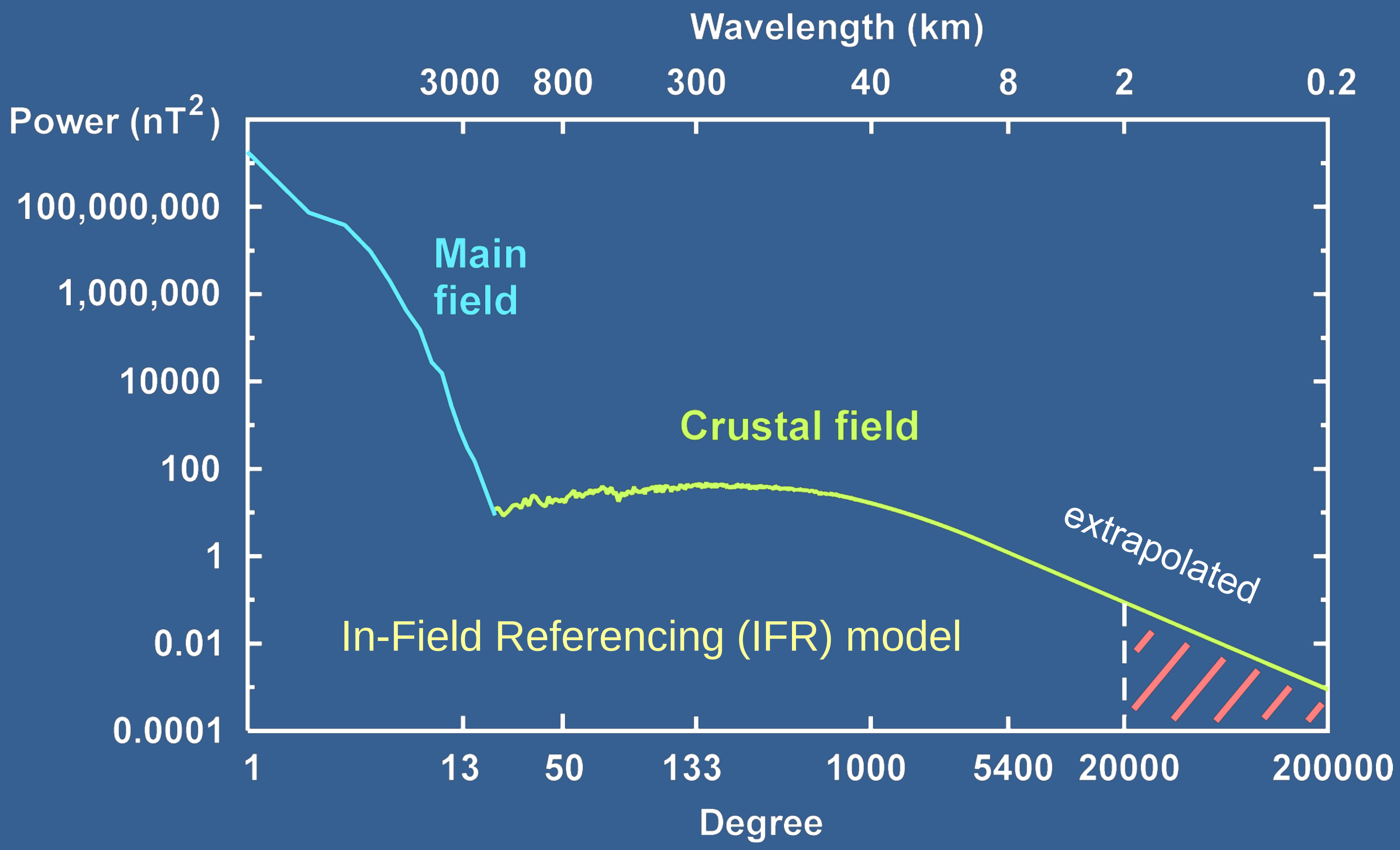
- This is a common approach used in weather models



Compute the IFR model as a global model using ellipsoidal harmonics (MagVAR IFR method, e.g. IADC/SPE-150107, 2012)

