Navigating Underground using the Earth's Magnetic Field

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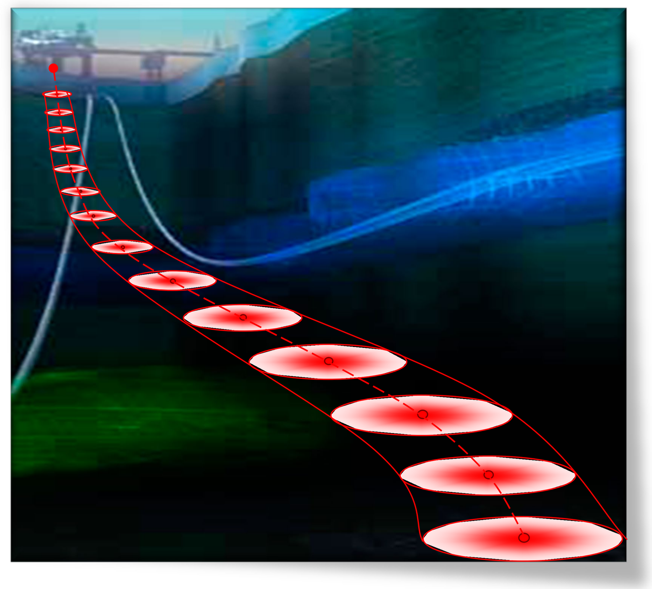
INTRODUCTION

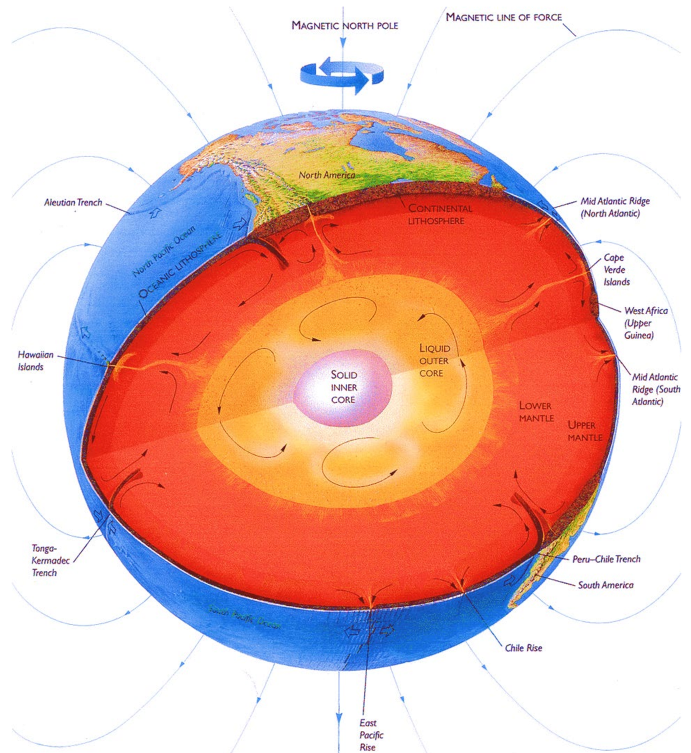
The Earth's magnetic field is ubiquitous and is still widely used as a reference direction with relatively low-cost sensors. One particular area of application is underground, in directional drilling. With hydrocarbon fields becoming "busy" with historic wells, and reservoir targets becoming smaller, the magnetic field estimates used to determine well positions need to be increasingly accurate and, importantly, with well-defined uncertainties.



The Earth's magnetic field comprises the vector sum of fields from 3 main sources:

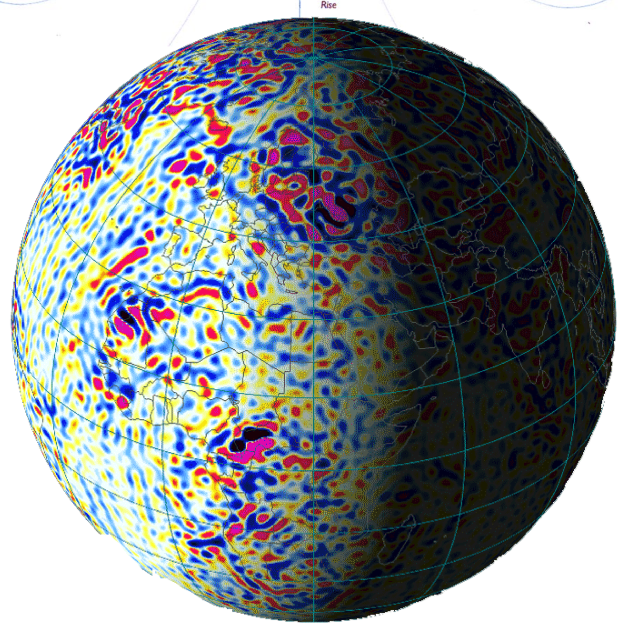
Core Field

- Generated by self-exciting dynamo process in fluid outer core region of the Earth
- Accounts for 95% of the field observable at the Earth's surface
- Large-scale features
- Changes slowly with time ,months to millennia



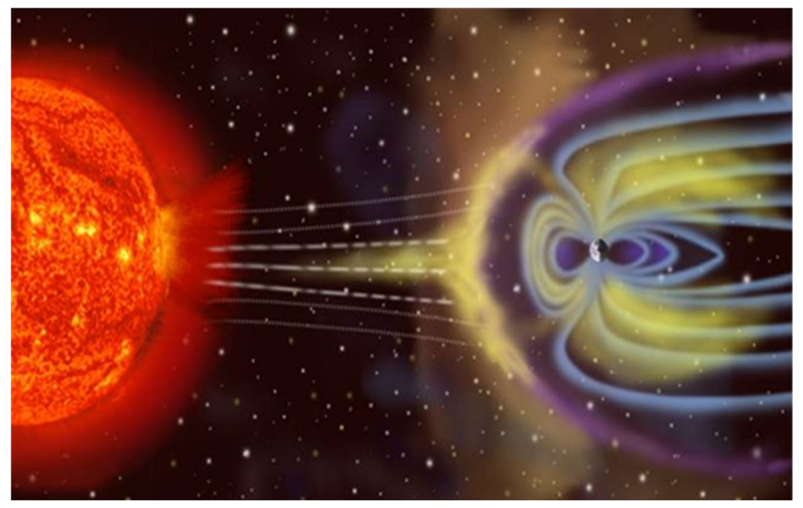
Crustal Field

- From magnetised rocks in the Earth's crust
- Small-scale features
- More or less static with time



External Field

- From processes in the ionosphere and magnetosphere
- Driven by the Sun
- Largest at auroral latitudes
- Changes with time, seconds & daily to decades

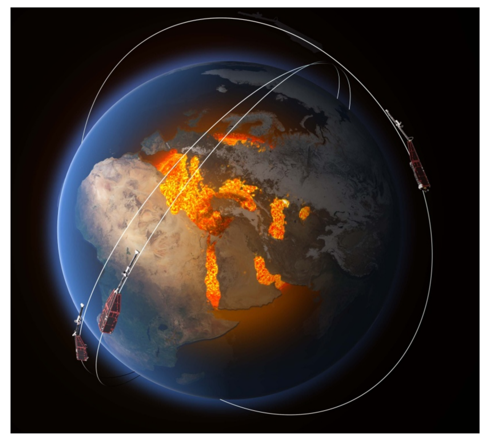


MEASURING & SENSING EARTH'S MAGNETIC FIELD

Measuring

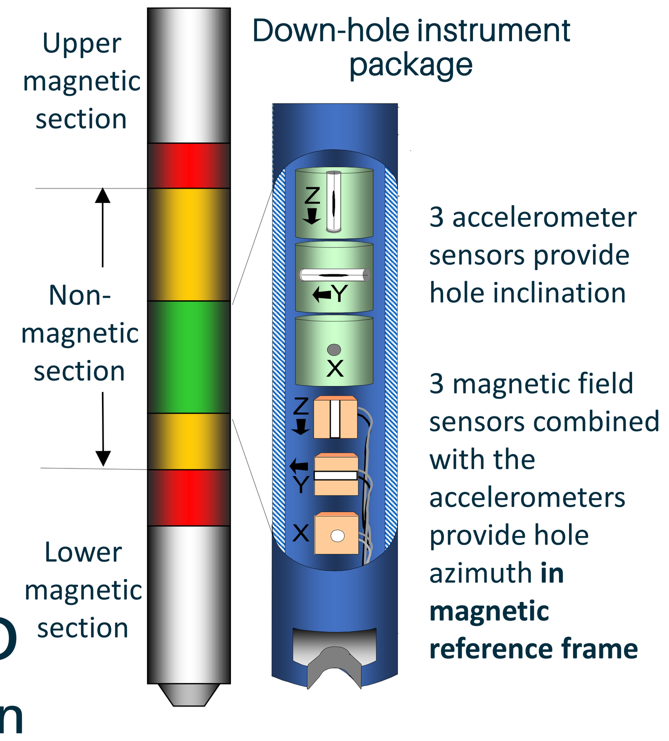
- 160 observatories provide excellent temporal but poor spatial coverage of vector data
- Satellites provide excellent spatial but poor temporal coverage of vector data
- Aeromagnetic surveys provide scalar data

