British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

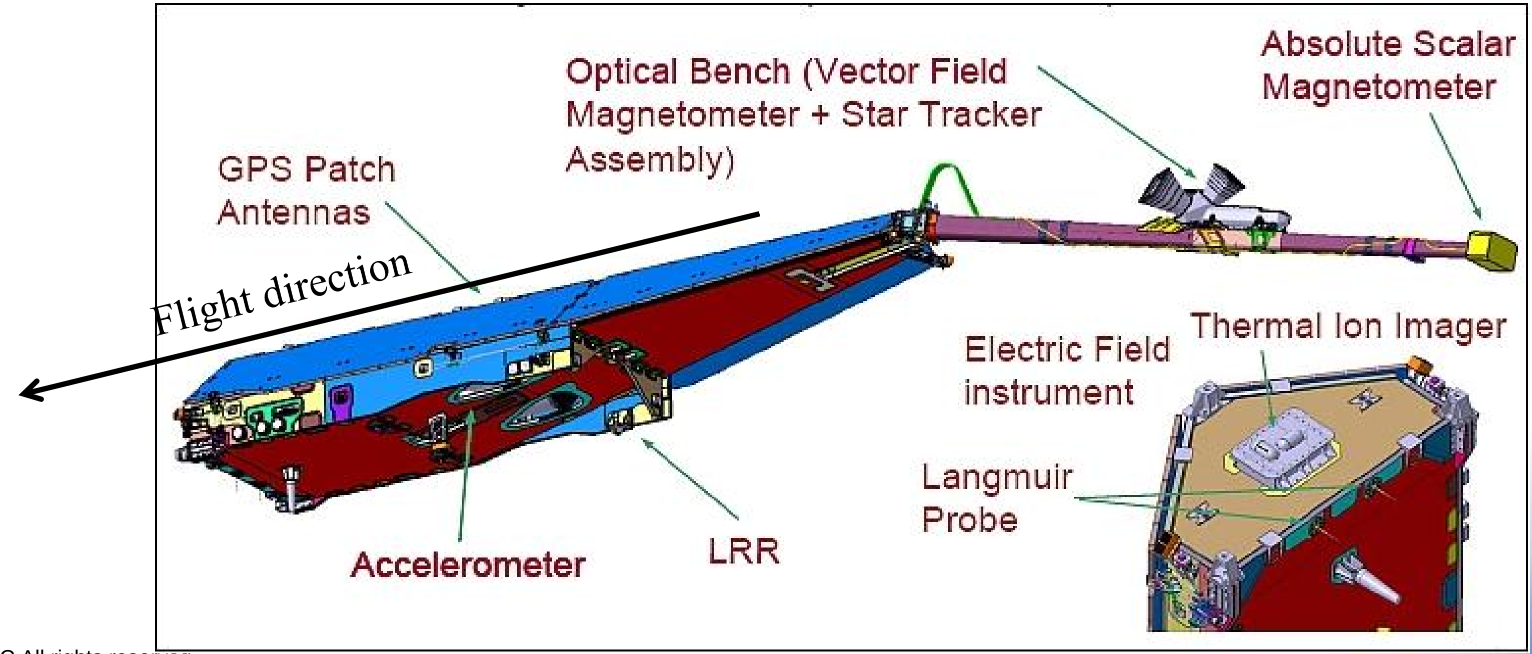
Gateway to the Earth

Recent developments in modelling the internal magnetic field of the Earth

Susan Macmillan and Laurence Billingham

New satellite data – ESA Swarm

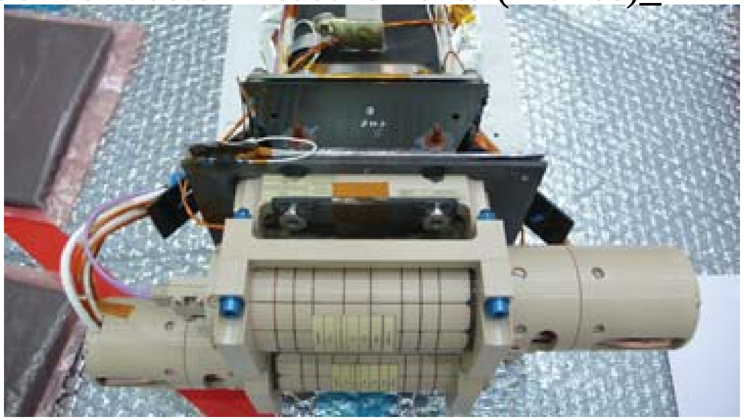
- Three identical satellites, each 9 m long with boom deployed, measuring the magnetic field and complementary plasma parameters



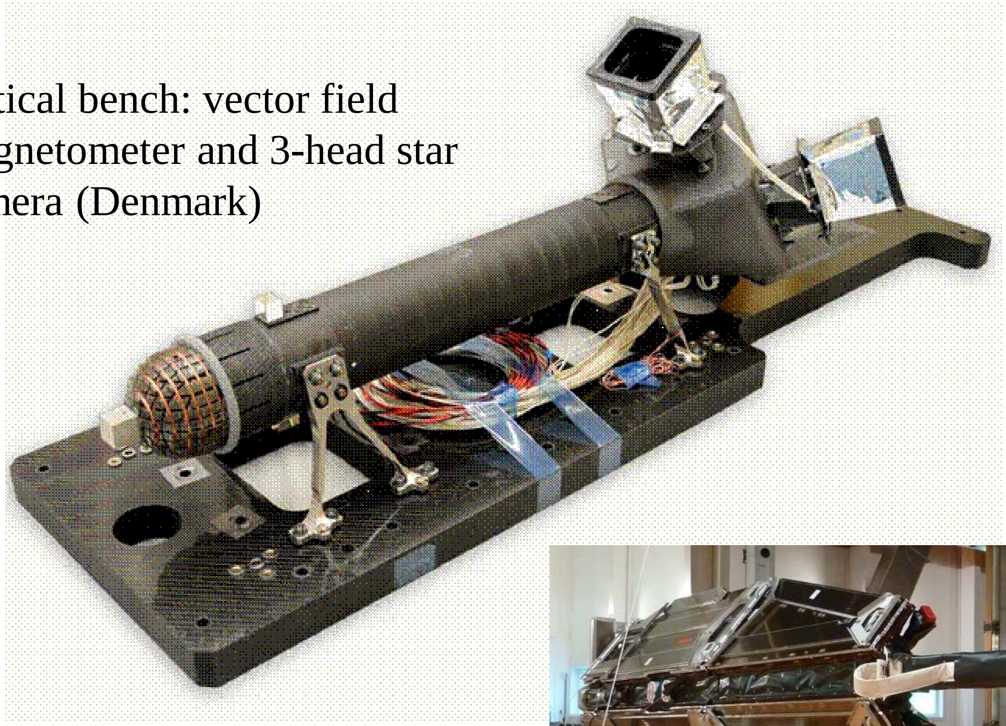
Credit: ESA/DTU

Swarm magnetic field sensors

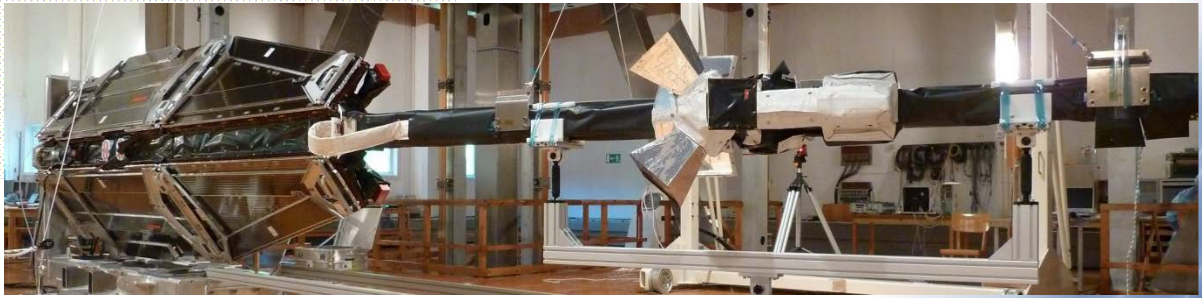
Absolute scalar magnetometer that can also deliver vector measurements (France)_



Optical bench: vector field magnetometer and 3-head star camera (Denmark)