- Also used to compute the true solution for the previous example

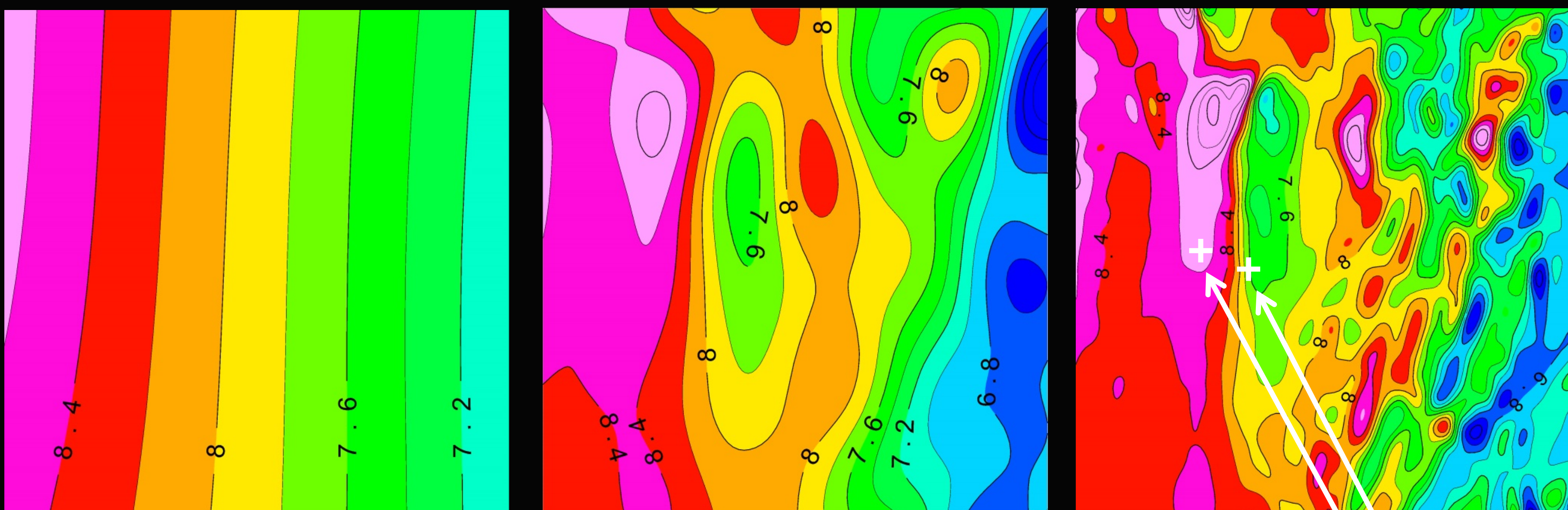
In-Field Referencing (MWD+IFR)



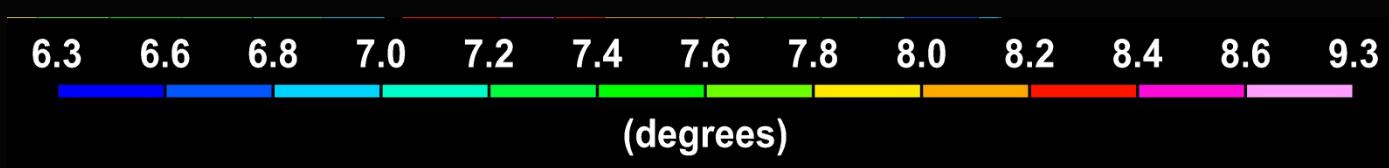
An accurate IFR model accounts for the entire spectrum without gaps

Declination Comparison (Bakken)

MVSD | MVHD | MagVAR IFR



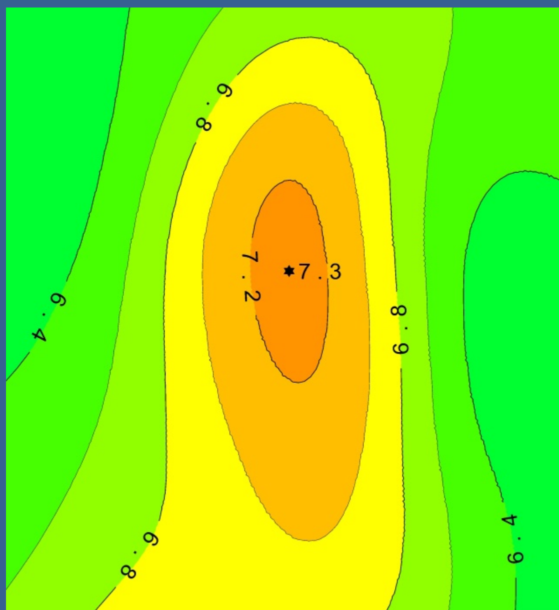
Increasing resolution and accuracy



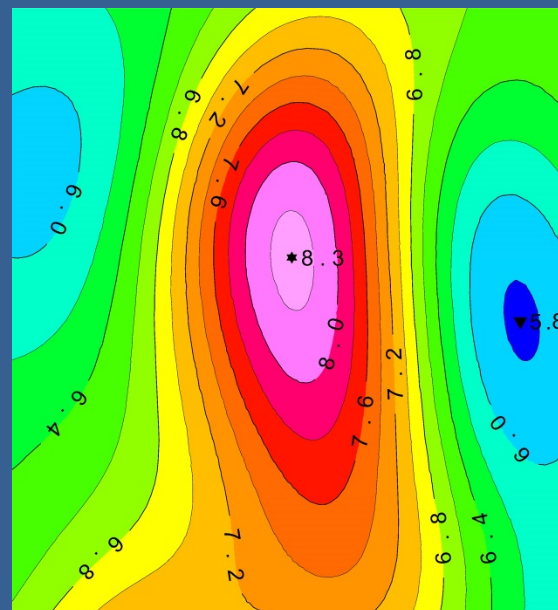
Validation by ground shots gave ± 0.07° for declination and ± 0.03° for dip

Why not just measure the vector at the surface?

