British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Applied geoscience for our changing Earth

# Using local observations of the geomagnetic field to improve crustal field estimates from global models

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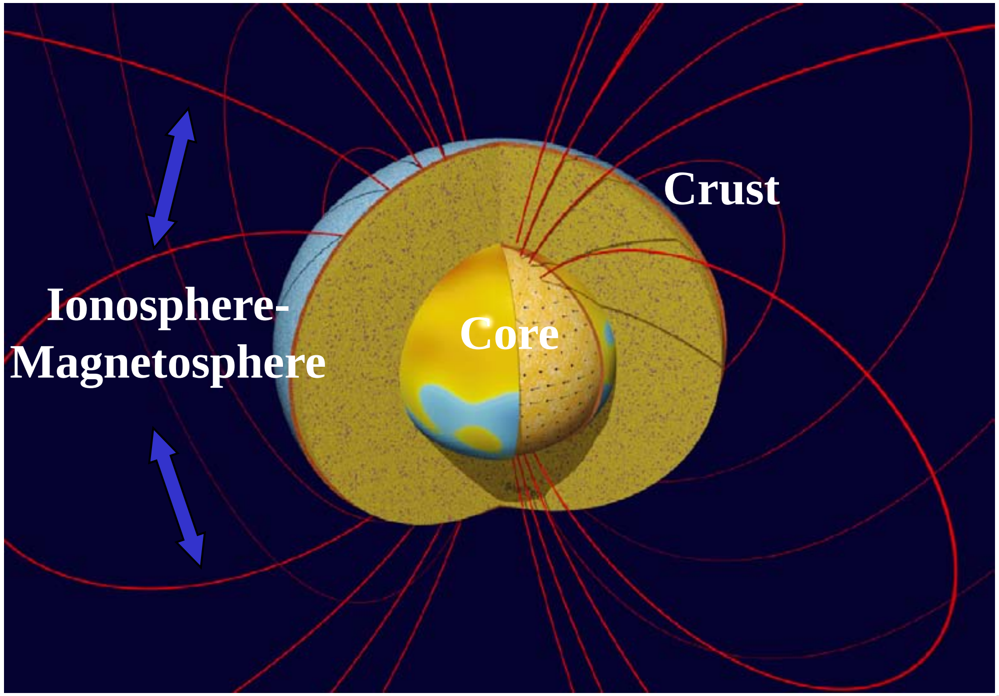
# The Earth’s magnetic field

- Most of the field is from the Earth’s core
  - varies slowly with time (months to years)
- Local fields from magnetized rocks in Earth’s crust
  - relatively stable with time
- Fields due to currents in the ionosphere and magnetosphere
  - variations from seconds to years

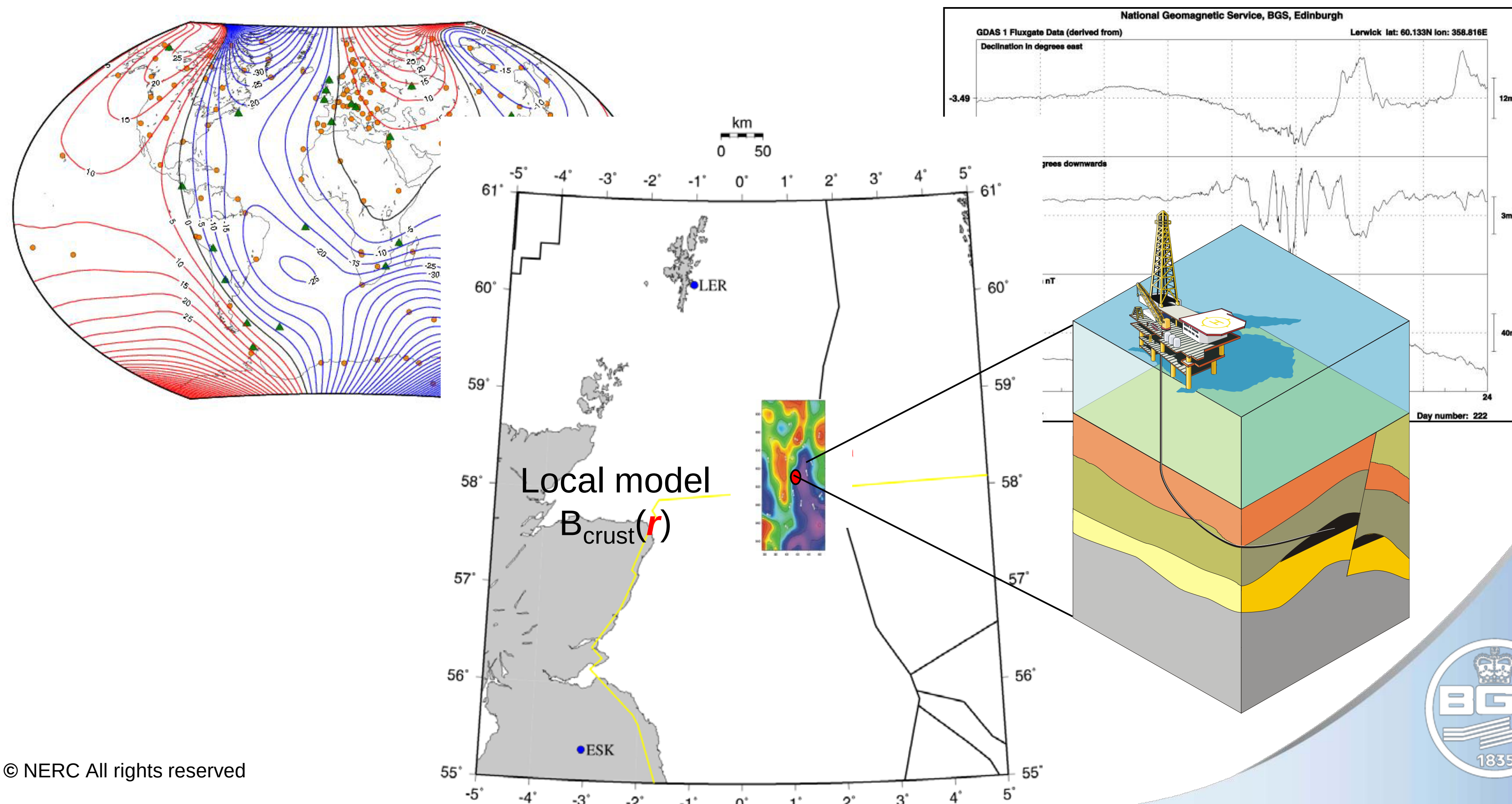


# Reconstructing the magnetic field vector at the drill site

$$B = B_{main}(\boldsymbol{r}, t) + B_{external}(\boldsymbol{r}, t) + B_{crust}(\boldsymbol{r})$$

Global model - $B_{main}(\boldsymbol{r}, t)$

Observatories – $B_{external}(\boldsymbol{r}, t)$



# Sources and errors

Reference field vector for drilling = B + $\varepsilon$

**1. Ideally, account for all sources**

$B_1 = B_{main} + B_{crust} + B_{external}$

$\varepsilon_1 = \varepsilon_{main} + \varepsilon_{crust} + \varepsilon_{external}$