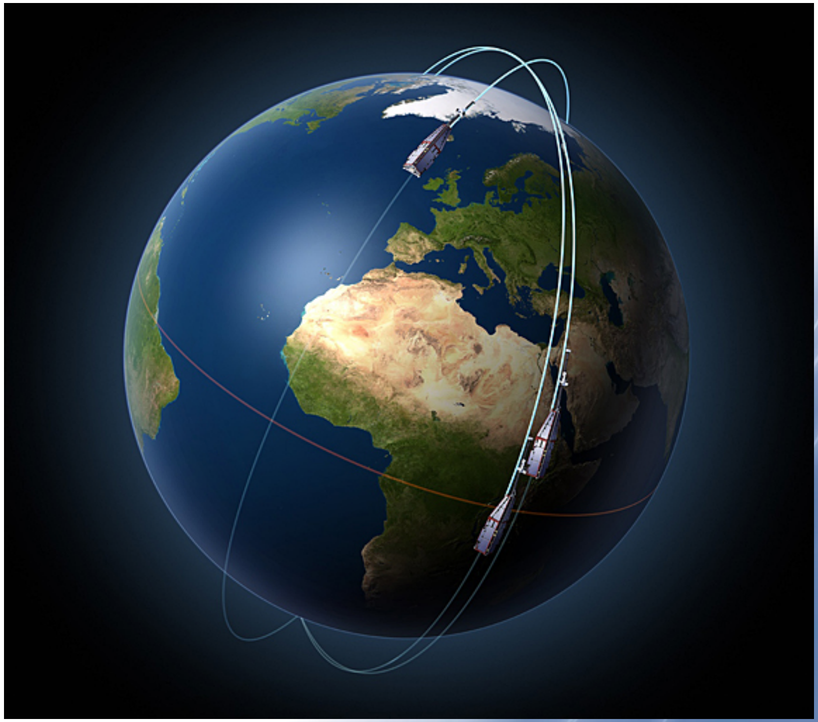


Magnetometers mounted on boom



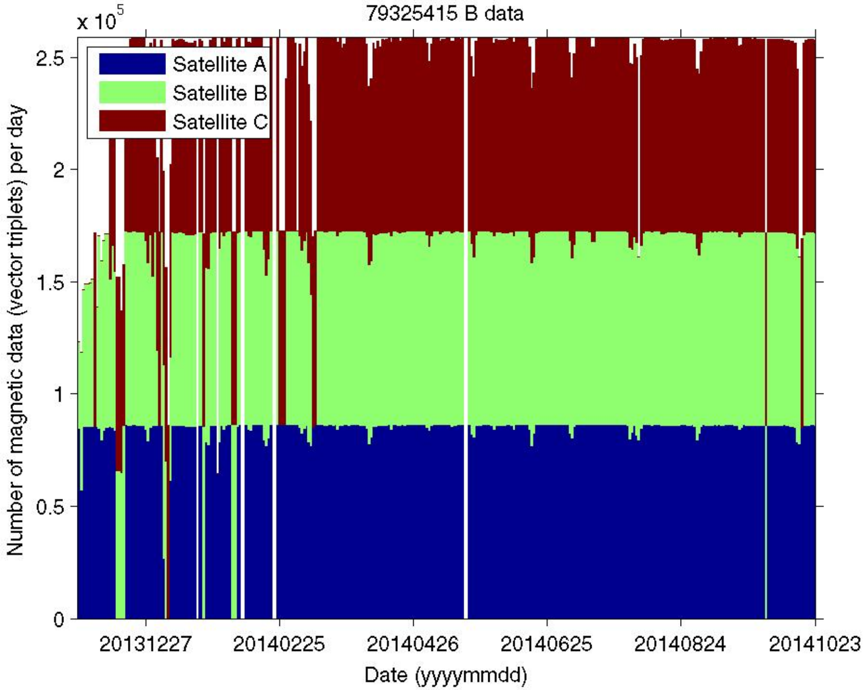
Launch/commissioning

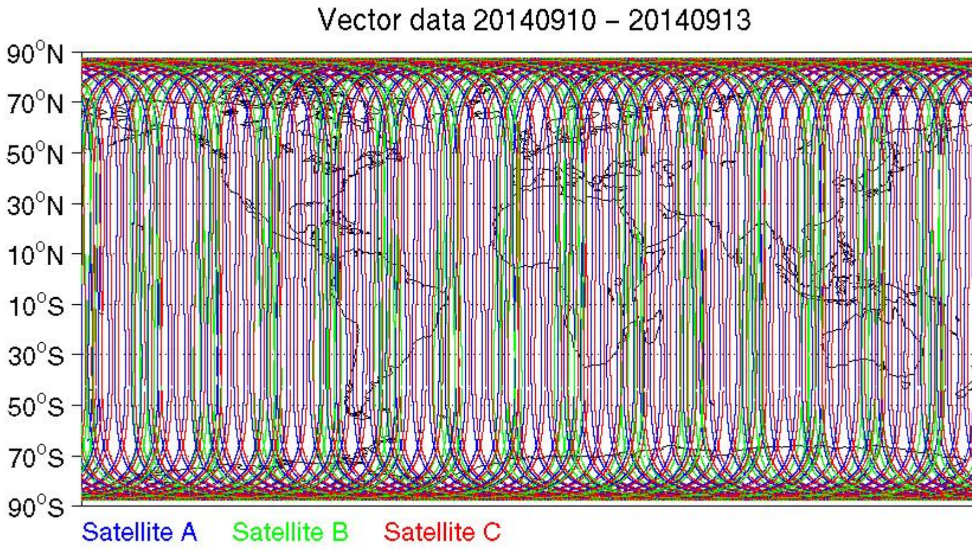
- Launched on 22 November 2013 on Rockot launcher from the Plesetsk Cosmodrome in Russia
- Breeze upper stage released the tightly packed satellites into near-polar circular orbit at an altitude of 490 km
- Final orbit configuration is two at a lower altitude, measuring the East-West gradient of the magnetic field, the third at a higher altitude in a different local time sector

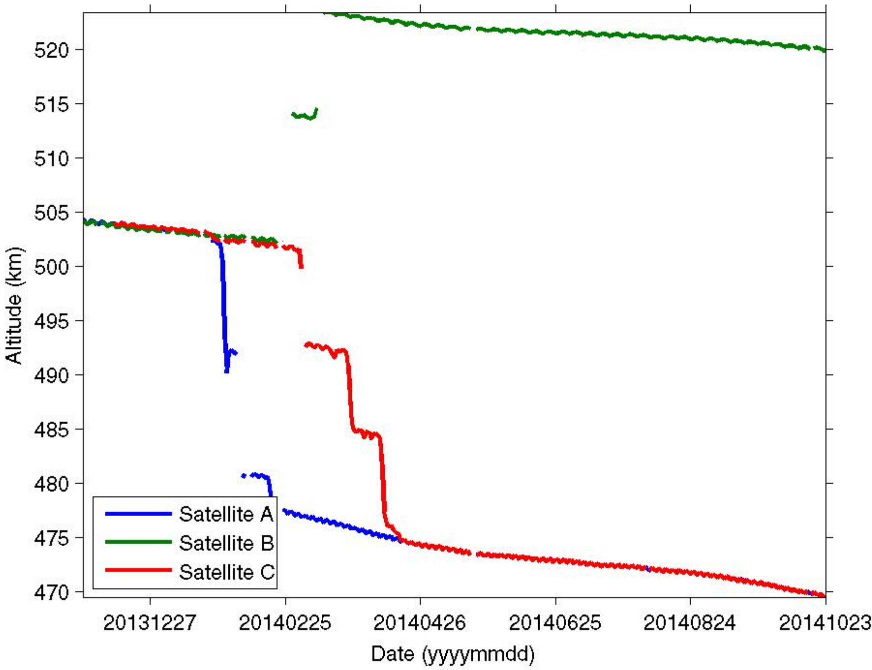


Data availability

- All instruments working to specification with exception of 1 (redundant) scalar magnetic field sensor and 1 accelerometer
- Unexpected thermo-electric/thermo-elastic behaviour in optical bench – very small, can be modelled
- Global coverage of data within a few days

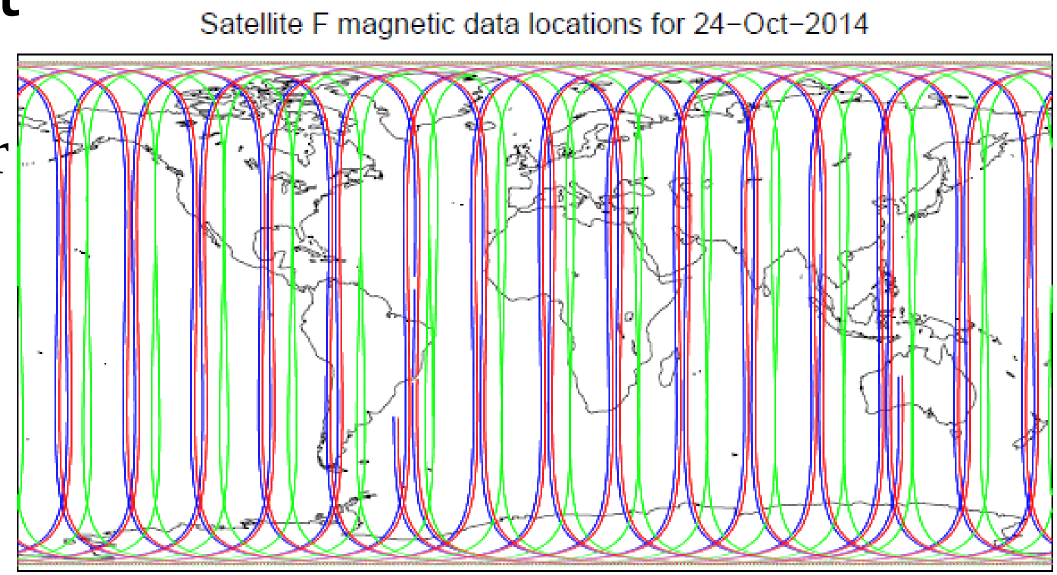




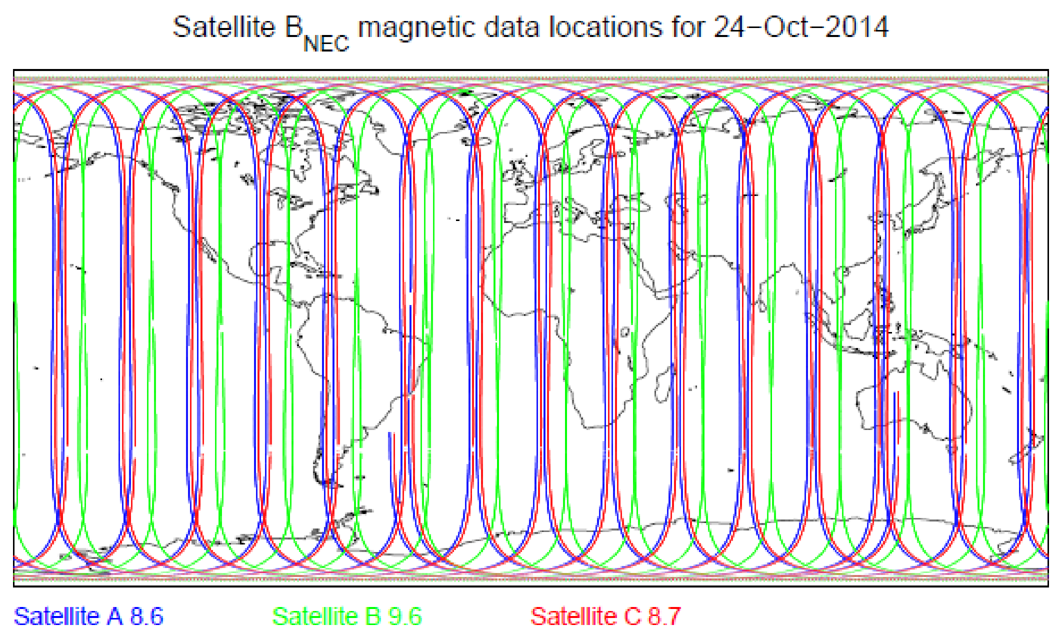


Data coverage 24 Oct

Scalar



Vector

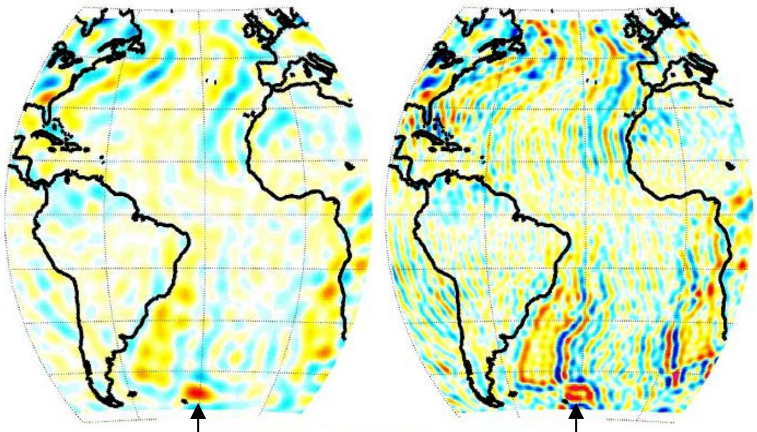


Local times of near-noon (UT) ascending nodes currently 08:39 for lower 2 satellites and 09:36 for higher satellite