Earth surface



9,000 ft TVD

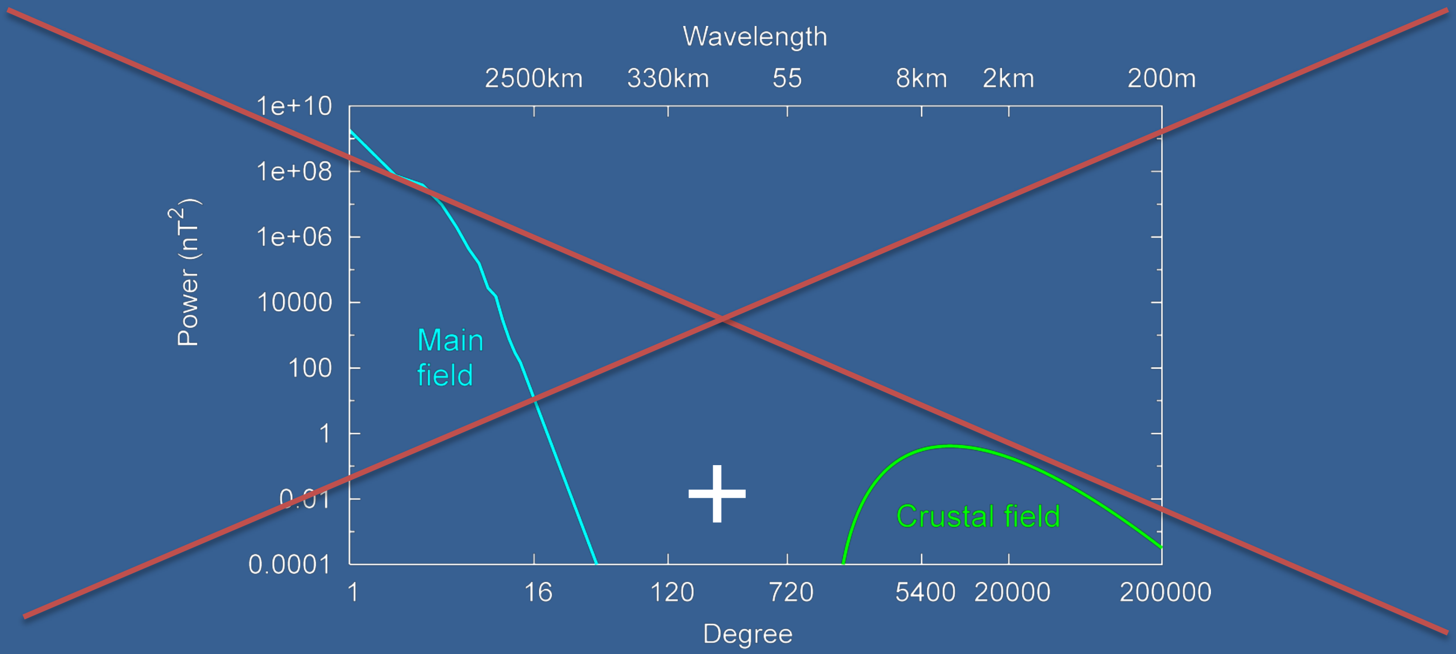


Magnetic anomalies increase with depth

- Even surface directional measurements need downward transformation
- Still need to solve LaPlace’s equation

- Surface directional measurements are valuable
- For an accurate reference field at depth one still needs a transformation