Each source is modelled or observed in some way

**2. If external fields are ignored**

$B_2 = B_{main} + B_{crust} + 0$

$\varepsilon_2 = \varepsilon_{main} + \varepsilon_{crust} + B_{external}$

Need to characterise the statistical nature of the errors and **signal**

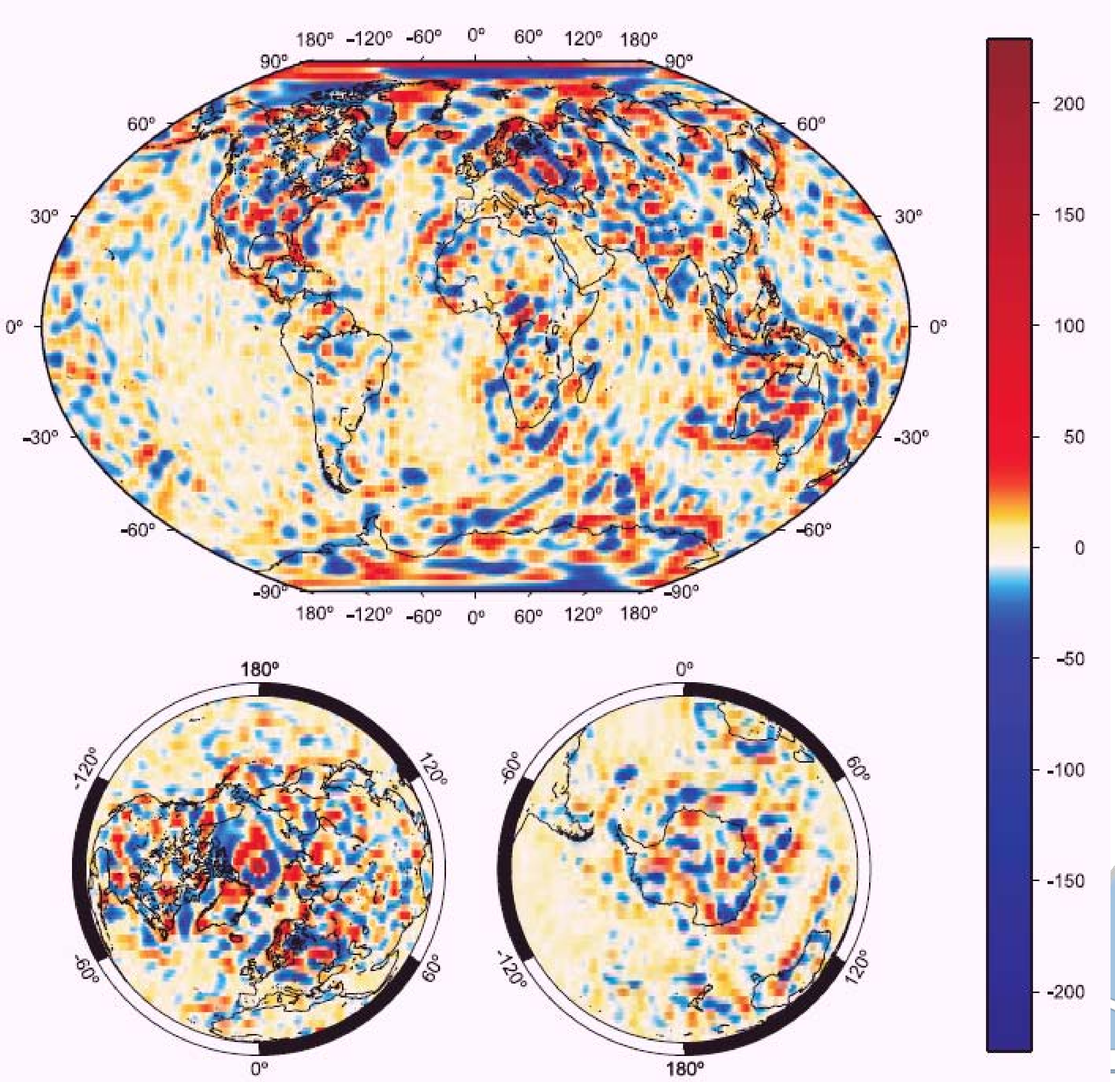
**3. If crustal and external fields are ignored**

$B_3 = B_{main} + 0 + 0$

$\varepsilon_3 = \varepsilon_{main} + B_{crust} + B_{external}$

# All global main field models capture some of the crustal field…

- Novel weighting methods applied to satellite data
- Vector data at all latitudes
- Low-noise lithospheric field model
- Piecewise linear SV
- External dipole magnetic field with VMD index rapid time-dependence




A. W. P. Thomson, B. Hamilton, S. Macmillan & S. J. Reay. A Novel Weighting Method for Satellite Magnetic Data and a New Global Magnetic Field Model. *Geophys. J. Int.*, 2010.

# …but local observations in vicinity of drilling site complete the picture

- Direct measurements of the vector field
  - on land
  - at sea

- Direct measurements of the scalar field
  - inversions for source properties followed by forward modelling
  - transformations

# Direct measurements of the vector field on land

← UK

Canada →

Canadian images courtesy of Halliburton

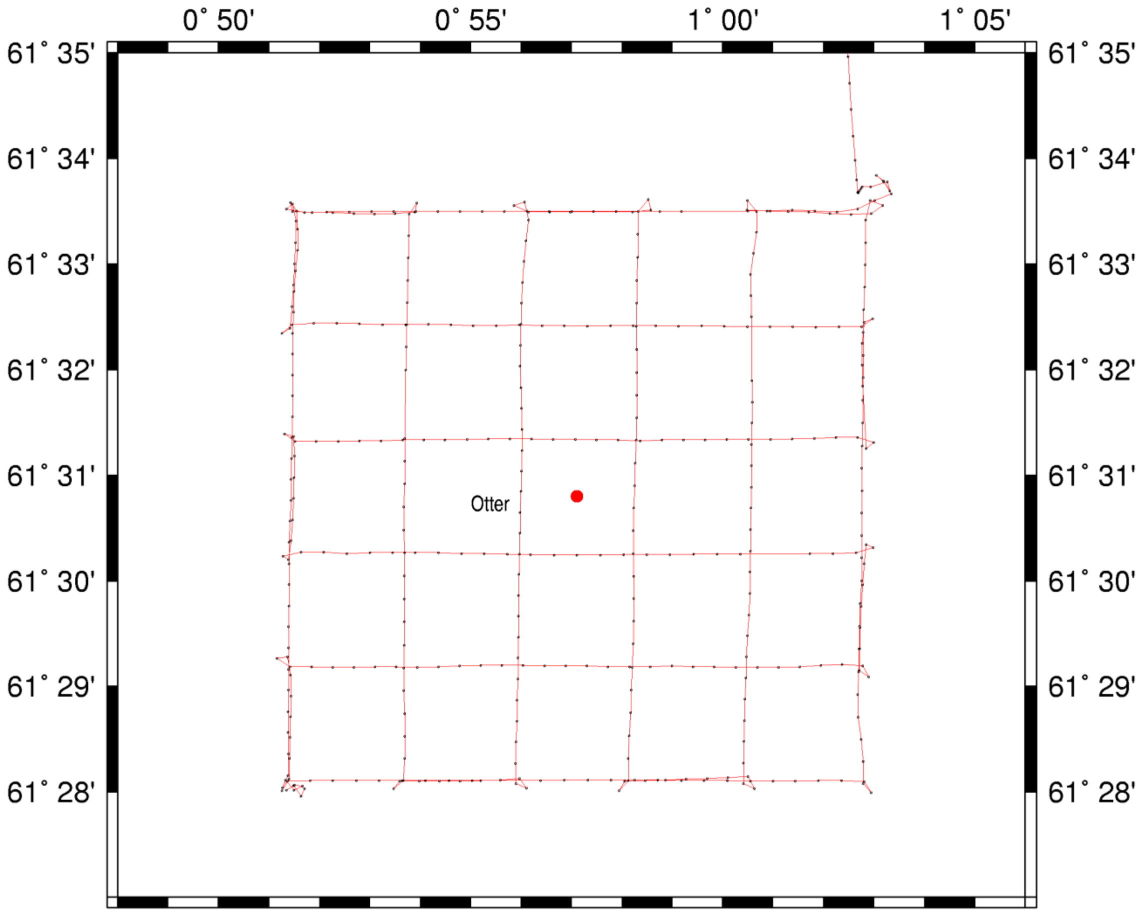
# Direct measurements of the vector field at sea

**Platform:** The Adventurer - holder of the record for the fastest circumnavigation of the globe – reasonably non-magnetic