Swarm

Science goals

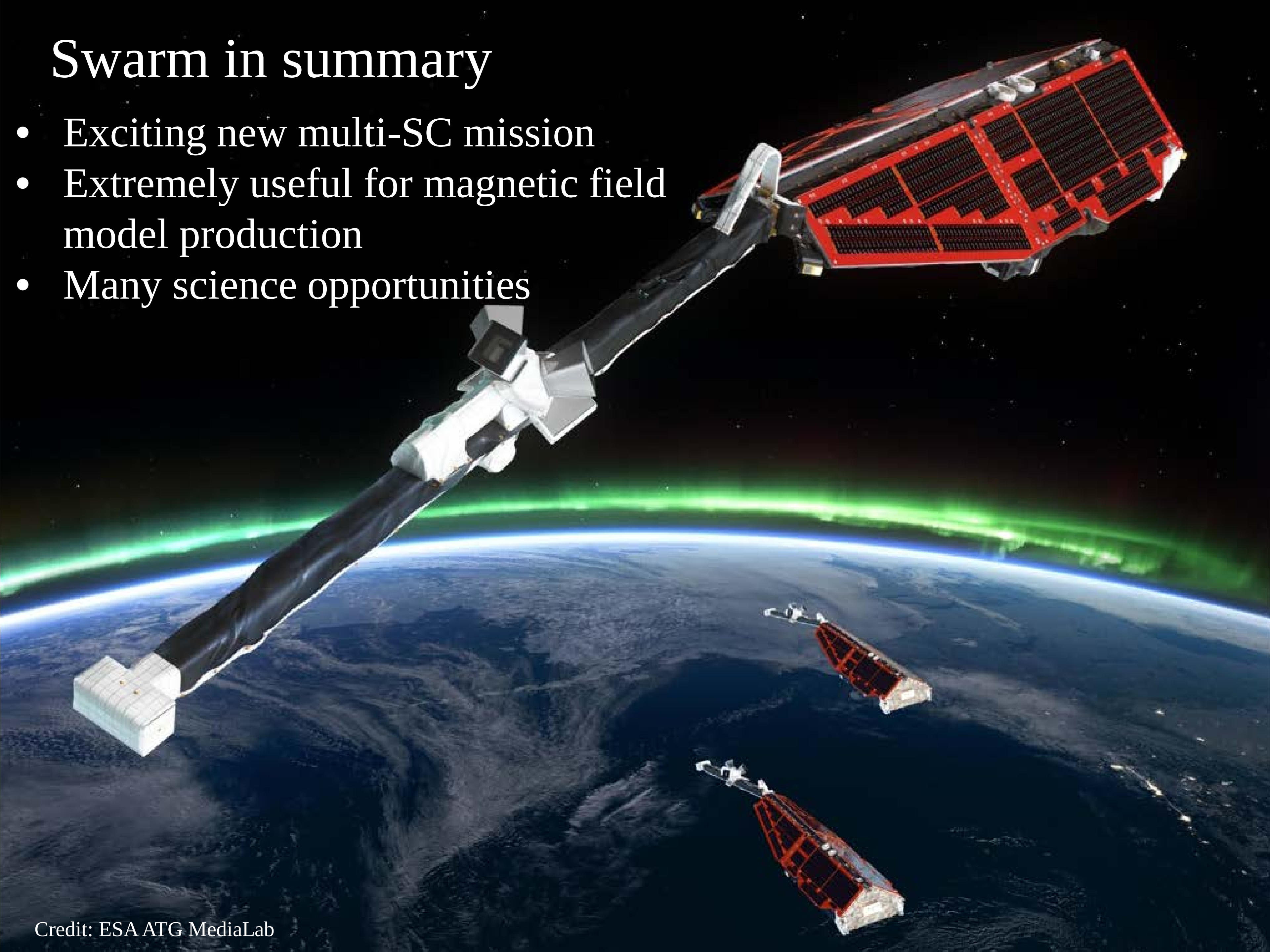
- **Core field dynamics**
  - Inner core control of outer core motion expected at poles?
  - Small-scale waves in core flows
- **Lithospheric field down to ~350 km wavelengths**
  - Deep lithospheric structure
  - World digital magnetic anomaly map
  - Bridging the gap to aeromag surveys
- **'External' magnetic fields**
  - Ionosphere and magnetosphere – short wavelength time/space variations
  - Magnetic forcing of atmospheric density, composition
  - 'Space weather' monitoring
- **3D mantle electrical conductivity**



Swarm 3rd science meeting June 2014
First results presented, 175 participants from 25 countries

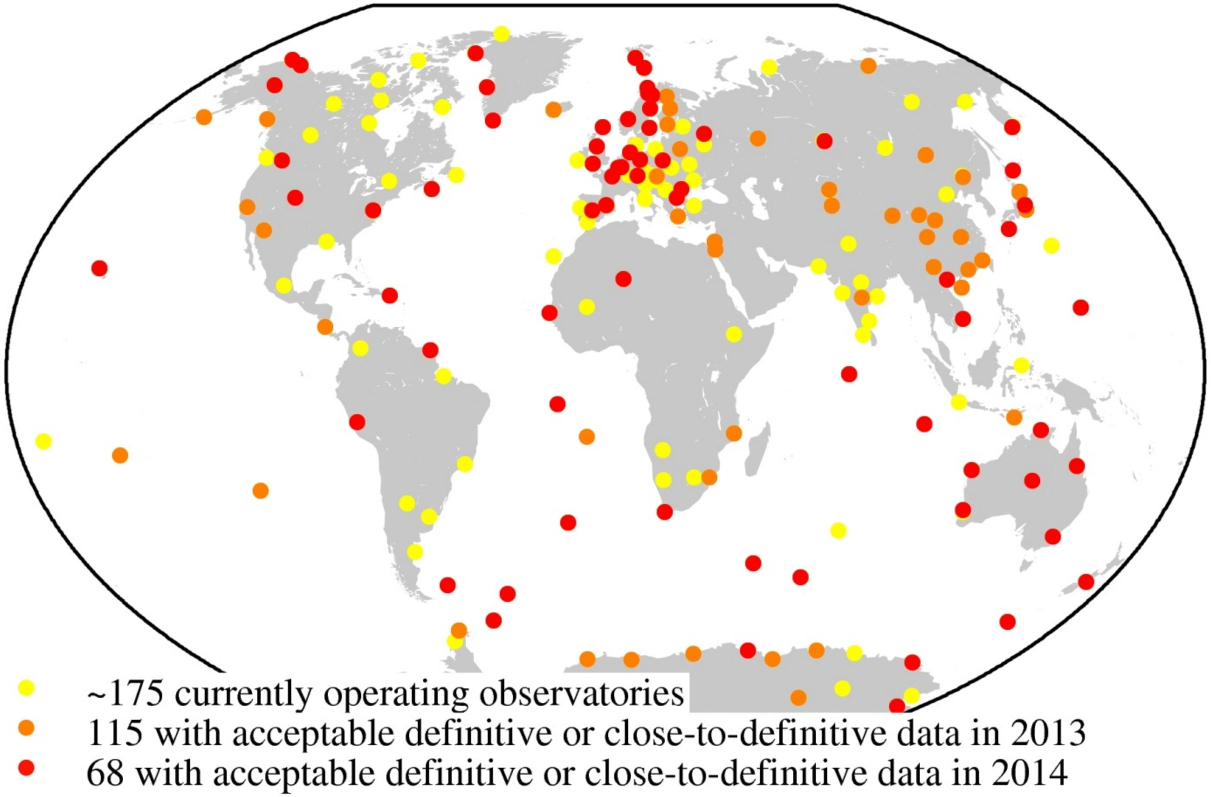
Swarm in summary

- Exciting new multi-SC mission
- Extremely useful for magnetic field model production
- Many science opportunities



Credit: ESA ATG MediaLab

New observatory data



What is close-to-definitive data?

- INTERMAGNET quasi-definitive data (data produced within 3 months of acquisition with accuracy close to that of definitive data)
- Good quality data from other observatories produced in a timely manner. Accounts for 10-20% of the data
- **In practice: almost-final baselines from manual measurements applied to cleaned variometer data and data released in a timely manner**

IAGA observatory workshop and INTERMAGNET meeting

- Successful measurement sessions
- ~40 talks
- Automatic absolute instrument (Belgium) and 1-second instrument developments (Ukraine/Denmark) coming along well
- Sable Island (SBL), South Georgia (KEP) (both UK) and Sonmiani (SON, Pakistan) accepted into INTERMAGNET

XVI IAGA WORKSHOP ON GEOMAGNETIC OBSERVATORY INSTRUMENTS, DATA ACQUISITION AND PROCESSING

Hyderabad, INDIA, October 7-16, 2014

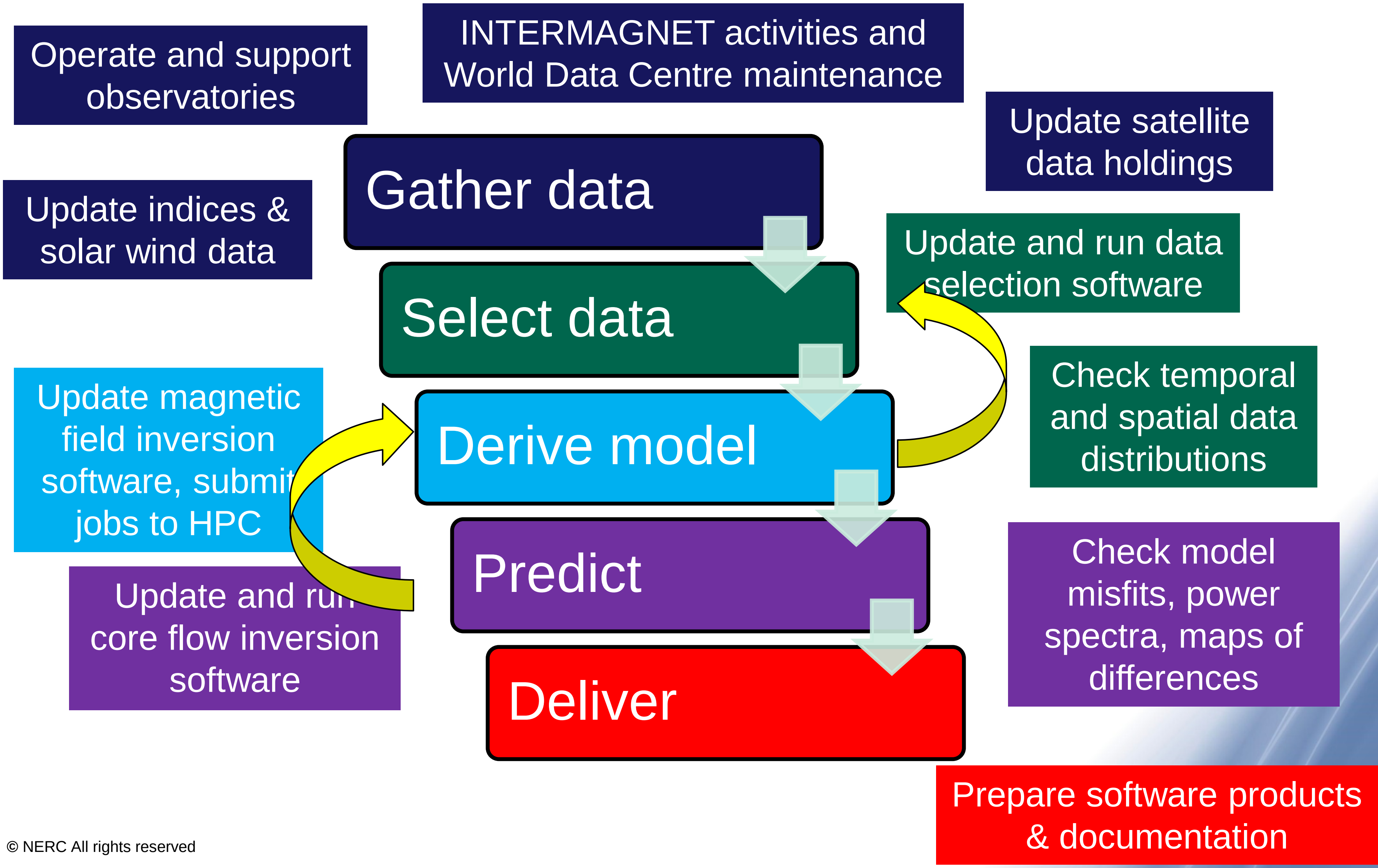
IAGA OBSERVATORY WORKSHOP
2014 HYDERABAD INDIA

