Estimating Source Depth—Overview (C01)

The depths to sources are a very useful product from any potential field interpretation. Reliable depths can help you to plan drillholes to test both magnetic and non-magnetic targets. If you can reliably estimate the thickness of unmineralised cover rocks, you can greatly improve the accurate budgeting and planning of any exploration program. In oil exploration, reliable estimates of depth to magnetic, seismic and density basement are essential.

The increasing size and resolution of aeromagnetic and FTG surveys means that automated ways of estimating depths are essential for cost effective interpretation.

Traditional depth estimation techniques involve the use of contours, stretched histogram pseudocolour compositions and first vertical derivative data. INTREPID tools can generate all of these products.

INTREPID has an exciting suite of new-generation depth estimation tools and products. These tools include

- Improved Naudy Automatic Model,
- Multi-scale edge detection linked to depth estimation and 3D surface or fault network (WormE)
- Matched filter depth separation and slicing,
- Traditional and Extended Euler/Werner Deconvolution,
- Phillips method,
- Murty & Rao method for simple density contrast in a basin
- Complex amplitude and instantaneous phase,
- Analytic signal,
- Magnetic coherence map,
- Vertical derivative, pass, continuation and directional filters,
- Powerful visualisation and hard copy composition language and tools.

INTREPID depth estimation methods and products

INTREPID has six automatic depth estimation techniques. The Naudy, Murty & Rao and Phillips methods are line-based, whilst the Euler, WormE and matched filter methods are grid-based. The depth estimation tools use the Total Magnetic Intensity (TMI) or First Vertical Derivative of TMI (1VD) data for their calculations.

INTREPID's analytic signal and Hilbert transform complex amplitude and instantaneous frequency products are useful for interpretation.

A product of one of our new tools, the MagMage coherence map, has proved useful for interpretation.

INTREPID also provides traditional interpretation products: vertical derivative, pass, continuation and directional filters.

This Cookbook also describes interpretation techniques that use a combination of tools, such as strand line enhancement.

INTREPID has visualisation tools and a powerful hard copy composition tool and language for displaying the results of enhancement and depth estimation processes.
Data Preparation Notes.

Little practical advice exists for the novice user in the area of preparing your survey data for depth estimation work. Before you use data for depth estimation it must be levelled and as free of errors as possible. For some depth estimation methods you need to produce a grid from the data.

As it happens, one size does not fit all, and you need to be quite careful in the preliminary steps required, to properly pose a depth estimation process.

By way of illustration -

Euler Deconvolution is critically dependent upon the gradient grids having proper curvatures consistent with potential field theory. Also for deeper depths, a cell size about 1/5 of the required depth estimate, is a minimum prerequisite. To achieve this, you often have to re-grid your data with a coarser cell size than a contractor may have made the data available, say 200m, and also in creating this grid a high emphasis must be placed on either Minimum Curvature, or BiCubic Splining.

In contrast to this preparation, the Fourier domain Spector Grant average power spectrum depth methods would go another way altogether. By way of illustration, you may receive 1/10 second TMI data that represents about one sample every 6 meters down a flight line. The data should be properly levelled between lines, and may enable you to create a grid of TMI data with quite a small cell size, say 30 m. When this grid is transformed into the Fourier domain, and then the auto-correlation of the data with itself is undertaken (Power Spectrum), a log vs frequency plot with up to a thousand bins might result. The deeper sources in your signal cluster to the left hand side of this graph, and are properly present. One other trap here for the novice, is to understand that there can be many sources of magnetism, coming from different depths, so perhaps a moving window, with no padding, might also help isolate these differing regions.

INTREPID has the tools to prepare and then estimate the depths, in all the variations mentioned.
The Naudy method

The **Naudy method** infers simple geological structures and estimates their depths by curve matching along profiles. The current INTREPID implementation creates models of two-dimensional dyke-like bodies and the edges of thin, plate-like structures. There is provision for TMI, Magnetic tensors and a start on FTG support. For more accurate results, you can use trend information from a trend-processed grid to include body strike in the Naudy model.

The matched filter method

The **matched filter** uses the spectral information in a magnetic grid transformed to the spectral domain. Magnetic sources at similar depths show straight-line segments on the power spectrum graph. These segments characterise the features in the principal depth ranges. Using the matched filter, you can extract the frequencies corresponding to these principal depth ranges. Ask about the training material we have created especially for you in the form of a power point.

The Euler method - standard and extended

The **Euler method**'s homogeneity equation relates the magnetic field and its gradient components to the location and depth of the source. This is best done on grids. The structural index (degree of homogeneity) is a measure of the fall-off rate of the field with distance from the source. It provides a way to discriminate between different source shapes.