Secular Variation Correction: The Old Way

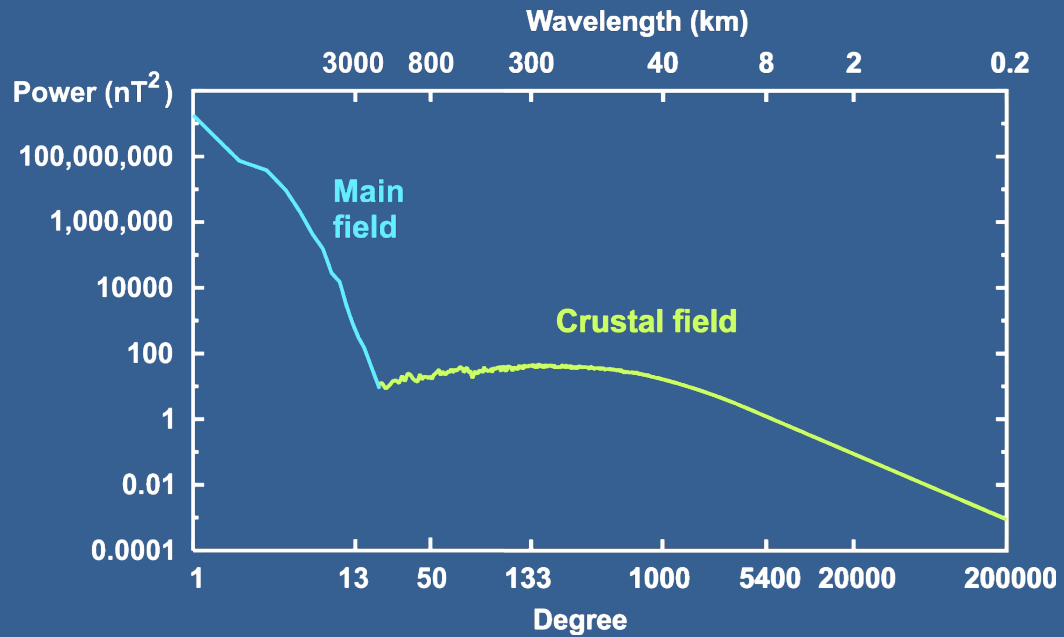


Often a "crustal correction" is added to a main field model for the desired date. This will lead to disagreements

- Between different main field models
- If the degree of the main field model changes

Example:
BGGM2004 = degree 20
BGGM2007 = degree 30
BGGM2010 = degree 50
BGGM2012 = degree 40
BGGM2014 = degree 50