CSIR-NGRI Hyderabad
www.ngri.org.in
and

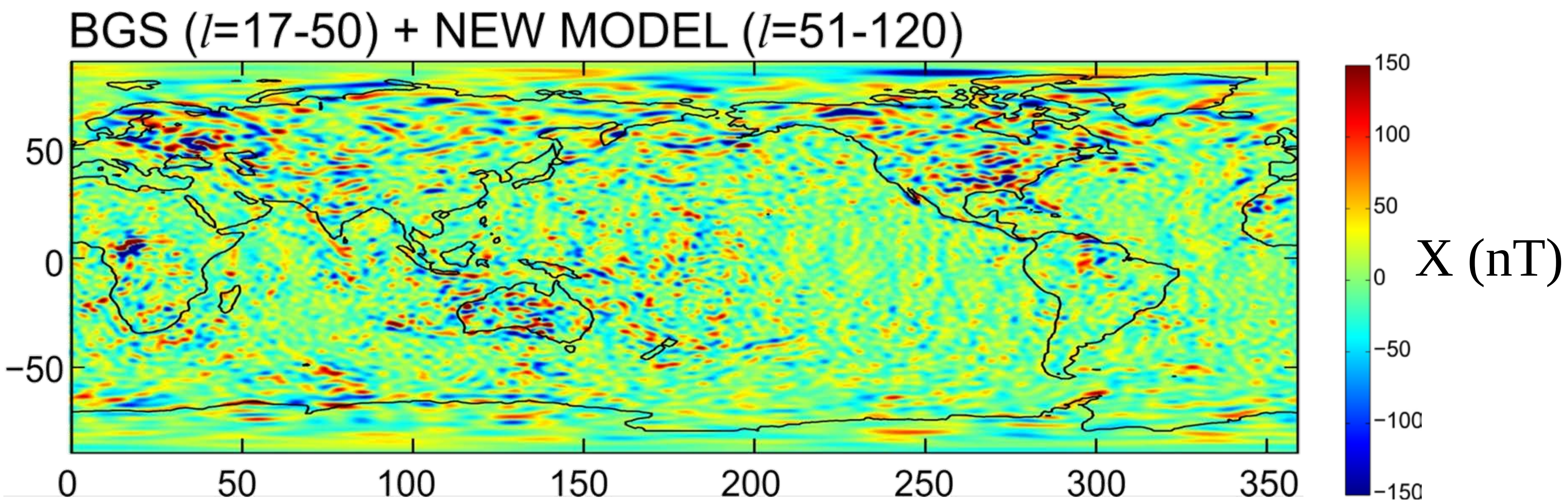
Indian Institute of Geomagnetism
Mumbai www.iigm.res.in

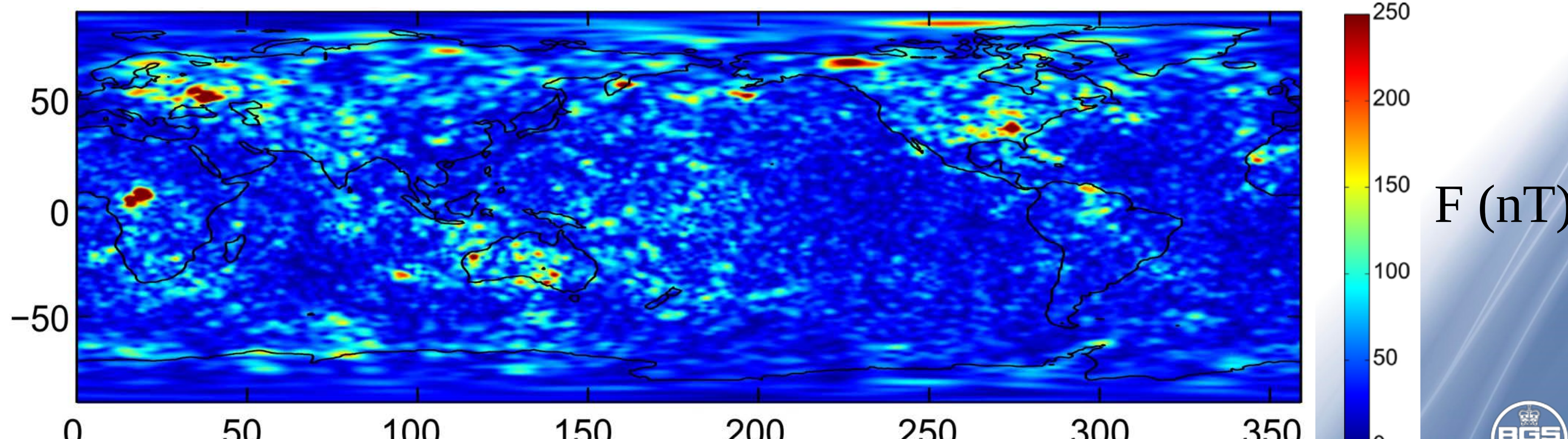
IAGA
International Association of Geomagnetism and Aeronomy
http://www.iugg.org/IAGA

Annual model revision cycle



Global modelling of more of the crustal field





Local modelling of the crustal field
Equivalent sources for In-Field Referencing

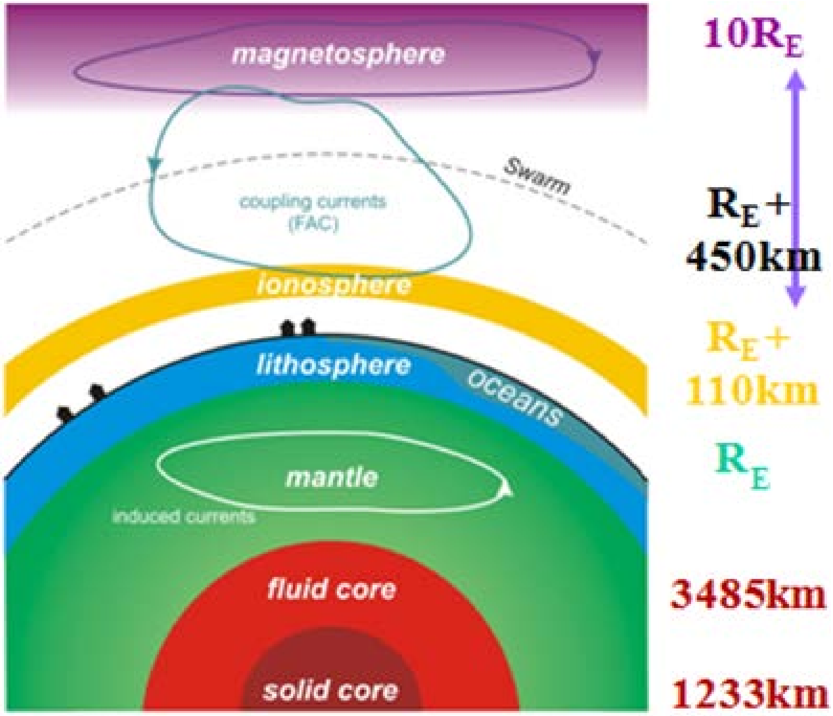
A method to provide reference vectors for directional drilling
as a complement to the currently used Fourier transform techniques

Outline

- Magnetic field source regions
- The crustal field
- Overview of IFR
- Existing Fourier Techniques (IFR-FT)
- New Method (IFR-EQS)
    - introduction to the technique
    - tests with synthetic data
- IFR-FT vs IFR-EQS for real data

Note on nomenclature:
Declination $\rightarrow$ Azimuth
Inclination $\rightarrow$ Dip

Magnetic Field Sources

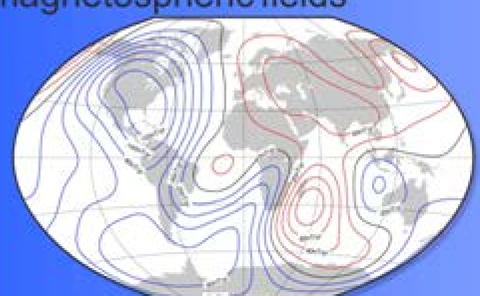


[After Hulot
Geomagnetism (2007)]

$$\mathbf{B}_{observed} = \mathbf{B}_{main} + \mathbf{B}_{crust} + \mathbf{B}_{external}$$

Global model

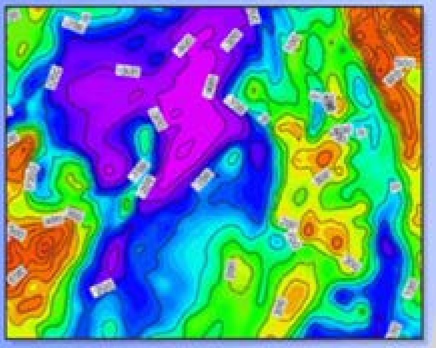
Global modelling of large scale core, crustal and magnetospheric fields



Rate of change of total intensity 31/12/13

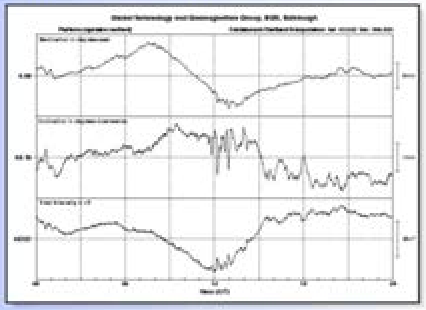
IFR(1)

Accounting for small scale crustal structure



External

Real time monitoring and correction for geomagnetic field variations

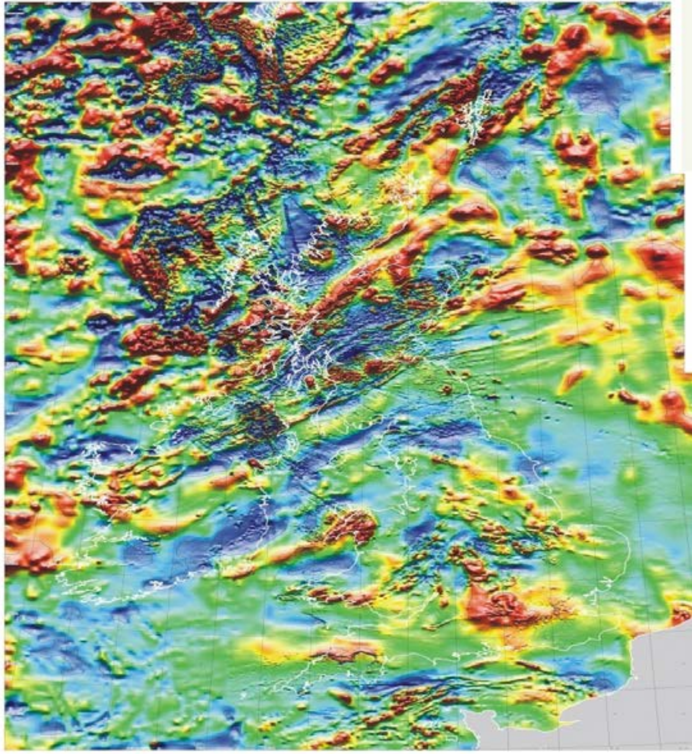


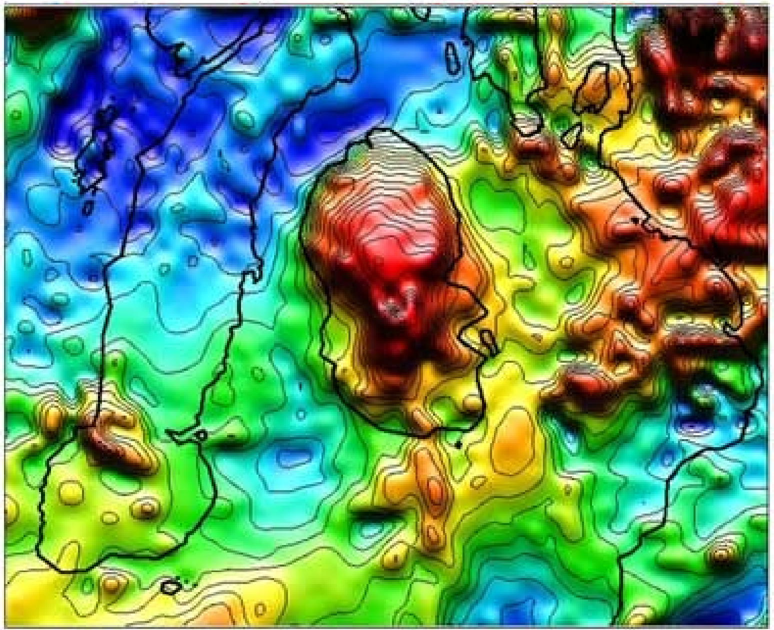
Crustal field ($\mathbf{B}_c$)

- $|\mathbf{B}_c|$ typically < 1 μT (~< 2% of $|\mathbf{B}_{total}|$)
- Magnetite-bearing rocks in crust and upper mantle
  - Depths: <7 km oceanic <30 km continental
- Hydrocarbon exploration often use aeromagnetic surveys

  (marine and land surveys sometimes used too)
- Processing
  - Lines levelled
  - B_m, B_e removed
  - Surface fitted

- Scalar data
  - 1 altitude
  - **Need vectors**
  - **Need many alts/depths**





Overview of IFR

How can we make sure we are drilling in the right direction?