**Instruments:** Vector and scalar magnetometers, ring-laser gyro and GPS


A collaborative project between Tech21 and BGS

# Typical marine vector survey




10 km by 10 km

# Direct measurements of the scalar field

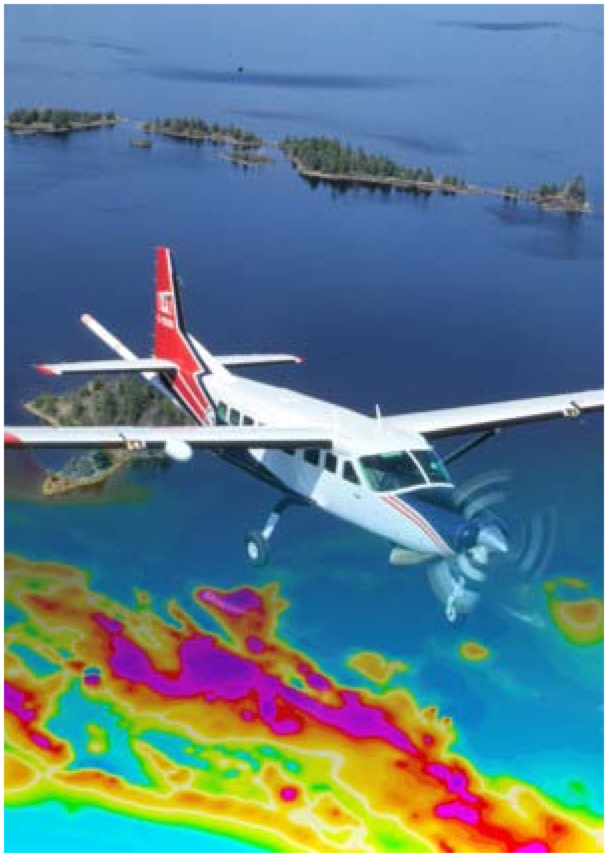
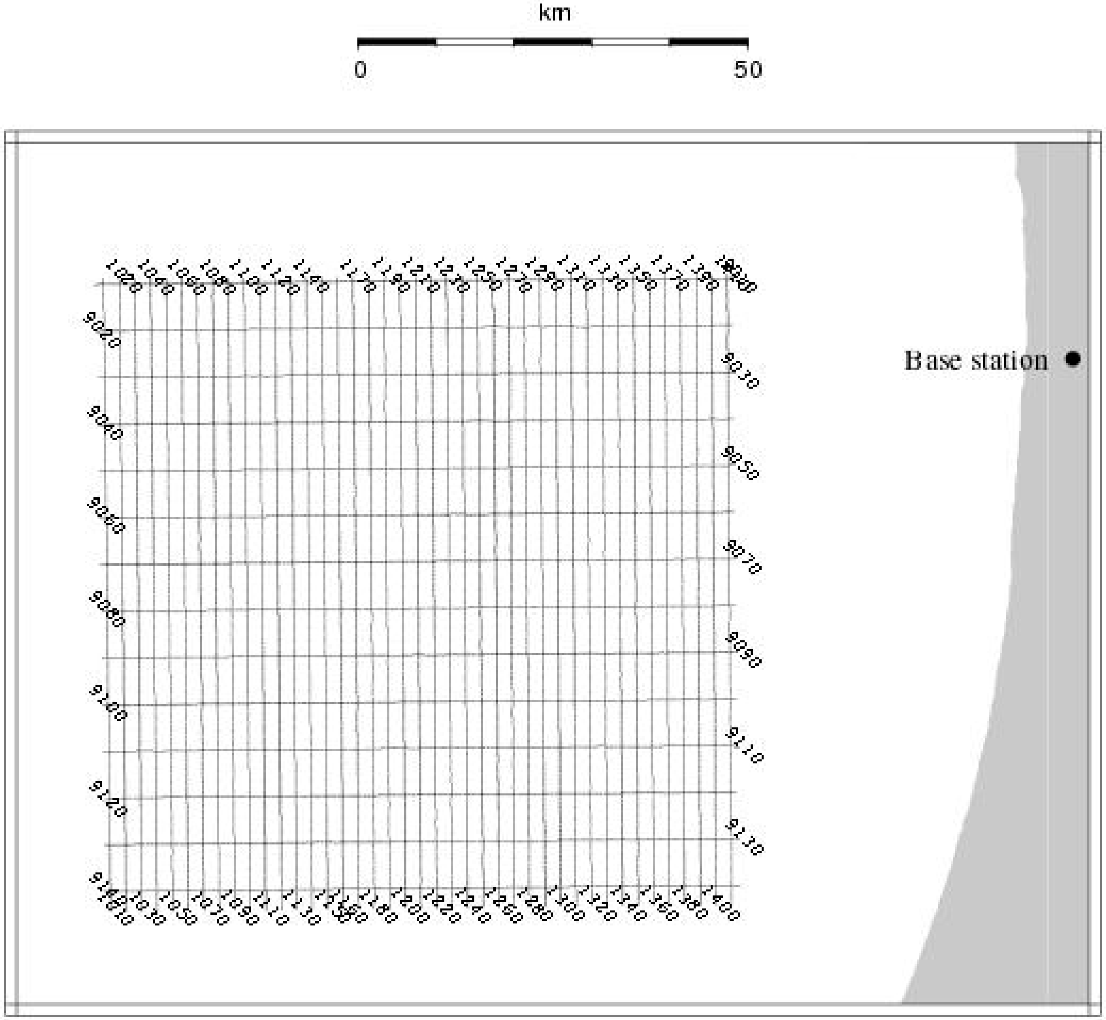