Secular Variation Correction

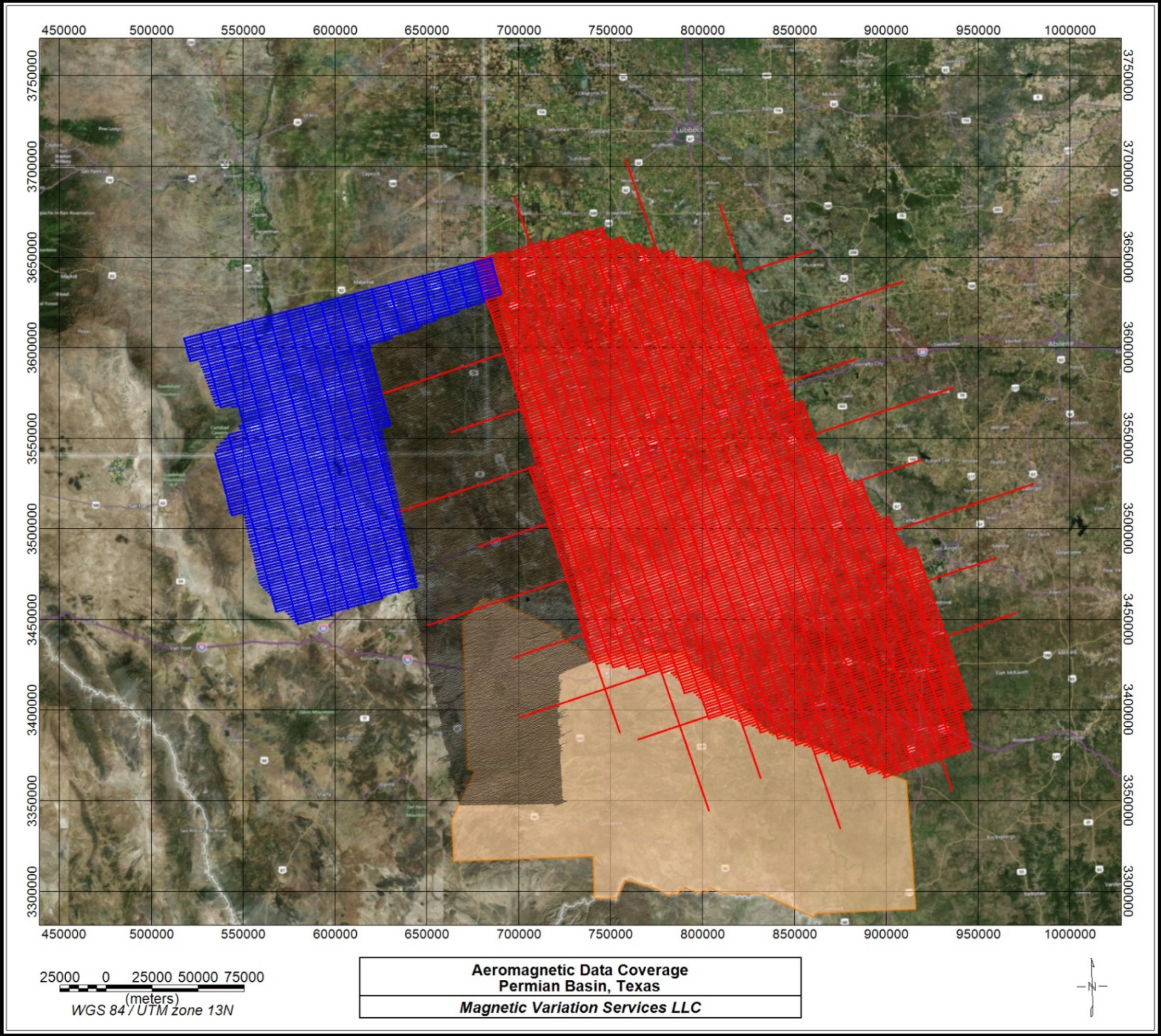


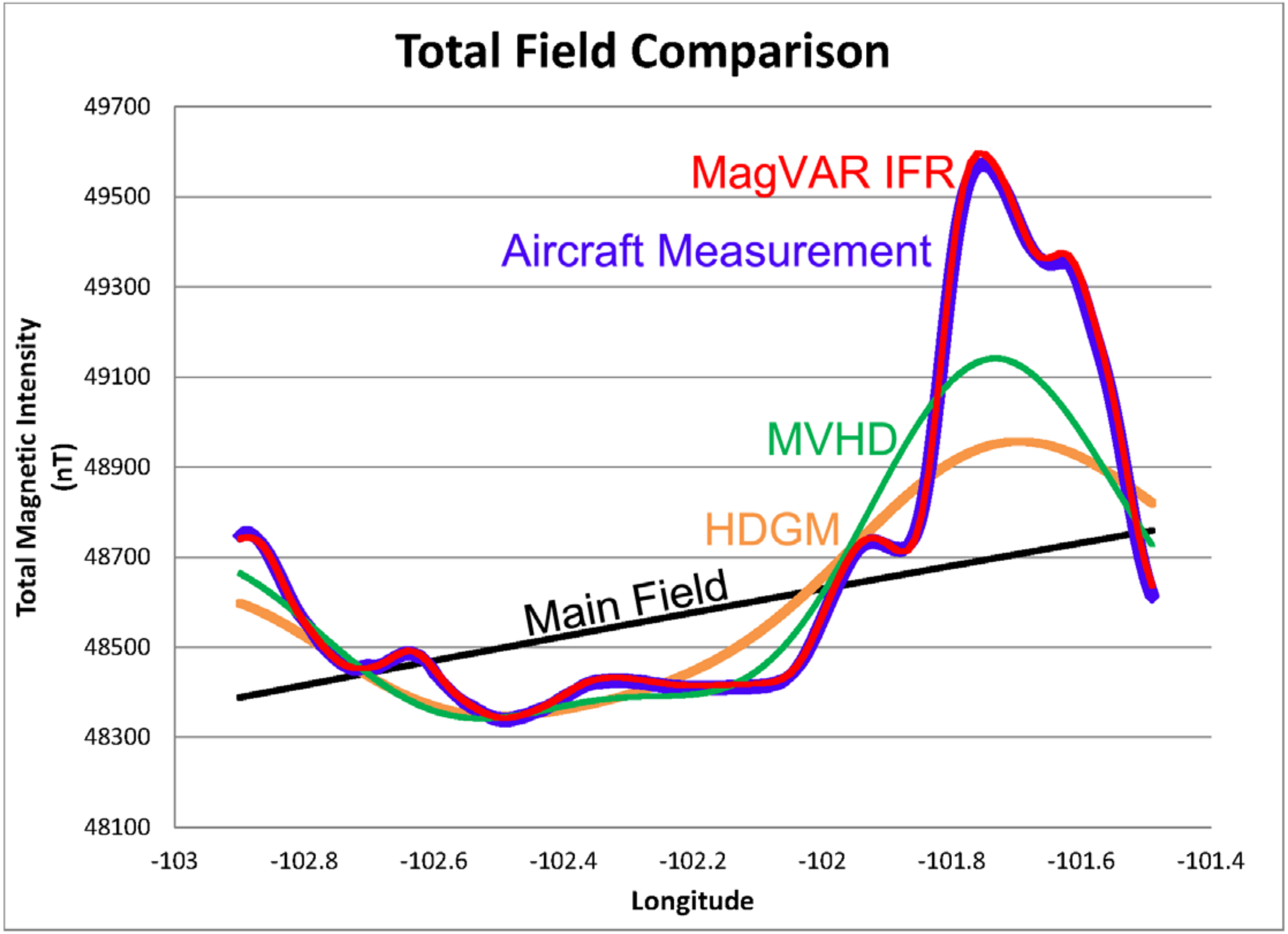
An accurate method of correcting for change in main field:

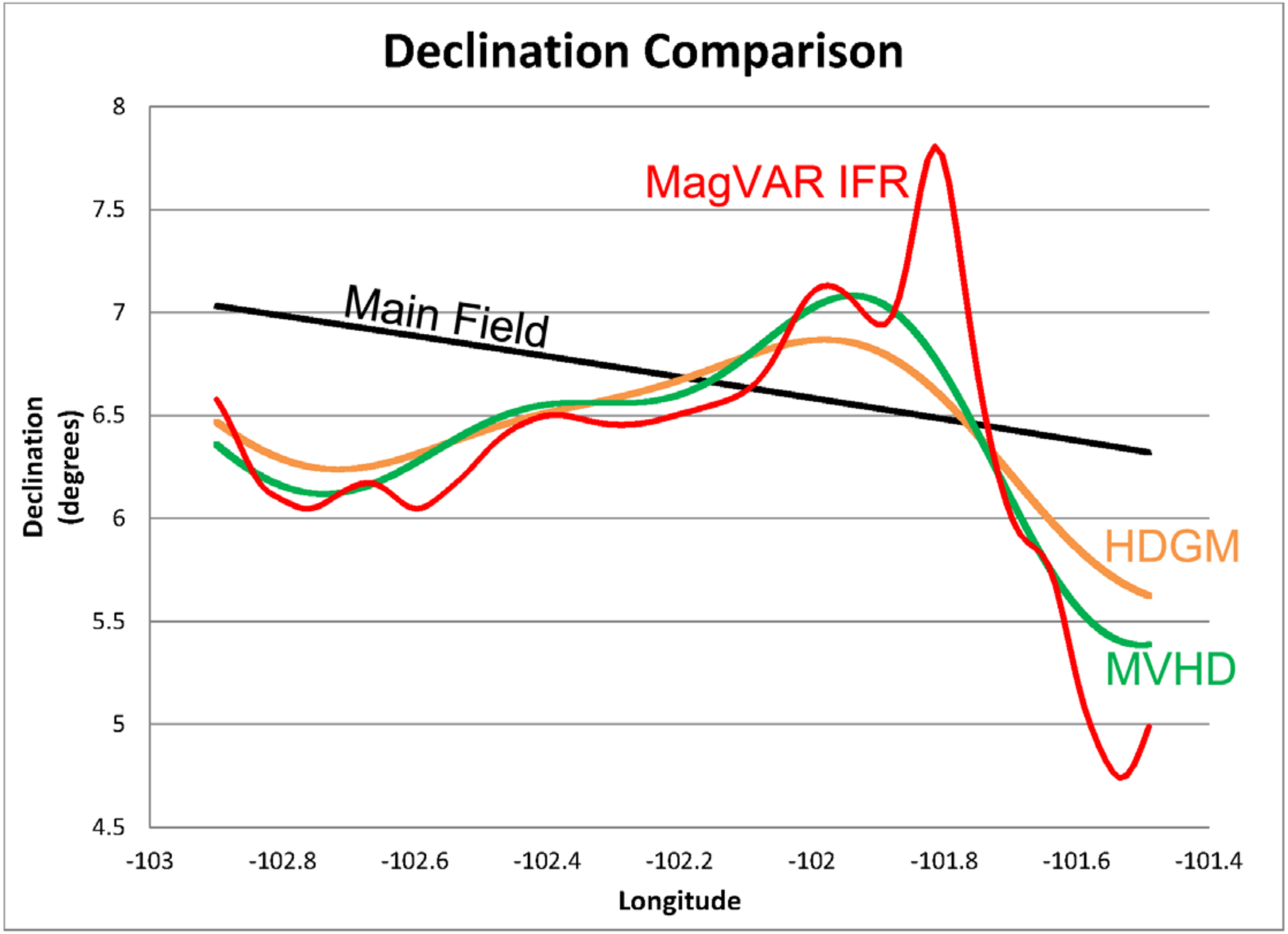
1. Start with complete field given for reference date
2. Subtract a yearly updated model for this reference date
3. Add the same model for the desired drilling date

Note: This does not work if the model degree changes with date:
Say we have a ground shot from 1998. By subtracting BGGM2014 for 1998 and adding BGGM2014 for 2015 we are in fact subtracting a degree 13 model and adding a degree 50 model, which is invalid.