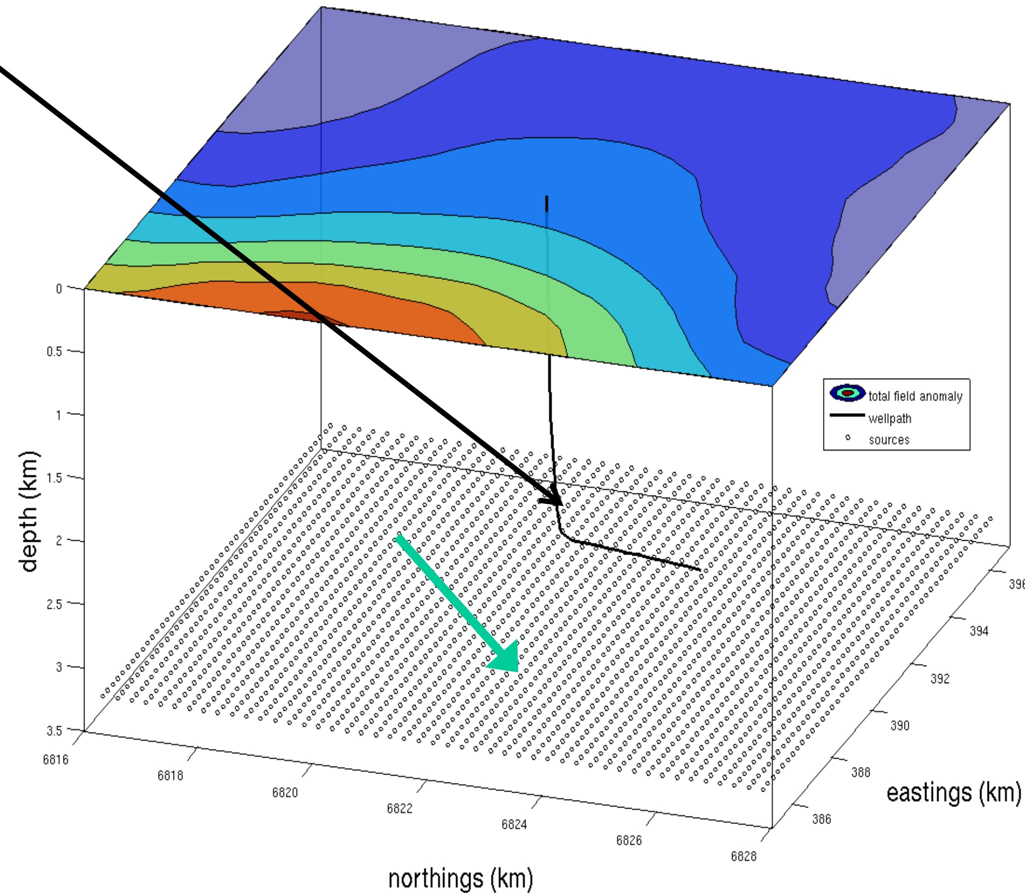
Vector magnetic field provides reference headings at depth

Survey Data

Source attribution

Fourier techniques

Vector **B** at depth



D°	I°	F(nT)
0.1	0.05	50

Target 95% confidence intervals from Russell *et al.* 1995

Overview of IFR: Fourier methods

Survey Data

Source attribution

Fourier techniques

Vector **B** at depth

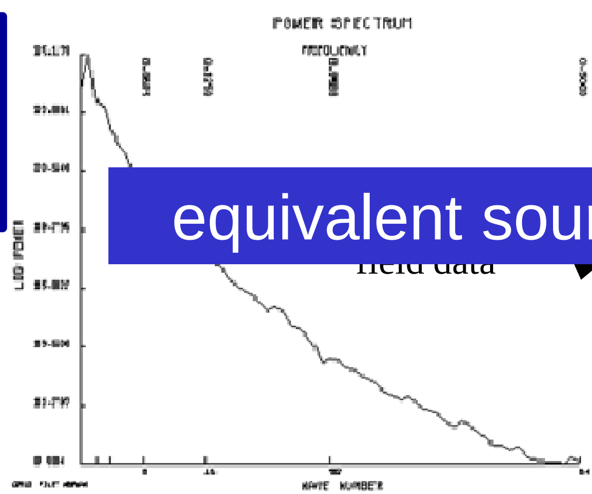
Away from magnetic sources

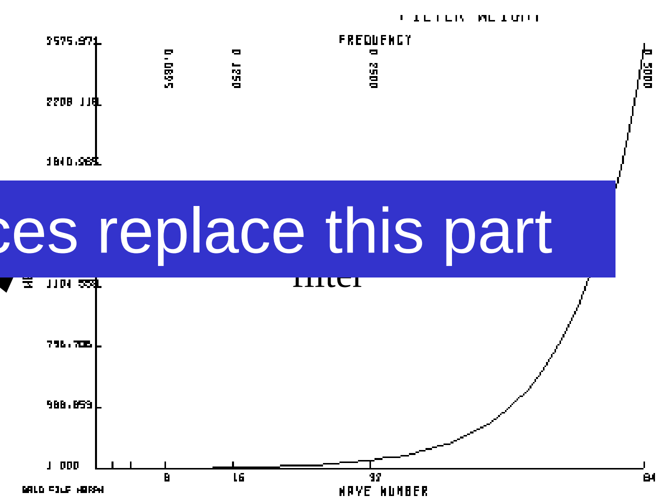
$$\nabla^2\Phi_b = 0 \quad \text{where} \quad \mathbf{b} = -\nabla\Phi_b$$

Can use Fourier techniques to find

$\mathbf{b}(\mathbf{r}_0 \pm \delta z)$ from | $\mathbf{b}(\mathbf{r}_0)$ |

Process of **downward continuation**





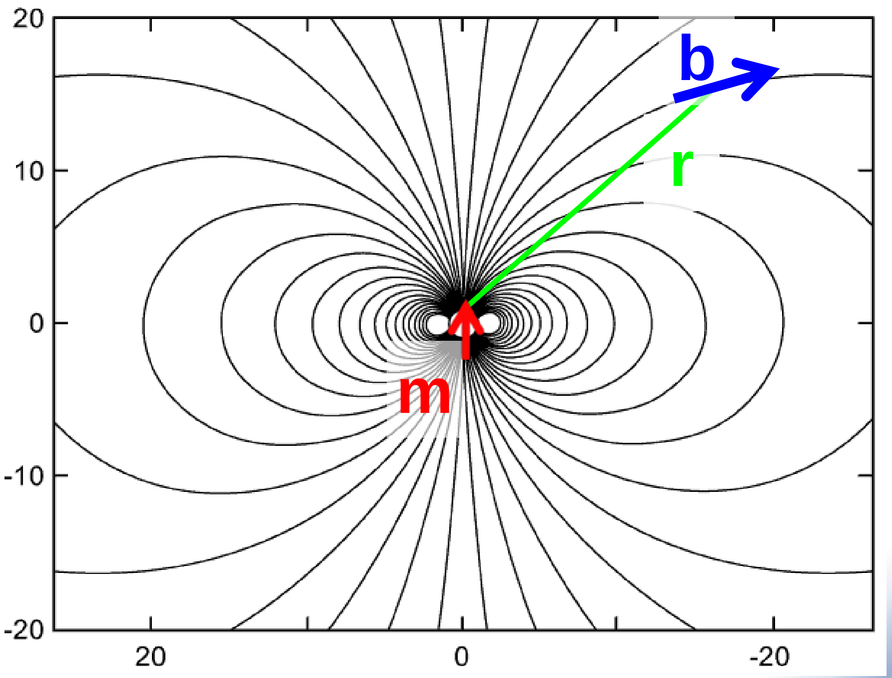
equivalent sources replace this part

Equivalent sources: simplest possible model

$$\mathbf{b}(\mathbf{r}) = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{r^5} - \frac{\mathbf{m}}{r^3}\right)$$

$$\mathbf{b} = \begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix} \quad \mathbf{m} = \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix}$$

Magnetic field lines
of a dipole in a vacuum



After: Russell, C.T. *et al.* Aust.J.Phys 1999

Quantity	base units:
|r|	(m)
|m|	(Am^2) or (JT^{-1})
|b|	(T)

Need a system we can invert

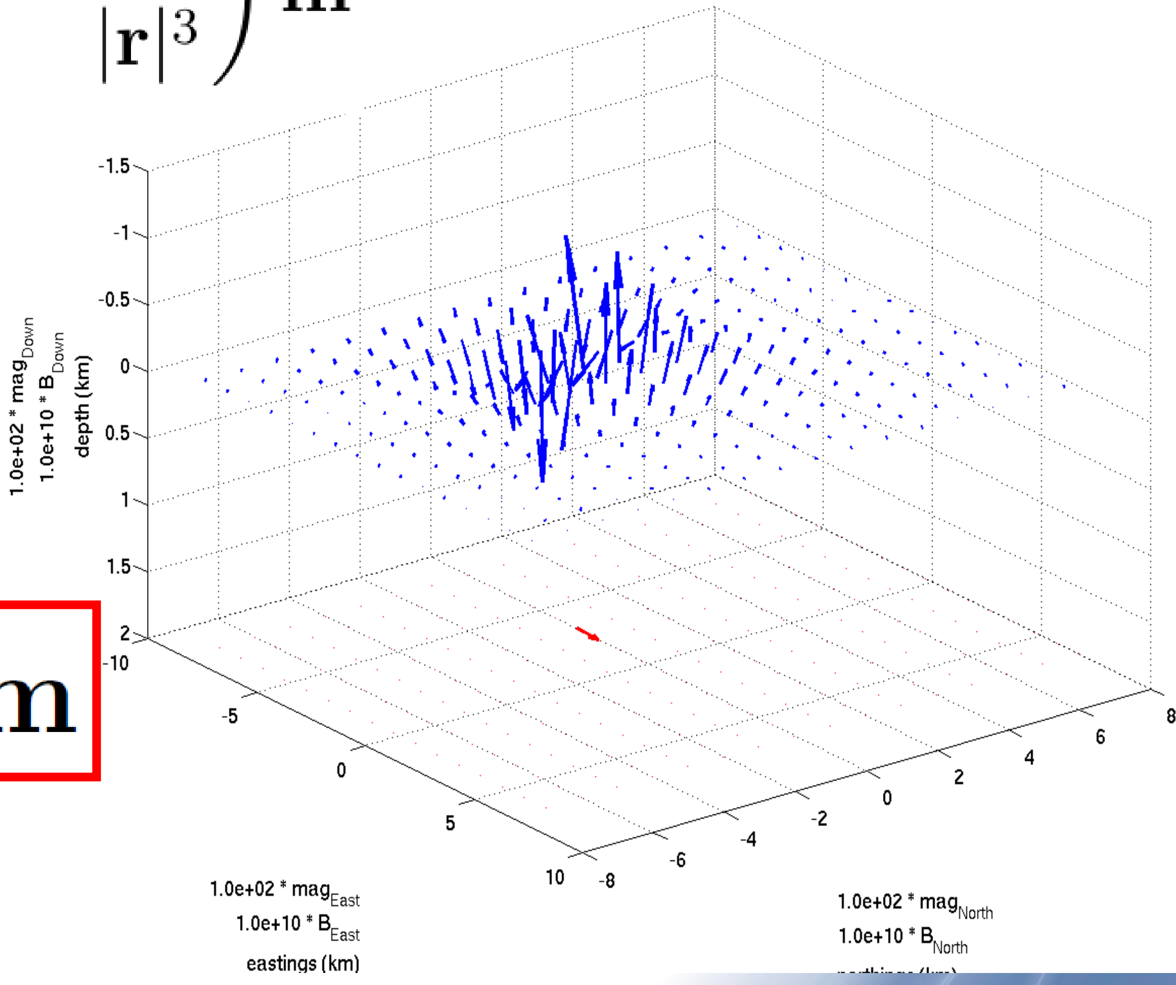
$$\mathbf{b}(\mathbf{r}) = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}\otimes\mathbf{r}}{|\mathbf{r}|^5} - \frac{\mathbb{1}}{|\mathbf{r}|^3}\right)\mathbf{m}$$