image courtesy of Sander Geophysics

image courtesy of Fugro

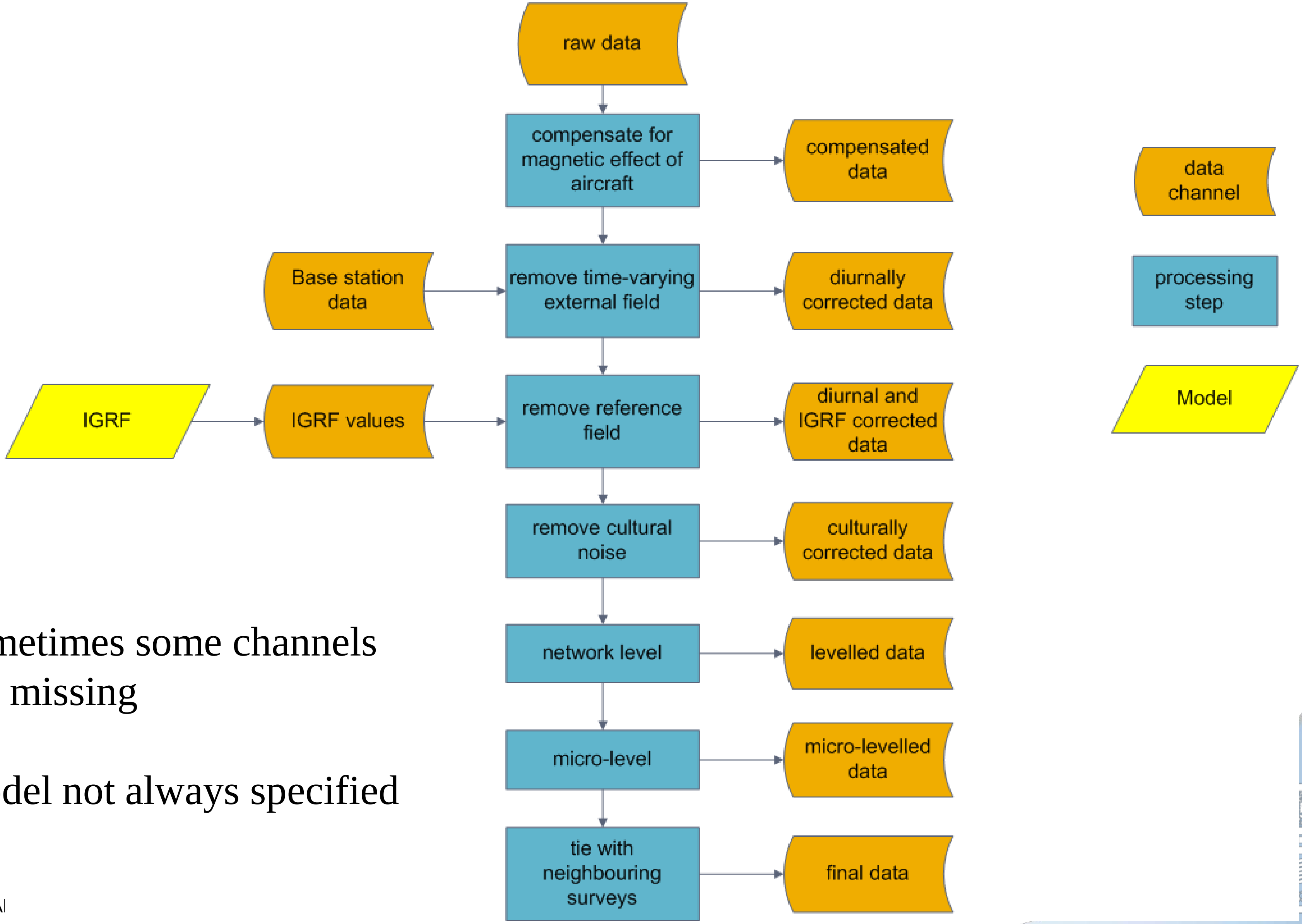
image courtesy of PGS

# Typical aeromagnetic survey




100 km by 100 km

# Aeromagnetic data processing



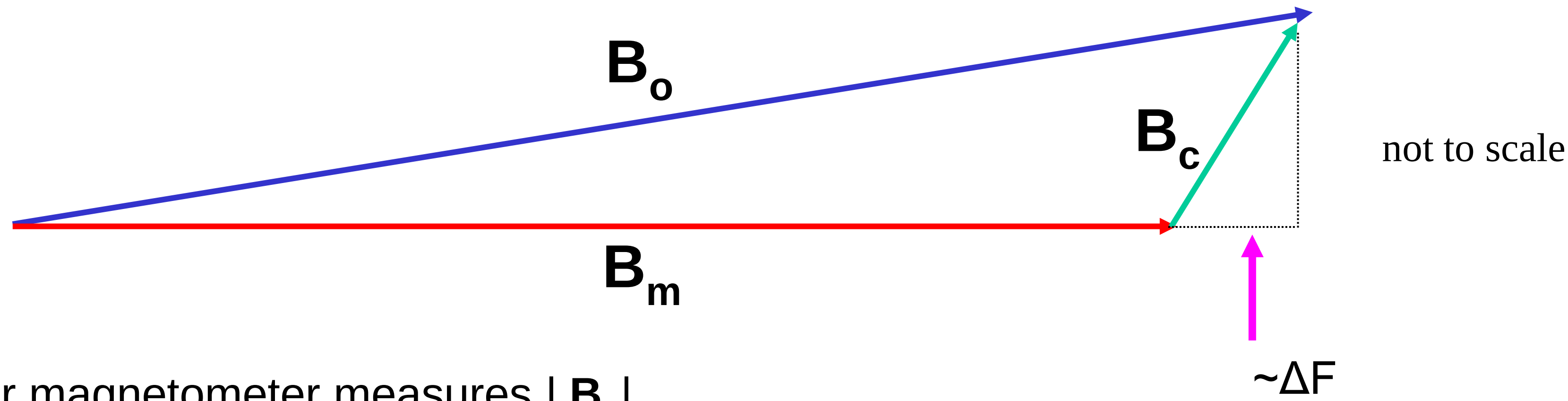

sometimes some channels are missing

model not always specified

# Validation of scalar data for gross errors, noise content and absolute level

- check coordinates
- check base station data
- check model
- check processing e.g. compare data channels
- compare with independent data
- downward and upward continuation

# Assumptions with scalar data




Scalar magnetometer measures | $\mathbf{B_o}$|
Total intensity anomaly ***defined*** as $\Delta F$ = | $\mathbf{B_o}$| - | $\mathbf{B_m}$|
This is **not** the same as | $\mathbf{B_c}$|

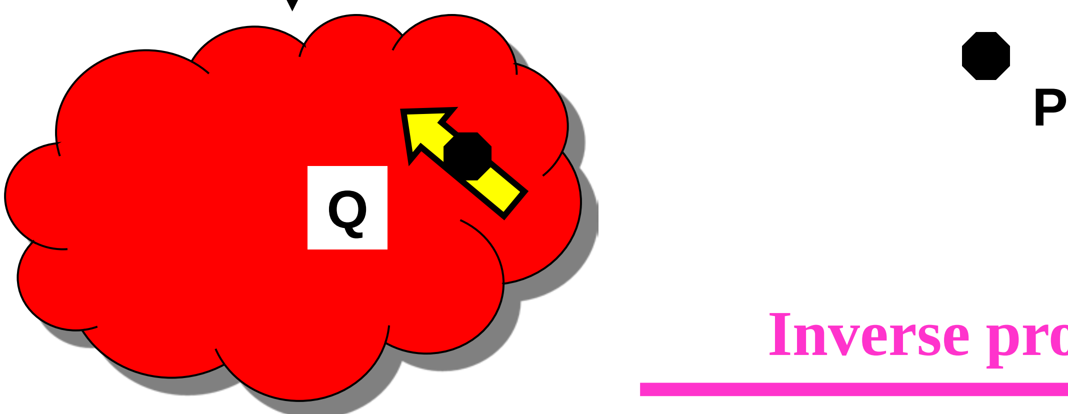
$\mathbf{B_m}$ = ($X_m$, $Y_m$, $Z_m$) estimated from a global model

If crustal field is *small* compared to main field (200 nT cf 50000 nT), ΔF is well approximated by the projection of crustal field vector onto the main field vector

$$\Delta F \approx (X_c X_m + Y_c Y_m + Z_c Z_m)/F_m \qquad \text{equation (1)}$$

# Inversions of scalar data

Magnetic rock (region R)




**Inverse problem** →

Geometrical function relating points P and Q

Magnetisation at point Q

$$V(P) = \int_R M(Q)\,\psi(P,Q)\,dv$$

Magnetic potential at point P (outside R)

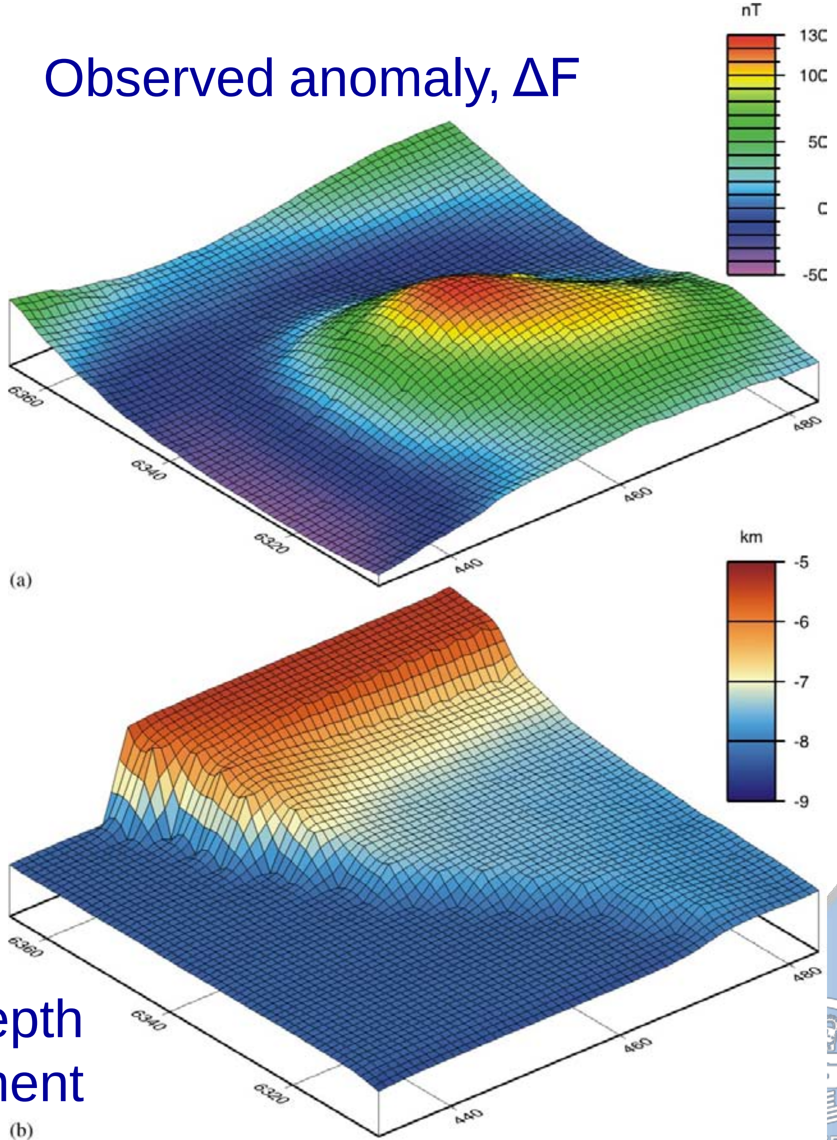
region containing magnetic sources

← **Forward problem**

# Inversions of scalar data

- Assume magnetisation induced by main field
- Assume magnetisation does not vary with depth
- Determine top surface of R from seismic data