3-satellite ESA SWARM mission launched 2013



Sensing (underground)

- 3-axis magnetometer and 3-axis accelerometer in package behind drill-bit
- Correct for drill-string contamination



CORRECTING FOR MAGNETIC FIELD

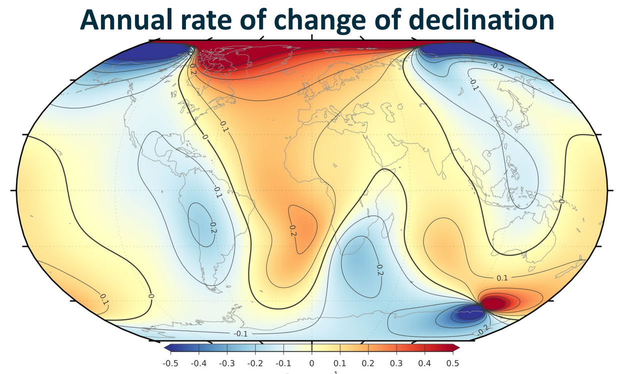
Correct for drill-string magnetic contamination
& rotate from magnetic to geographic reference frame using:

Reducing uncertainties

High resolution global field model

- Includes Core and long/medium wavelength Crustal Fields (> 300 km) and quiet night-time External Field

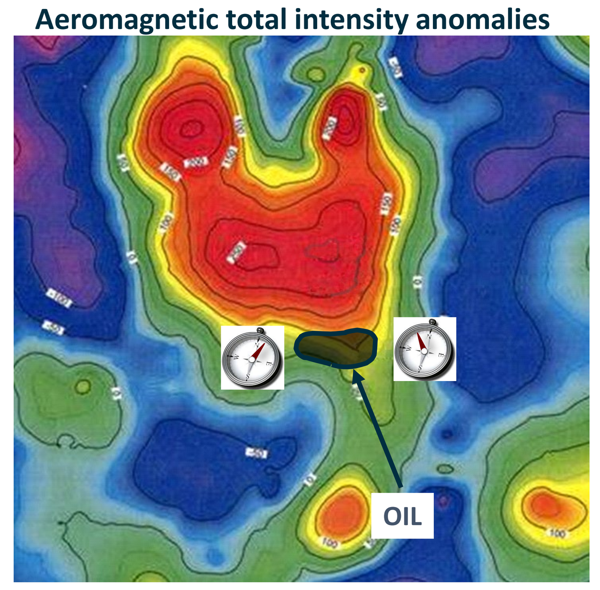
Annual rate of change of declination



In-Field Referencing (IFR) combining global model with estimates of local Crustal Field

- Aeromagnetic total intensity data transformations
  - Scalar to vector
  - Downward continuation

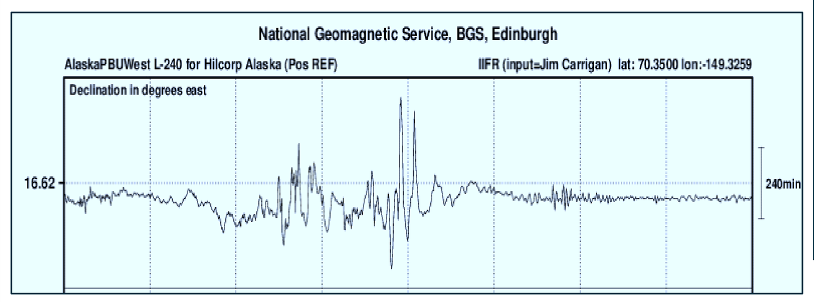
Aeromagnetic total intensity anomalies



< - 100 km - >

IFR including External Field

- Real-time 1-minute data at drilling site derived from local observatories - 10° range in declination for Nov 2021 storm