Is of the form

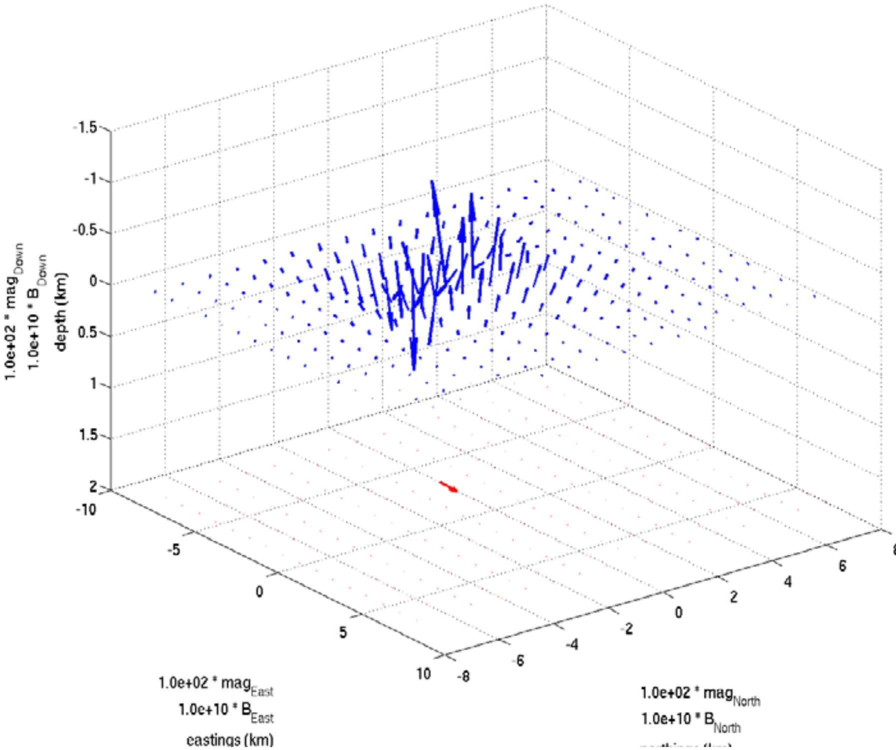
$$\mathbf{b}(\mathbf{r}) = \underline{\mathbf{G}}\mathbf{m}$$

Hence:

$$\underline{\mathbf{G}}^{-1}\mathbf{b}(\mathbf{r}) = \mathbf{m}$$



Multiple dipoles & Multiple observations



1 dipole 1 observation

$$\mathbf{b}(\mathbf{r}) = \underline{\mathbf{G}}\mathbf{m}$$

n dipoles m observations

sources →

observations ↓

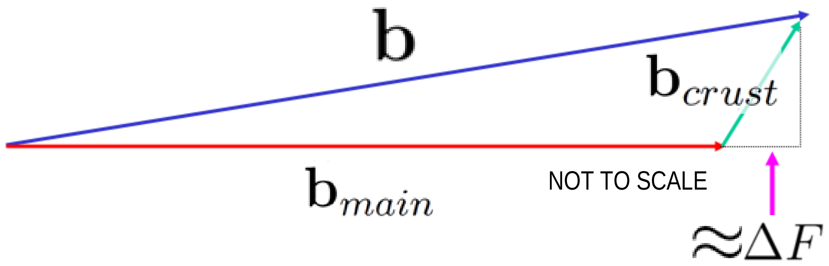
$$\begin{pmatrix} b_{x\,1} \\ b_{y\,1} \\ b_{z\,1} \\ b_{x\,2} \\ b_{y\,2} \\ b_{z\,2} \\ \vdots \\ b_{x\,m} \\ b_{y\,m} \\ b_{z\,m} \end{pmatrix} = \begin{pmatrix} \underline{\mathbf{G}}_1^1 & \underline{\mathbf{G}}_1^2 & \cdots & \underline{\mathbf{G}}_1^n \\ \underline{\mathbf{G}}_2^1 & \underline{\mathbf{G}}_2^2 & \cdots & \underline{\mathbf{G}}_2^n \\ \vdots & \vdots & \ddots & \vdots \\ \underline{\mathbf{G}}_m^1 & \underline{\mathbf{G}}_m^2 & \cdots & \underline{\mathbf{G}}_m^n \end{pmatrix} \begin{pmatrix} m_x^1 \\ m_y^1 \\ m_z^1 \\ m_x^2 \\ m_y^2 \\ m_z^2 \\ \vdots \\ m_x^n \\ m_y^n \\ m_z^n \end{pmatrix}$$

Quickly end up with a fairly large (non-sparse) matrix

But tractable on modern workstation
~1e8 elements

But this assumes vector data.
Need a system that works with scalar data

Include $\mathbf{B}_{\text{main}}$ from a global model



- recall: $\Delta F \approx \mathbf{b}_{crust} \cdot \hat{\mathbf{b}}_{main}$
- hence: $\Delta F \approx (\underline{\mathbf{G}}_{crust}\mathbf{m}) \cdot \hat{\mathbf{b}}_{main}$
- need something separable in **m** ...
  - after a bit (... OK, lots) of bookkeeping:

$$\Delta F \approx \underline{\mathbf{H}}\mathbf{m}$$

- where: $\underline{\mathbf{H}} = \underline{\mathbf{H}}(\hat{\mathbf{b}}_{main}, \mathbf{r})$

But this assumes vector data.
Need a system that works with scalar data

Include $\mathbf{B}_{main}$ from a global model

- recall: $\Delta F \approx \hat{\mathbf{b}}_{crust} \cdot \hat{\mathbf{b}}_{main}$

- hence: $\Delta F \approx (\underline{\mathbf{G}}_{crust}\mathbf{m}) \cdot \hat{\mathbf{b}}_{main}$

- need something separable in $\mathbf{m}$ ...
  - after a bit (...OK, lots) of bookkeeping:

$$\Delta F \approx \underline{\mathbf{H}}\mathbf{m}$$

- where: $\underline{\mathbf{H}} = \underline{\mathbf{H}}(\hat{\mathbf{b}}_{main}, \mathbf{r})$

WARNING

The magnetization model is non-unique:

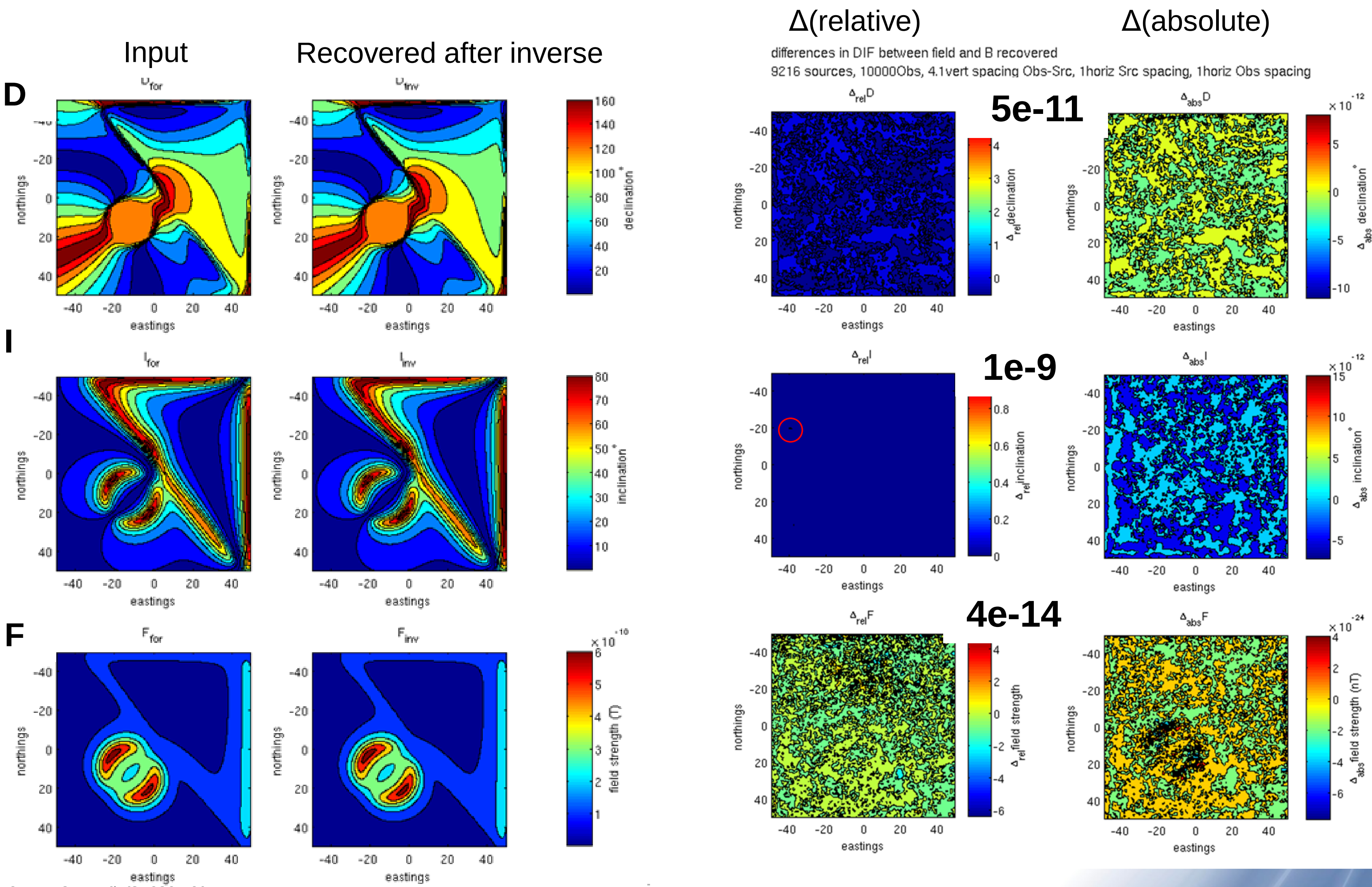
infinitely many $\mathbf{m}$ forward model to same $\Delta \mathrm{F}_{obs}$

$$\{\mathbf{m}_1(\mathbf{r}), \mathbf{m}_2(\mathbf{r}), \cdots, \mathbf{m}_\infty(\mathbf{r})\} \rightarrow \Delta \mathrm{F}_{obs}(\mathbf{r})$$