Observed anomaly, ΔF




Seismically-determined depth to magnetic basement

# Transformations of scalar data

## Applications of Fourier transformation techniques

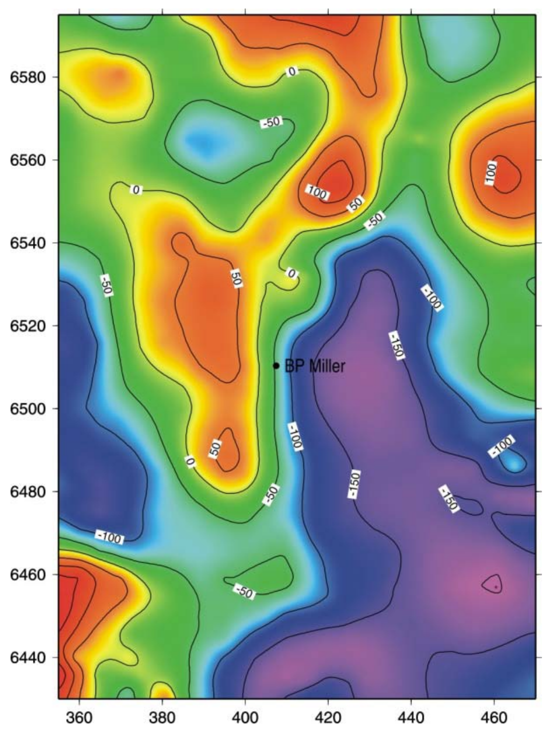
| | |
|---|---|
| **IN:** | F anomalies at surface |
| **OUT:** | D and I anomalies at surface |
| | D, I and F anomalies at depth |

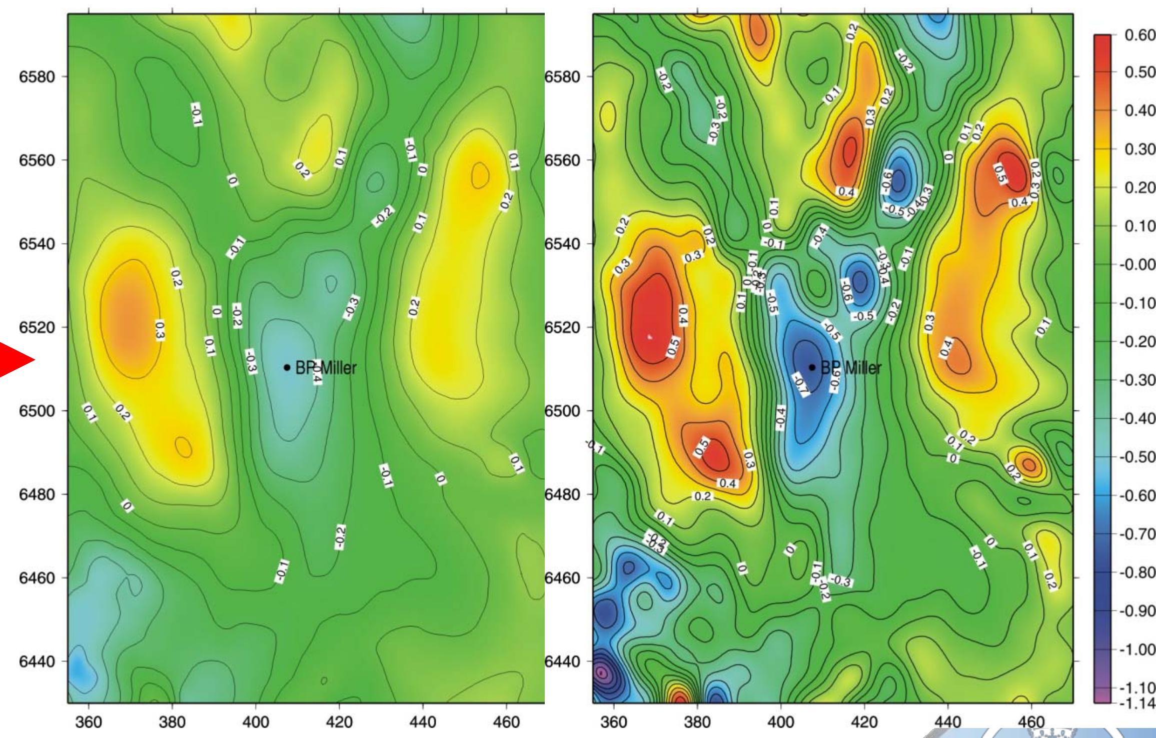
# Transformations of scalar data

## Applications of Fourier transformation techniques

F anomalies at surface

D anomalies at surface and at depth 4 km



# Scalar to vector transformations

$\mathbf{B_c}$ = ($X_c$,$Y_c$, $Z_c$) is the gradient of a scalar potential $V_c$
which satisfies Laplace's equation $\nabla^2 V_c = 0$

A solution to Laplace's equation is:

$$V_c(x,y,z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{2\pi(i(ux+vy)+z\sqrt{u^2+v^2})} A(u,v)\,du\,dv$$

ΔF also satisfies Laplace's equation and can be written as (assuming data collected at constant altitude):

$$\Delta F(x,y,0) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{2\pi i(ux+vy)} C(u,v)\,du\,dv$$

Use equation (1) linking ΔF and $\mathbf{B_c}$ to get an expression for *A(u,v)* in terms of *C*(*u,v*)

**Fewer assumptions about the geometrical or magnetic properties of the sources than with inversions**

# Downward continuation

$$\tilde{\Phi}(u,v,z) = \Lambda_{uv}\tilde{\Phi}(u,v,z_0)$$

$$\Lambda_{uv} = \exp(2\pi\sqrt{u^2+v^2}\Delta z)$$

Small error in $\tilde{\Phi}(u,v,z_0)$ with large $u$,$v$ (short wavelengths) results in large errors in $\tilde{\Phi}(u,v,z)$. Consequence is high amplitude and short wavelength noise in resulting anomalies

Equivalent filter operator but with damping (parameter $\lambda$):

$$\Lambda_{uv} = \frac{\exp(-2\pi\sqrt{u^2+v^2}\Delta z)}{\exp(-4\pi\sqrt{u^2+v^2}\Delta z) + \lambda\left(2\pi\sqrt{u^2+v^2}\right)^4}$$