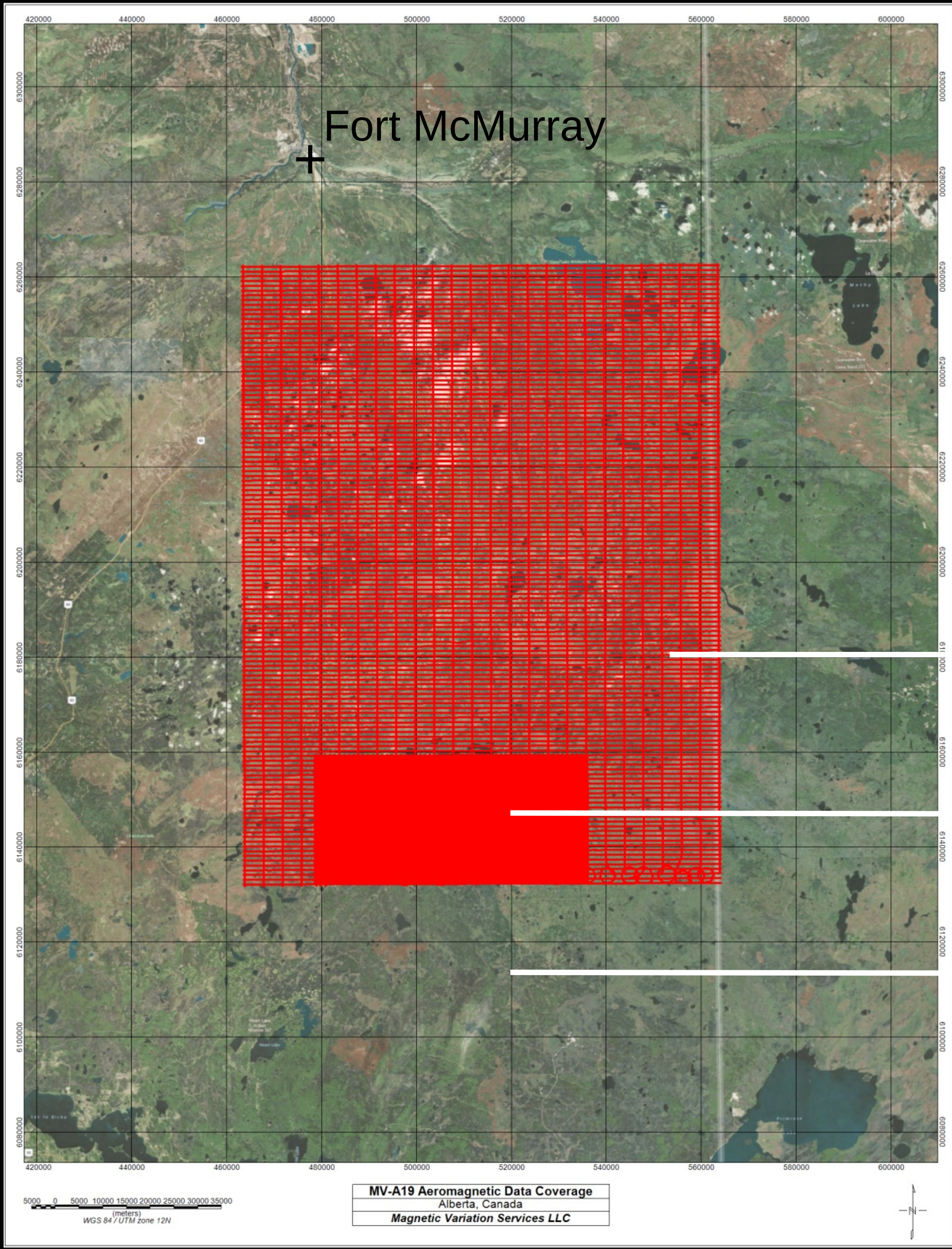
Permian Basin Aeromag Example




Total Field Comparison
49700
49500
49300
49100
48900
48700
48500
48300
48100
Total Magnetic Intensity (nT)
MagVAR IFR
Aircraft Measurement
MVHD
HDGM
Main Field
-103
-102.8
-102.6
-102.4
-102.2
-102
-101.8
-101.6
-101.4
Longitude



Declination Comparison
8
7.5
7
6.5
6
5.5
5
4.5
Declination (degrees)
-103
-102.8
-102.6
-102.4
-102.2
-102
-101.8
-101.6
-101.4
Longitude
MagVAR IFR
Main Field
HDGM
MVHD