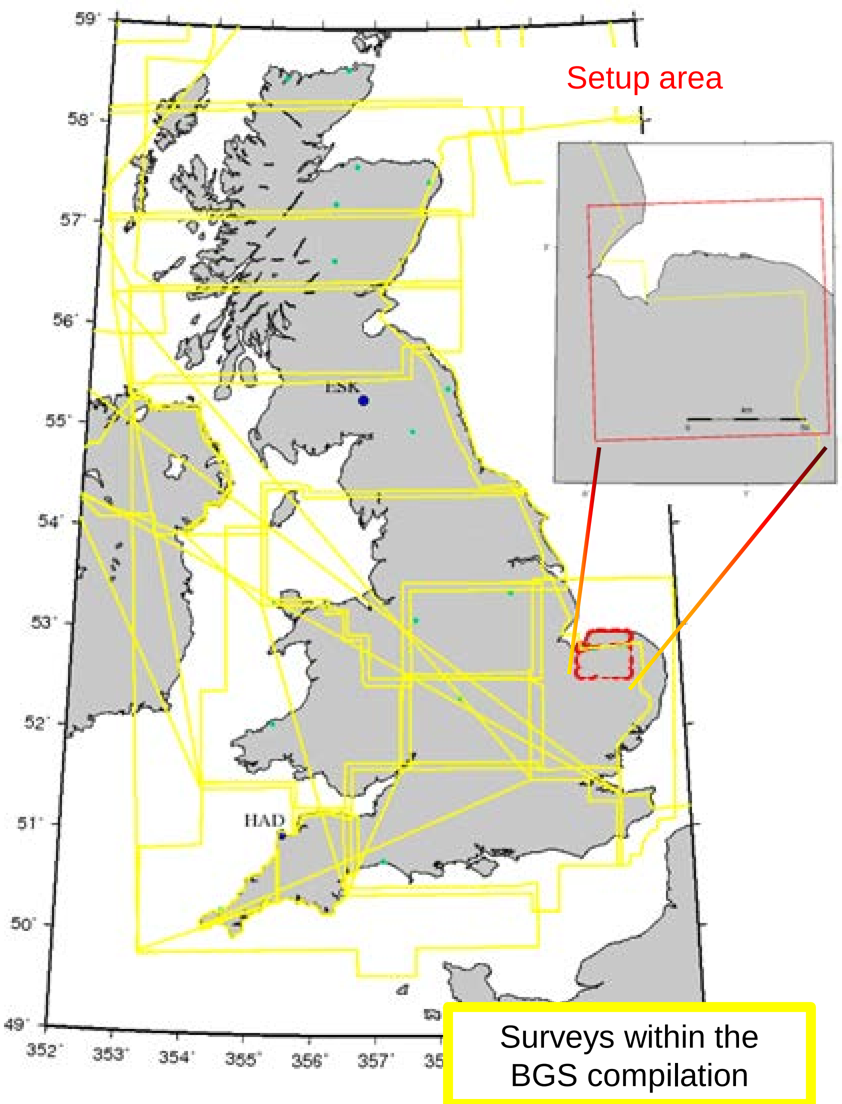
we're going to leave the detail out of this talk

Synthetic data

these errors are small



Real data



IFR setup within the area of BGS compilation

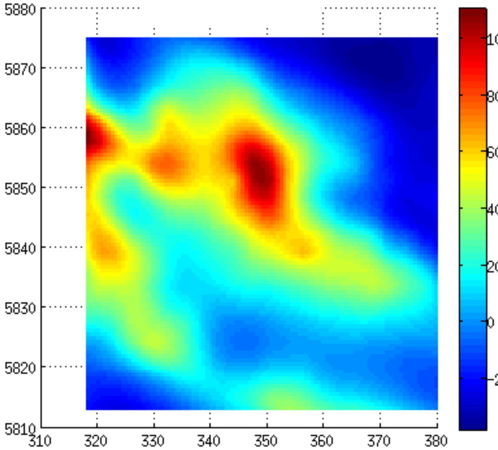
FT vs EQS

Setup over:

- Norfolk
  - Relatively low anomalies and gradients
  - Proxy for North Sea drilling areas

After we downward continue/invert for model: How well can we fit the input anomalies?

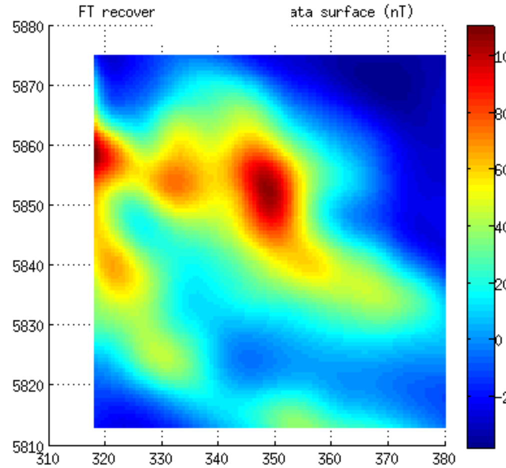
input



100

-20

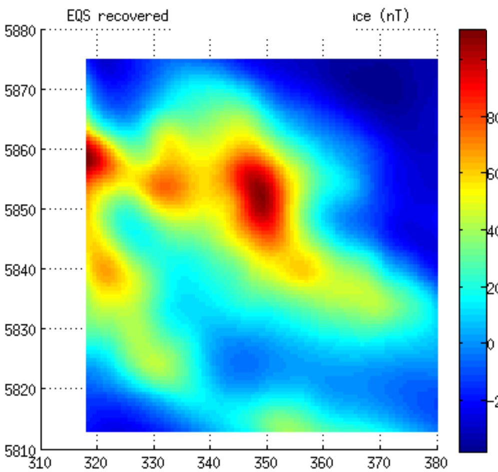
FT



100

-20

EQS



100

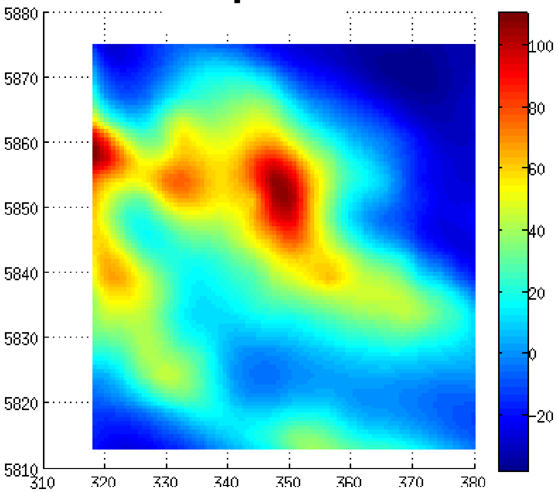
-20

Norfolk

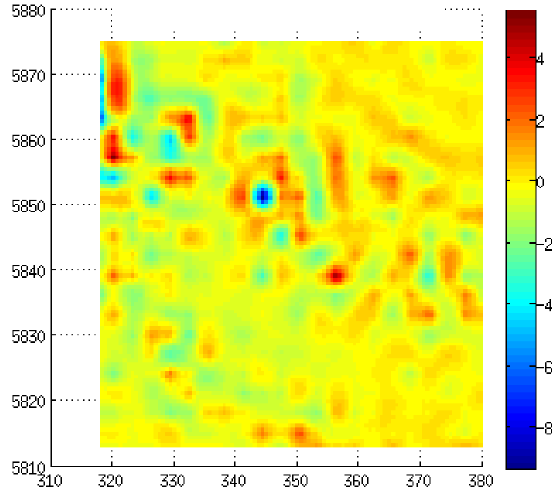
We can recover the input data very well

After we downward continue/invert for model: How well can we fit the input anomalies?