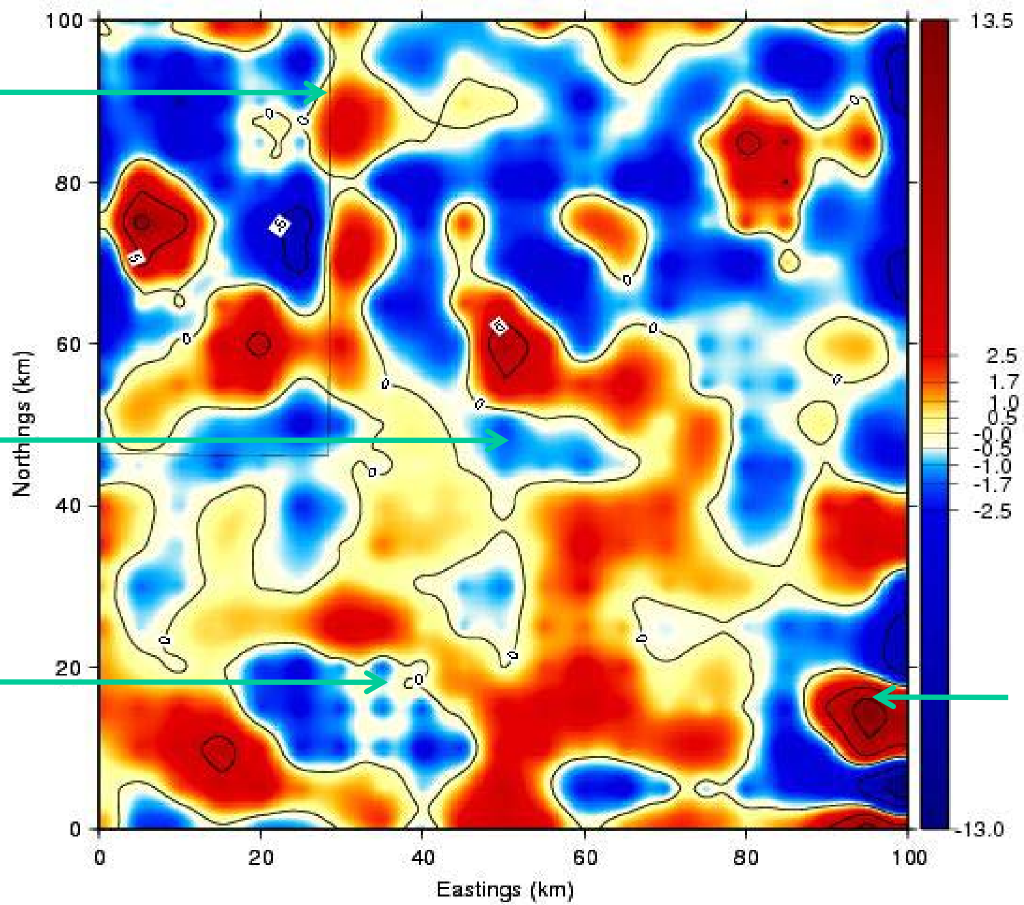
# Validation of downward continuation

## Compare damped downward-continued anomalies which are then upward-continued, with input data

survey boundary

differences in drilling area small

sampling noise

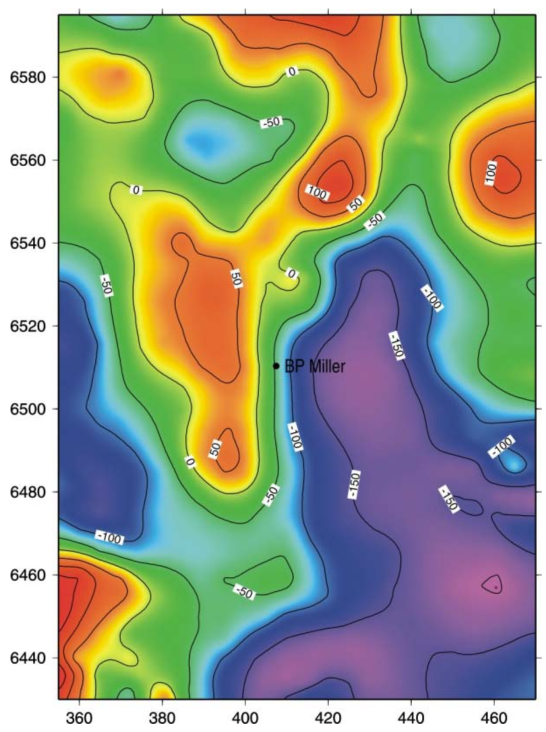



depth 4 km differences in nT

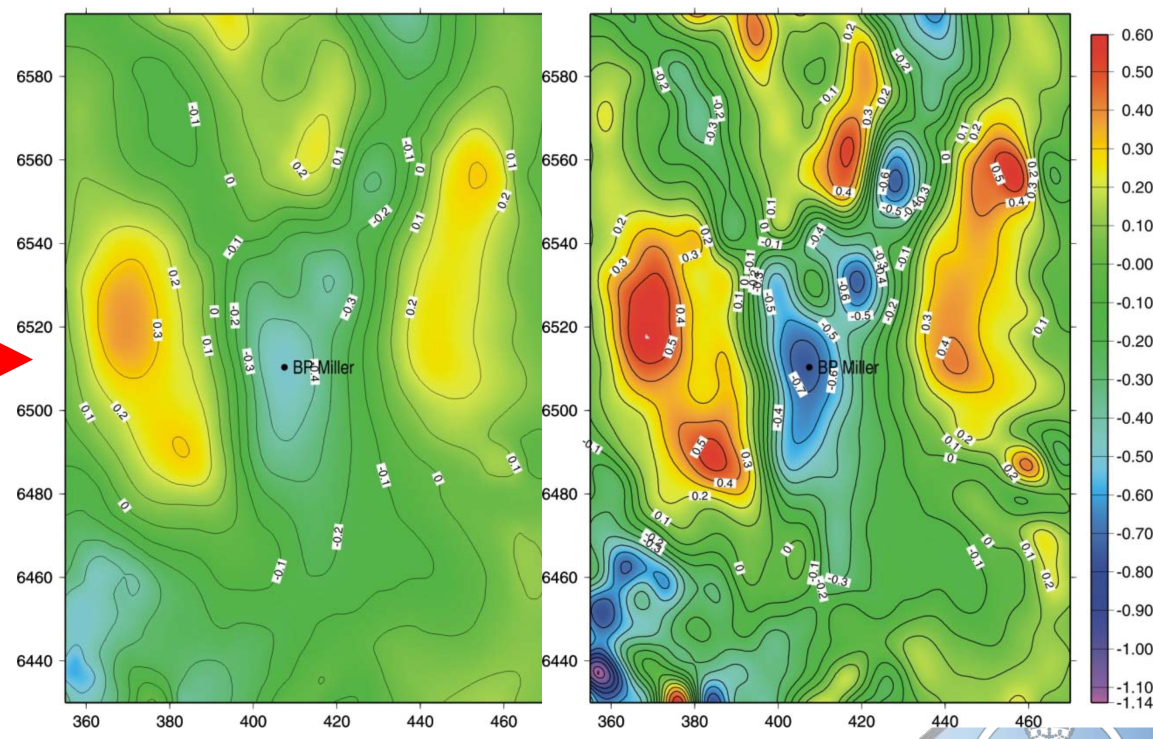
high gradients

# BP Miller field - small F anomaly does not mean small D anomaly

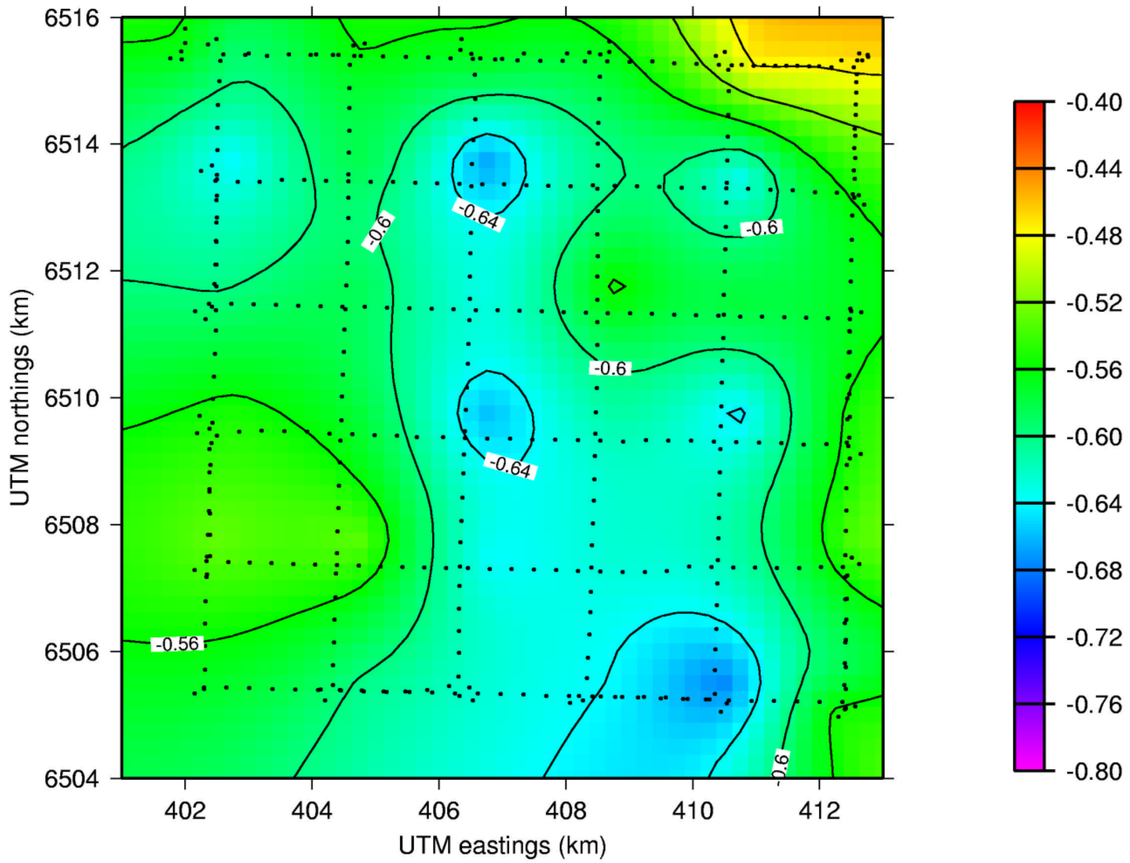
F anomalies at surface




D anomalies at surface and at depth 4 km



# BP Miller field – D anomalies from marine vector survey agree



# Downward continuation

BP Miller – effect of downward continuation
4 km ~ max drilling depth

| | declination | inclination | total intensity |