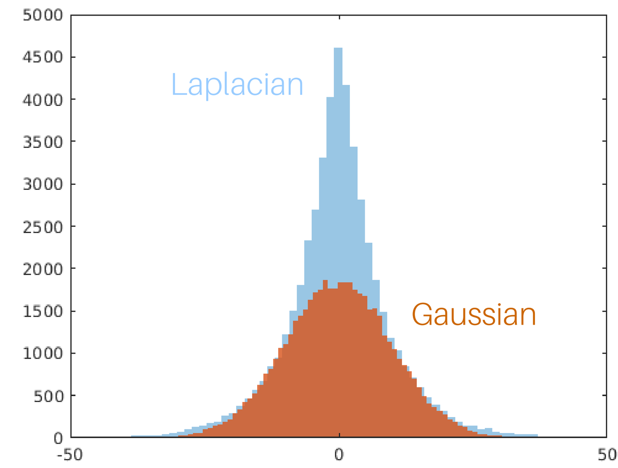


QUANTIFYING UNCERTAINTIES

Many errors contribute to well-path positional uncertainties but one of the largest is that associated with magnetic field. The error distribution is location- and time-specific and is non-Gaussian with long tails and large central peak.

Errors arise from

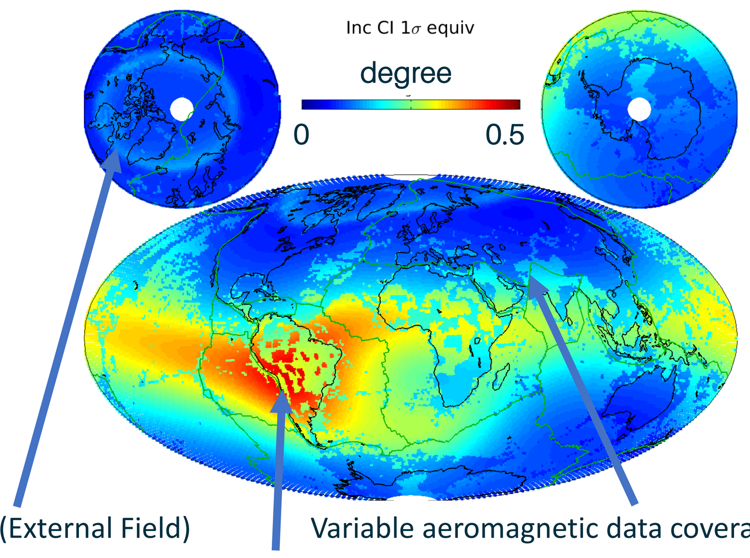
- residual Crustal Field / poor data coverage
- residual External Field
- Core Field prediction



To estimate errors, comparisons are made with appropriate independent data for each magnetic field source.

As the industry uses high confidences, e.g. 4-sigma or 99.99%, the 1-sigma errors are computed so that they can be safely multiplied up.

Estimated error in magnetic dip from a global model



COMMUNICATING UNCERTAINTIES

The Industry Steering Committee on Well-bore Survey Accuracy promotes standards in wellbore positioning. Their error model, comprising 10s of error sources, propagates each along the wellbore according to their correlation. For example error arising from Core and Crustal Fields is correlated but error arising from External Field is uncorrelated.

Default error values exist but are globally constant. As shown here, the values for the magnetic field vary. The defaults are conservative but there are exceptions, e.g. compare 0.16° with map above. With smaller targets and more potential collisions, there is a general need to reduce errors. BGS provides more realistic magnetic field errors - geomag.bgs.ac.uk/bggm.html.

References

Beggan, C. D., Macmillan, S. , Brown, W. J., and S. J. Grindrod. "Quantifying Global and Random Uncertainties in High Resolution Global Geomagnetic Field Models Used for Directional Drilling." *SPE Drilling & Completion* 36 (2021): 603-612. https://doi.org/10.2118/204038-PA

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