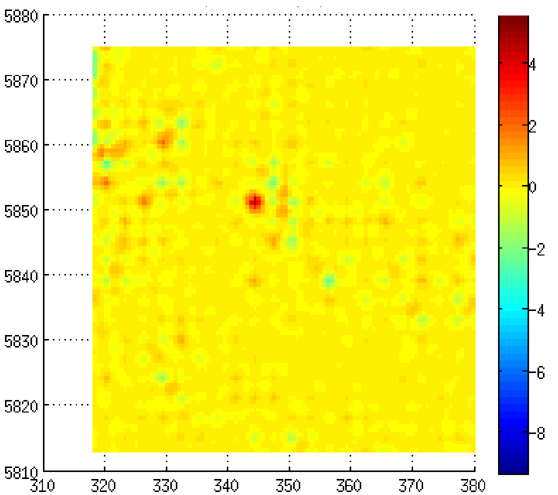
input



FT - input



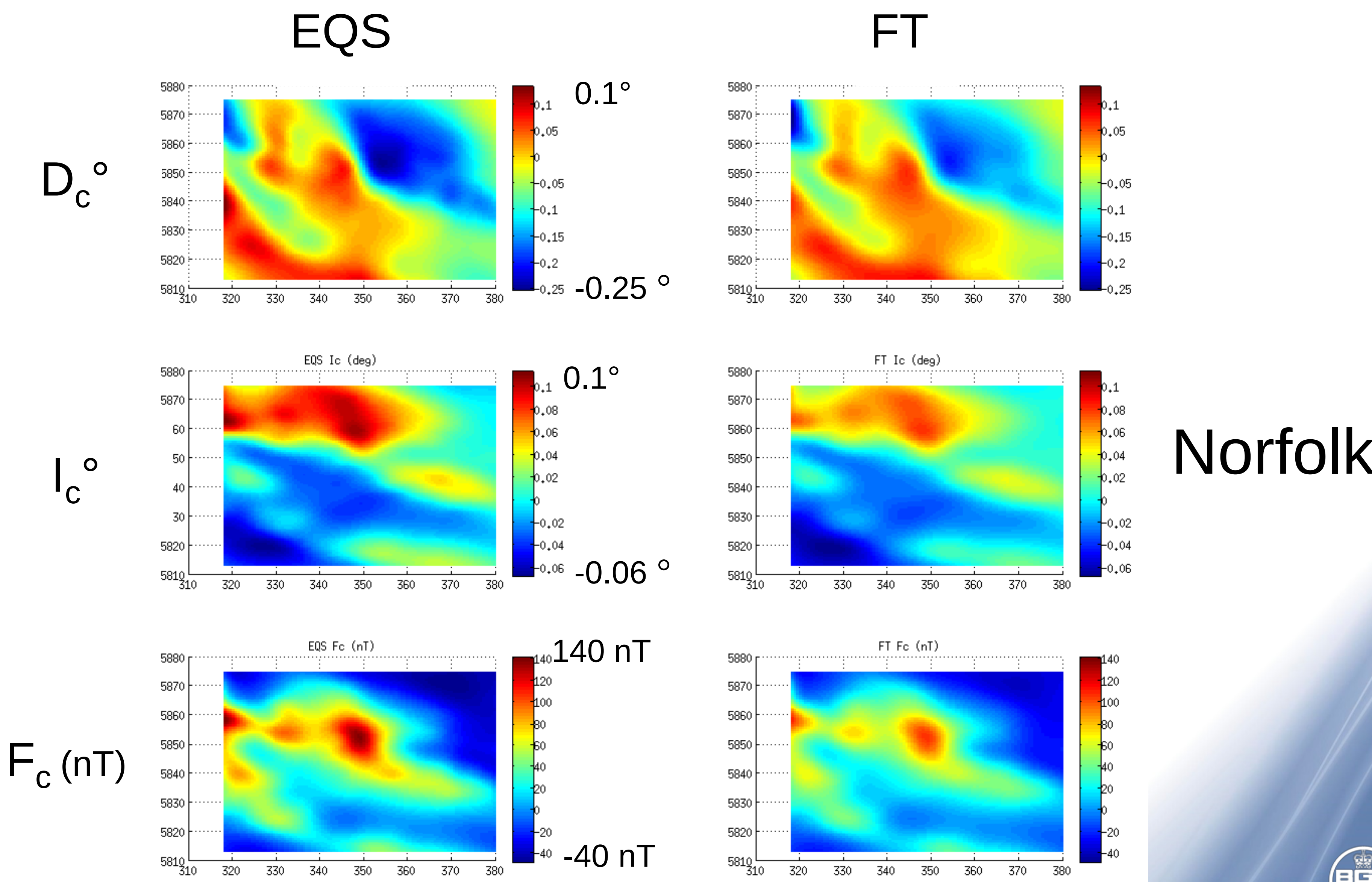
EQS - input



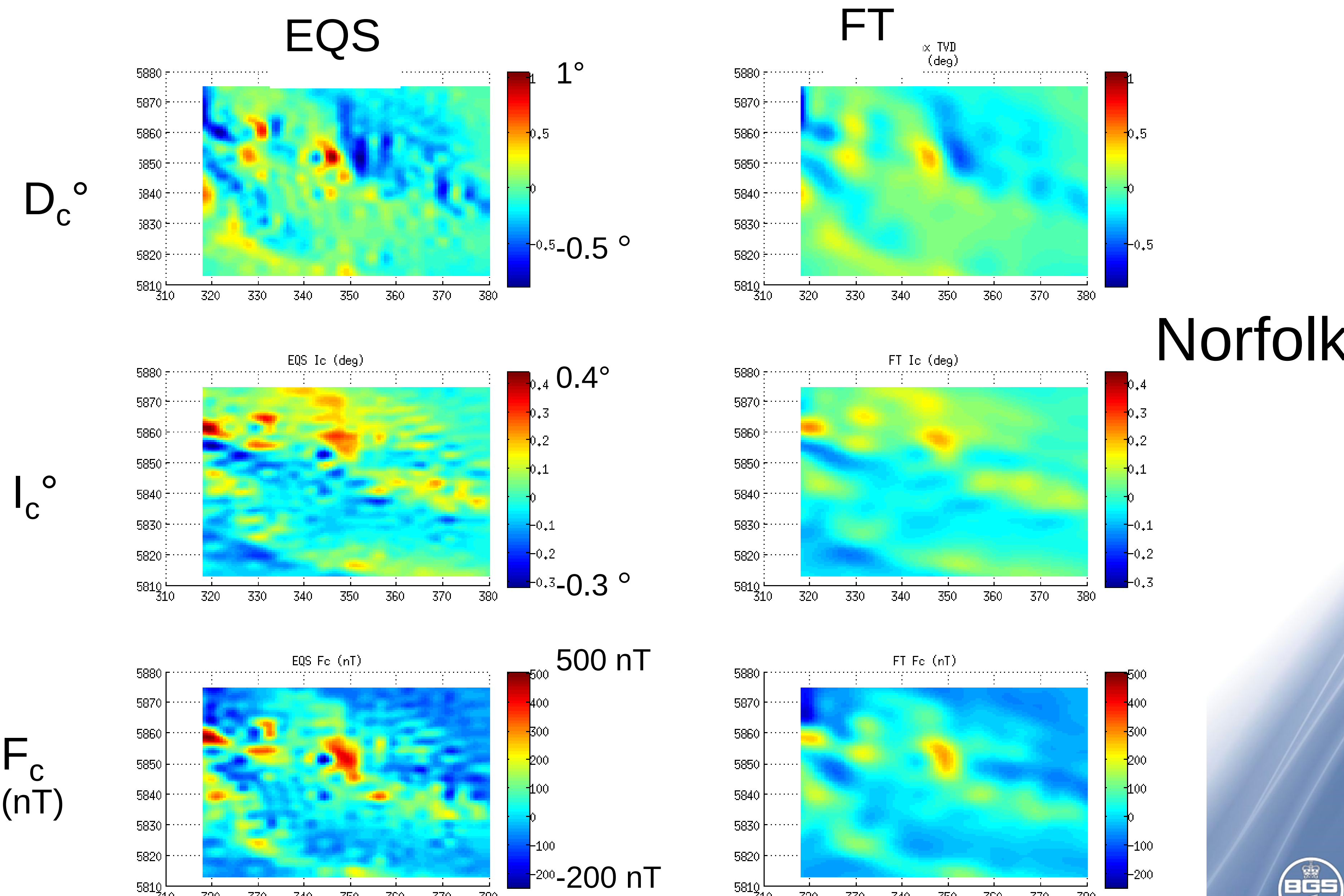
Norfolk

With EQS, fitting the input data is easy. Getting realistic vectors at range of depths is much harder

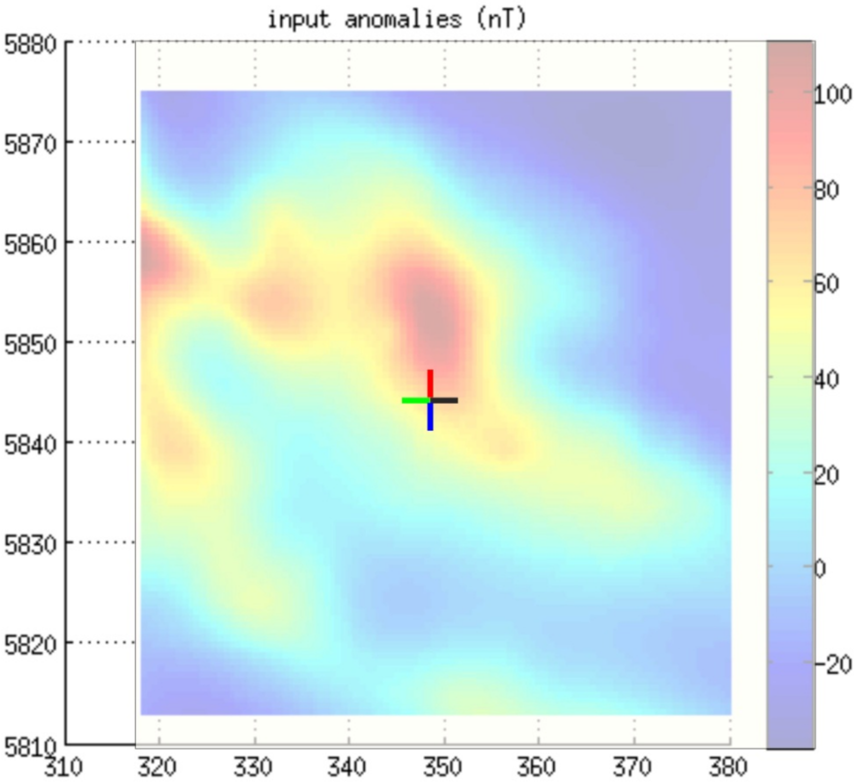
Vector anomalies at input data surface



Vector anomalies at 3.5 km depth



Vector anomalies along typical wellbores

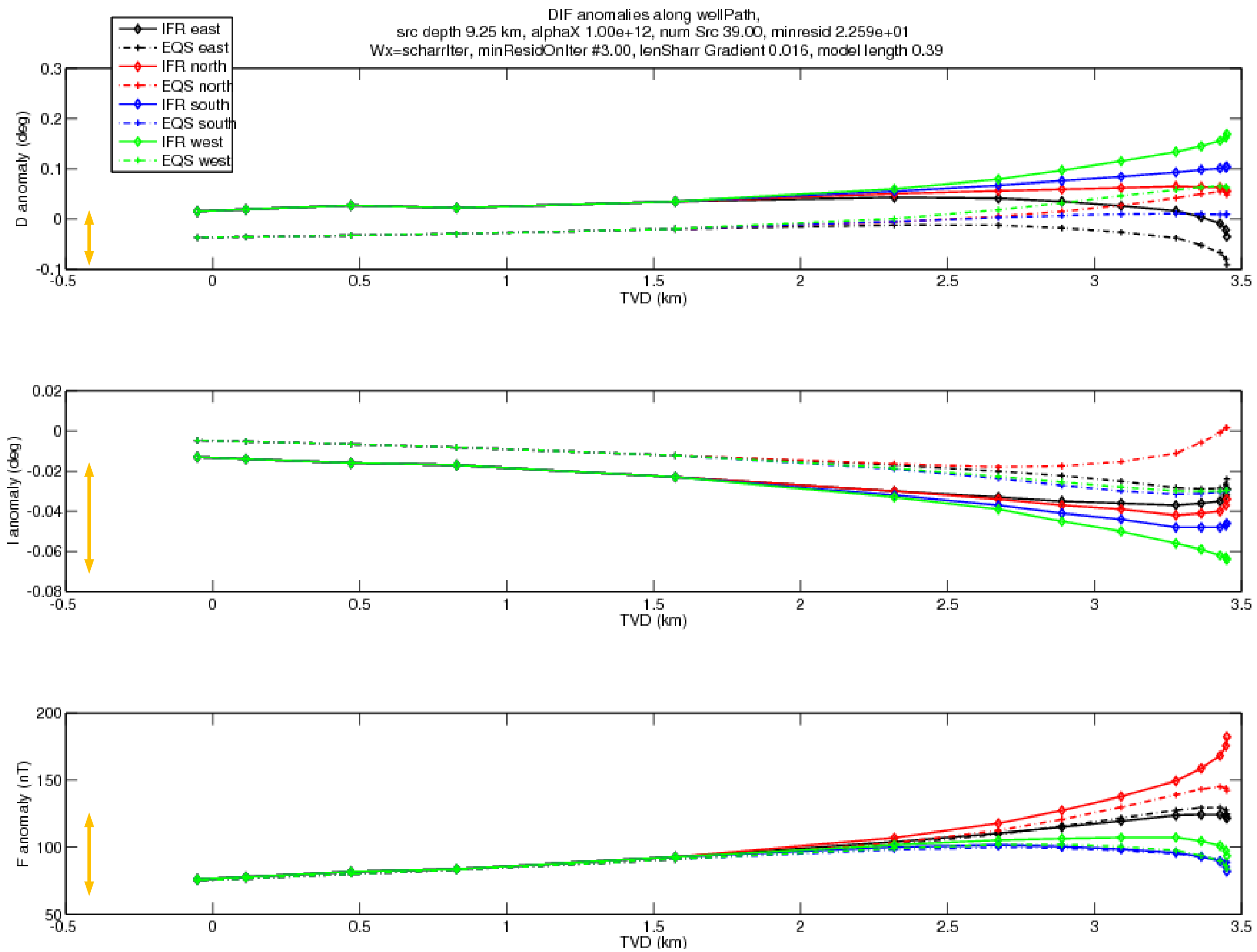


Compute vector anomalies along 4 well trajectories

North, East, South and West of setup centre

Down to 3.5 km TVD

Wells in different directions



Some systematic offset in D and I

Differences grow with depth

Russell *et al*. target 95% CI

Summary

Strengths

IFR-FT	IFR-EQS
Used successfully in 1000s of wells	Needs less input data: similar results to FT with 40% of areal coverage
Simple to implement	Once set-up, fast to compute DIF
Small parameter space	Potential to use vector **B** survey data
Quick to set-up	Can use other geophysical data e.g. in complex regions, source locations inferred via seismic reflection depth to basement

Weaknesses

IFR-FT	IFR-EQS
Slow to give DIF	Large parameter space
Lots of data required	Long time to setup
Cannot include vector data	Iterative inversion *sensitive* to parameters and initial conditions

Conclusions

Overall:
We reproduce FT like results using a technique and a different set of underlying assumptions.

However, not enough evidence that EQS improves upon FT to support routine EQS deployment.

IFR-EQS

Strengths	Weaknesses
Needs less input data: similar results to FT with 40% of areal coverage	Large parameter space
Once set-up, fast to compute DIF	Long time to setup
Potential to use vector **B** survey data	Iterative inversion *sensitive* to parameters and initial conditions
Can use other geophysical data e.g. in complex regions, source locations inferred via seismic reflection depth to basement	