|---|---|---|---|
| surface | -0.497 | -0.035 | -56.2 |
| depth 4 km | -0.751 | -0.026 | -68.6 |
| **difference** | **0.254** | **-0.009** | **12.4** |

(declination and inclination in degrees, total intensity in nT)

# Sources and errors

Reference field vector for drilling = B + $\varepsilon$

**1. Ideally, account for all sources**

$B_1 = B_{main} + B_{crust} + B_{external}$

$\varepsilon_1 = \varepsilon_{main} + \varepsilon_{crust} + \varepsilon_{external}$

**2. If external fields are ignored**

$B_2 = B_{main} + B_{crust} + 0$

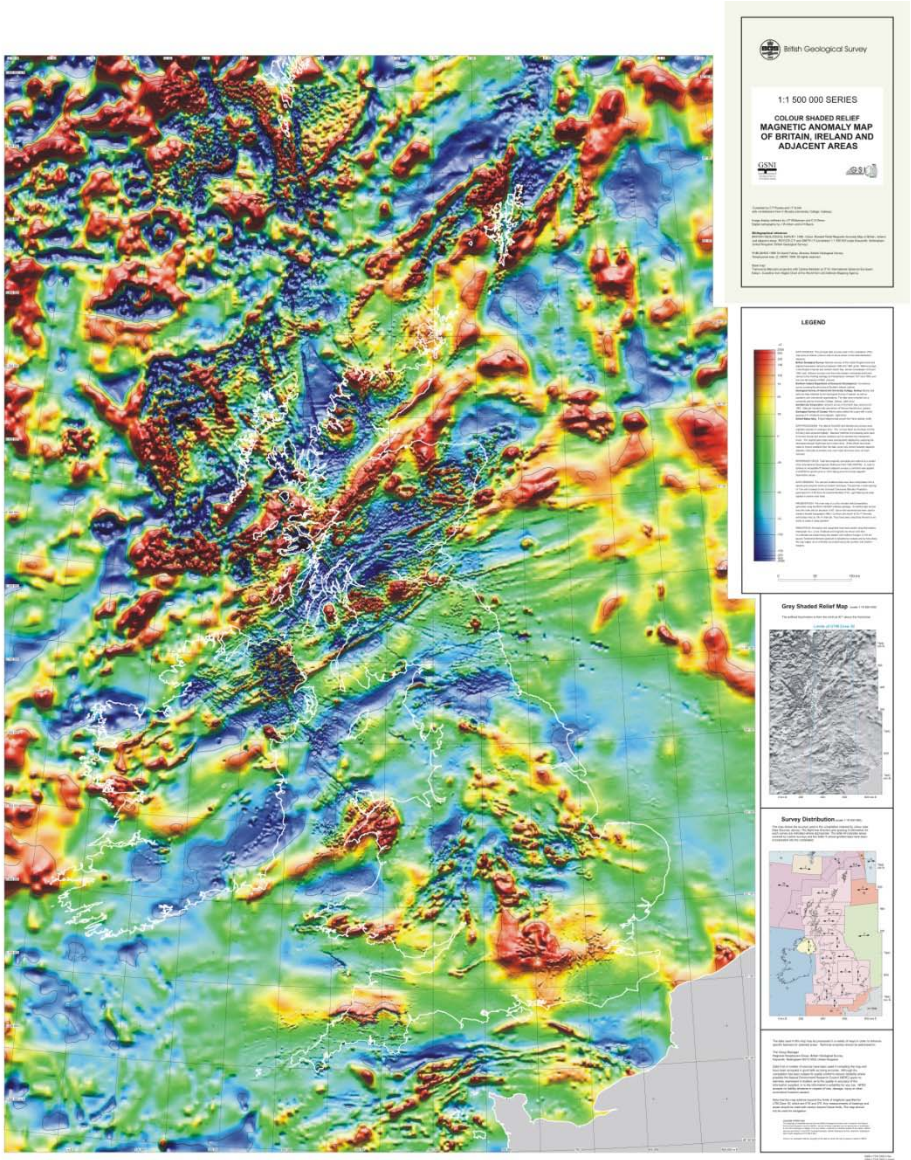
$\varepsilon_2 = \varepsilon_{main} + \varepsilon_{crust} + B_{external}$

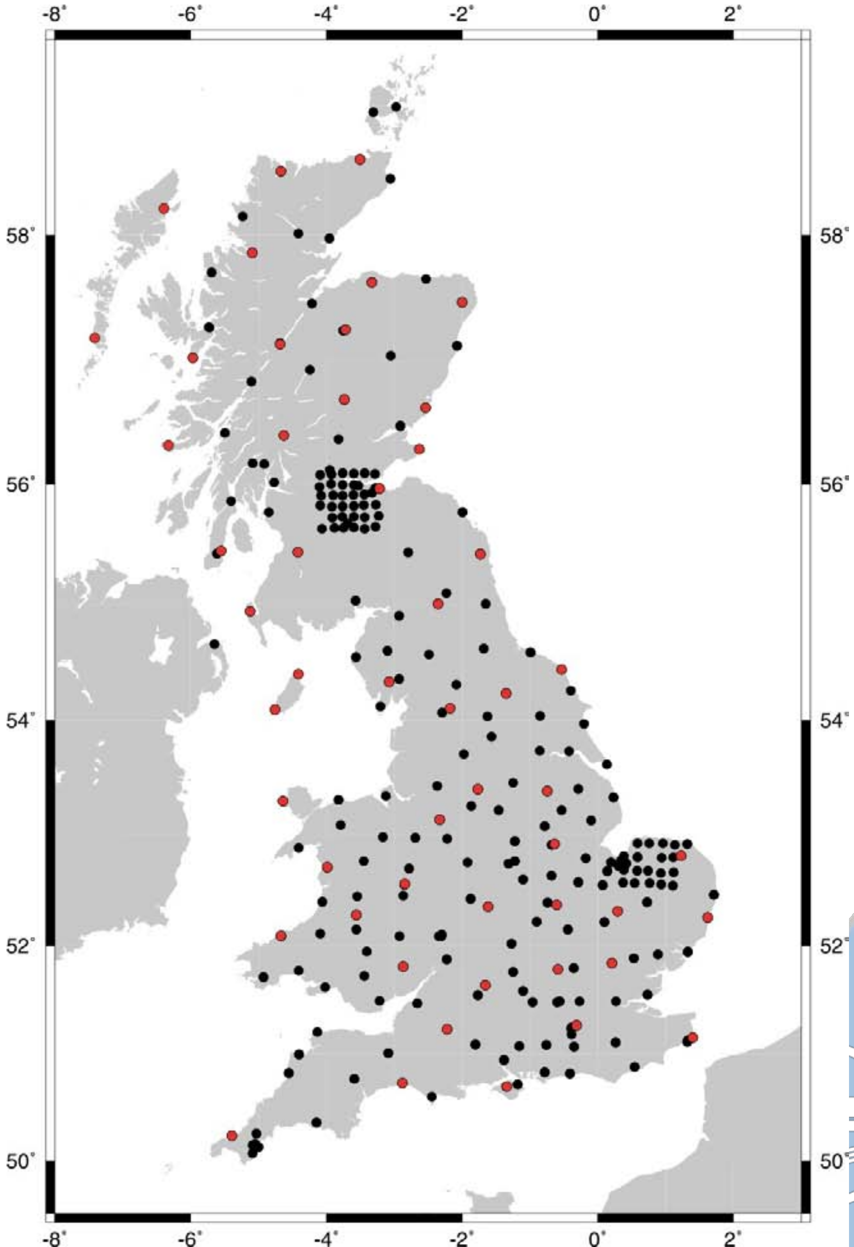
**3. If crustal and external fields are ignored**