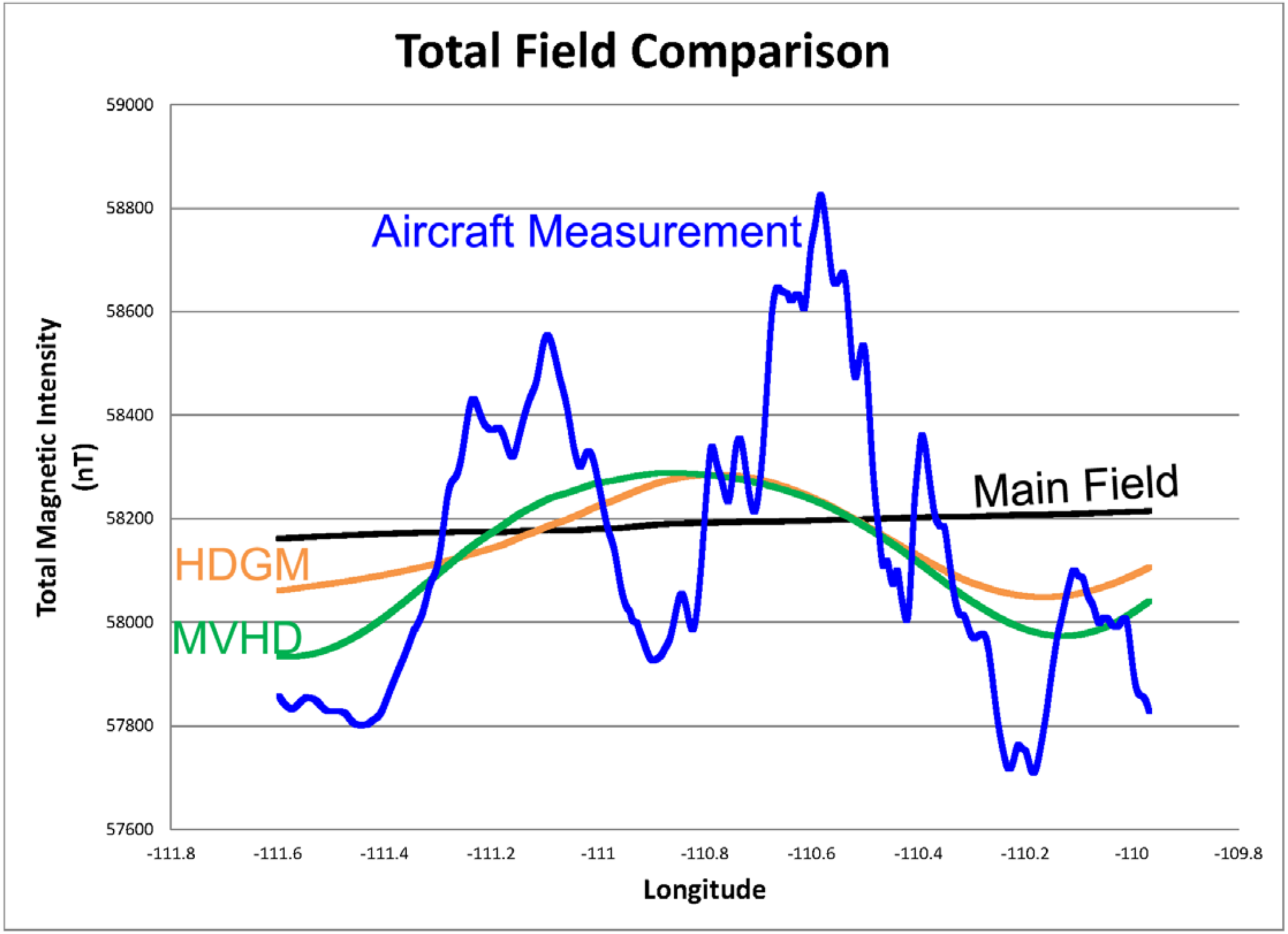


Alberta Oil Sands Aeromagnetic Survey

1000 m spacing

250 m spacing

Cold Lake
Weapons Range


Total Field Comparison
Aircraft Measurement
Main Field
HDGM
MVHD
Total Magnetic Intensity (nT)
59000
58800
58600
58400
58200
58000
57800
57600
-111.8
-111.6
-111.4
-111.2
-111
-110.8
-110.6
-110.4
-110.2
-110
-109.8
Longitude

Relevant Tool Codes for Well Planning and Anti-Collision Scans

Tool Code	Magnetic reference model	Survey corrections	~EOU*
MWD+IGRF	IGRF or WMM	-	+10%
MWD	**BGGM or MVSD**	**-**	**Standard**
MWD+HD	HDGM or MVHD	-	-10%
MWD+IFR1	Local In-Field Referencing (IFR1)	-	-30%
MWD+IFR1+MS	Local In-Field Referencing (IFR1)	Multi-Station	-50%

More Accurate

*Approximate values, actual EOU sizes depend on location and orientation of wellbore

New set of consolidated error models from the Operator Wellbore Survey Group. These are available as tool codes for well planning software.

Conclusions and Outlook

- Important to use annually updated models
- Don't mix models & degrees in secular variation corrections
- New line of global models
  - Standard Definition MVSD to degree 133 (tool code MWD)
  - High Definition MVHD to degree 1000 (tool code MWD+HD)
- IFR models have to cover the spectrum without gaps
  - Adding a crustal correction from a 80x80 km grid to a main field model can result in declination errors of over 1 degree
  - Ground shots: Still need a transform to give the declination at depth
- New aeromagnetic surveys in areas with strong crustal anomalies
  - Provide opportunity for testing and validation studies
  - Particularly interested in MWD versus Gyro comparisons