$B_3 = B_{main} + 0 + 0$

$\varepsilon_3 = \varepsilon_{main} + B_{crust} + B_{external}$

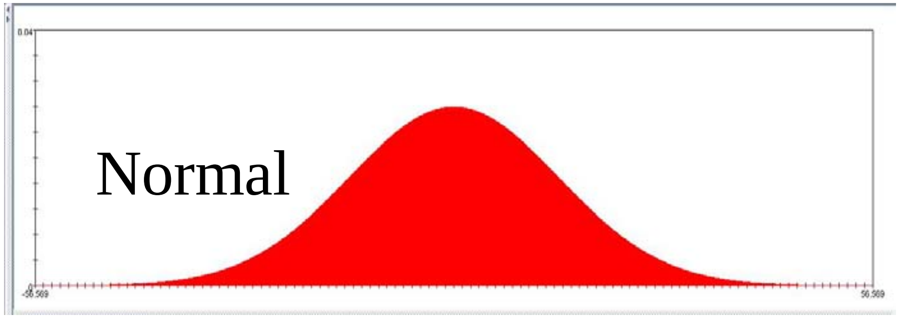
# Estimating $\varepsilon_{main} + \varepsilon_{crust}$

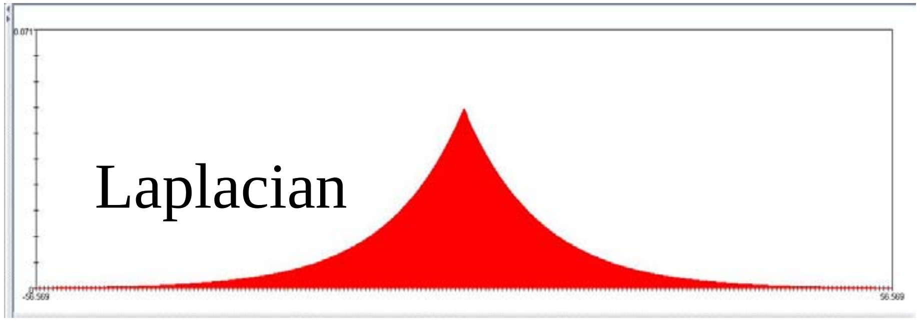


# Confidence levels

- Error distributions are not usually normal



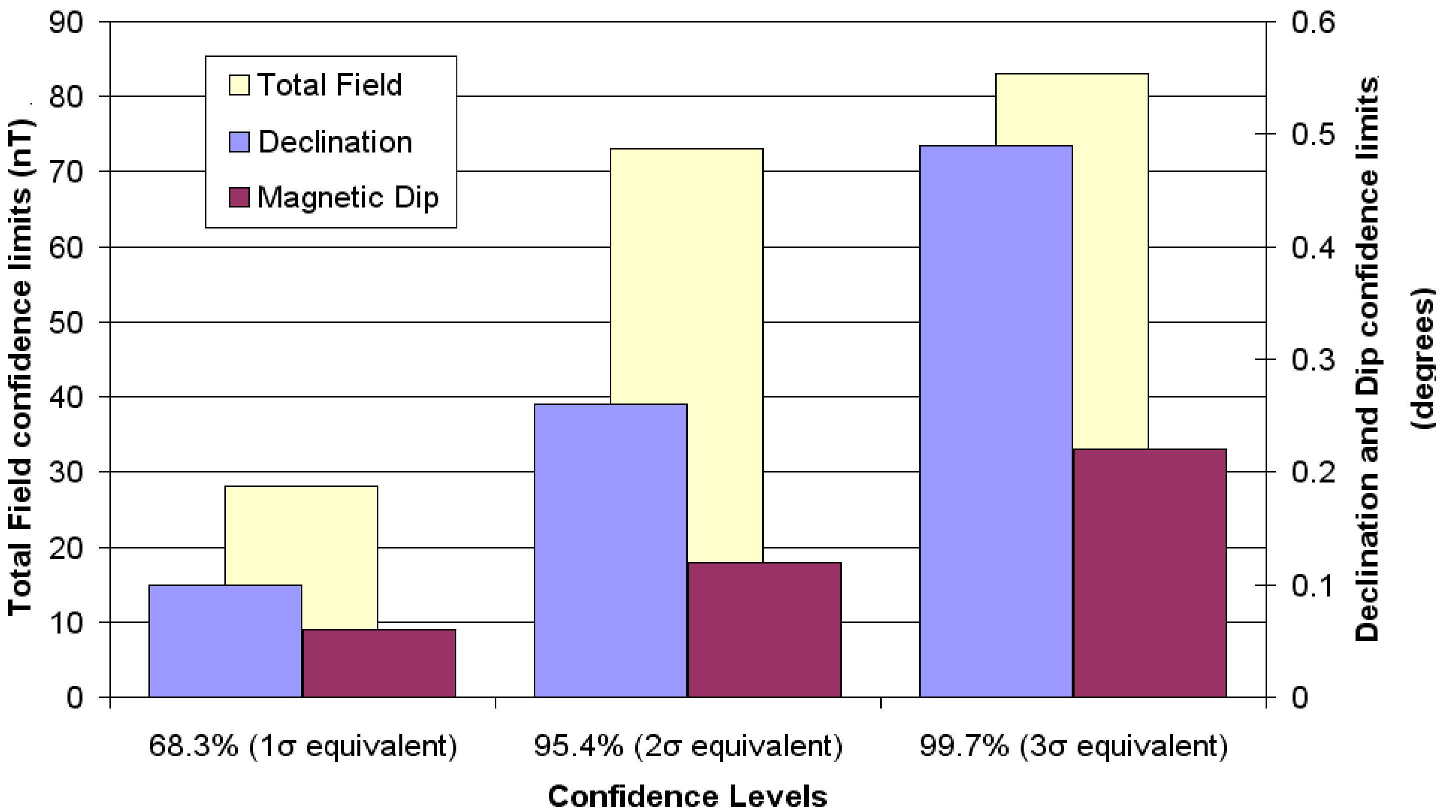

- Should not use multiples of σ and assume same confidence as with a normal distribution
- Confidence levels relevant for any error distribution
- Uncertainties presented as limits for confidence levels…
  - 68.3% (equivalent to 1σ if normal)
  - 95.4% (equivalent to 2σ if normal)
  - 99.7% (equivalent to 3σ if normal)

# $\varepsilon_{main} + \varepsilon_{crust}$

$$B_2 = B_{main} + B_{crust} + 0$$

$$\varepsilon_2 = \varepsilon_{main} + \varepsilon_{crust} + B_{external}$$

| 95.4% confidence limit | | |
|---|---|---|
| *D* | *I* | *F* |
| 0.26° | 0.12° | 73 nT |



# Conclusions

- The crustal field $B_{crust}$ represents an offset error to the geomagnetic field vector from a global model
- Local magnetic observations are necessary to determine $B_{crust}$ and reduce errors
- Further improvement in estimates of B are possible with use of real-time magnetic data for external field $B_{external}$

# Acknowledgements

Companies and institutes undertaking local magnetic surveys around the world and managing magnetic survey databases are thanked for their tireless efforts. The local magnetic data around oil fields have come from a wide variety of sources, and we thank in particular the survey companies Halliburton Sperry Drilling Services, Baker Hughes INTEQ, Schlumberger, and Tech21 for helping make some of them available.

Global magnetic field models are dependent on data from magnetic survey satellites, and the Danish-led Ørsted and German-led CHAMP science teams are thanked. Models are also dependent on magnetic observatories around the world and the various institutes operating them are thanked.