Standard Euler uses the components of the analytic signal (3 orthogonal derivatives) all in the spatial domain, usually determined by Fourier methods. The Structural Input is supplied by the user. For the extended case the Hilbert transform is used to formulate 2 or 3 equations, which are solved for position, errors and Structural Index, assuming a constant background.

Good results are also coming from the use of this tool on Full Gravity Gradient tensor grids.

The Phillips method

The **Phillips method** attempts to match the magnetic response of a smoothly varying two-dimensional magnetic basement by summing the response of many very thin inferred two-dimensional dykes. This is a profile based method. An autocorrelation function compares the various responses in a narrow window. Those that converge to a constant value provide the best depth estimates. For more accurate results you can use trend information from a trend-processed grid to include body strike in the resulting model.

Hilbert transform products

Using the Hilbert transform you can produce the **complex amplitude** and **instantaneous frequency**. The complex amplitude enhances edges of anomalies. Instantaneous frequency sharpens edges of anomalies, also enhancing peaks and troughs.

Magnetic coherence map

The **magnetic coherence map** detects discontinuities in a grid of magnetic data. We have found it useful for mapping peaks and troughs of magnetic trends.
Analytic signal

The analytic signal can sharpen and enhance regional structure and the edges of anomalies in a grid.
**Vertical gradient**

The **vertical gradient** can sharpen and enhance regional structure and the edges of anomalies. Fractional orders permit control over the degree of sharpening.

**Pass, continuation and directional filters**

**Pass and continuation filters** are traditional aids to interpretation. They can remove ranges of wavelengths from the data, enhancing the features at depths characterised by the remaining wavelengths. Directional filters enhance features in certain directions.

**Depth estimation methods and products - summary**

The following table lists the INTREPID depth estimation methods and products, showing the INTREPID tool to be used, the dataset type(s) it can process and the format of the results.

<table>
<thead>
<tr>
<th>Method</th>
<th>INTREPID tool</th>
<th>Input dataset type</th>
<th>Output dataset type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naudy</td>
<td>Naudy Automatic Model</td>
<td>Line</td>
<td>Point</td>
</tr>
<tr>
<td>Euler</td>
<td>Euler Deconvolution</td>
<td>Grid</td>
<td>Point</td>
</tr>
<tr>
<td>Multi-scale edge detection</td>
<td>WormE</td>
<td>Grid</td>
<td>Point, Line, 3D surfaces</td>
</tr>
<tr>
<td>Phillips</td>
<td>Line Filter</td>
<td>Line</td>
<td>Line field</td>
</tr>
<tr>
<td>Murty &amp; Rao</td>
<td>Line Filter</td>
<td>Line</td>
<td>Line</td>
</tr>
<tr>
<td>Matched filter</td>
<td>gfilt</td>
<td>Grid</td>
<td>Grid</td>
</tr>
<tr>
<td>Complex amplitude,</td>
<td>Line Filter</td>
<td>Line</td>
<td>Line field</td>
</tr>
<tr>
<td>Instantaneous frequency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analytic signal</td>
<td>Grid FFT tool</td>
<td>Grid</td>
<td>Grid</td>
</tr>
<tr>
<td>Vertical derivative</td>
<td>Line Filter, Grid FFT tool</td>
<td>Line, Grid</td>
<td>Line field, Grid</td>
</tr>
<tr>
<td>Pass, continuation,</td>
<td>Line Filter*, Grid FFT tool</td>
<td>Line, Grid</td>
<td>Line field, Grid</td>
</tr>
<tr>
<td>directional filters</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Not for directional filters

This chapter gives an overview of the four methods and the criteria you should use for selecting the appropriate method for your survey.
Flowchart for depth estimation

The following flowchart gives an overall view of a typical depth estimation process.

Recently acquired data

If you acquired your data recently, it is most likely that your data acquisition contractor will have used GPS navigation and performed all of the following corrections. The table in Data preparation processes below shows the corrections that are required before depth estimation processing.
Older data

If your data was acquired before GPS navigation became available, you should ensure that you are aware of its limitations.

Note: The depth information for shallow sources can be degraded by

- Data containing significant noise (You can use the INTREPID Profile Editor to remove this noise of required.)
- Navigation errors (magnetic source shape and location errors).

Data preparation processes

The following table lists the preparation recommended before depth estimation processes. INTREPID has tools for performing most of the preparation processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>Purpose</th>
<th>INTREPID tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height corrections</td>
<td>For low altitude high resolution surveys with inconsistent ground clearance, this correction enhances shallow sources</td>
<td>&quot;Downward Continuation filter&quot; in Line Filtering (T31)</td>
</tr>
<tr>
<td>Noise and spike removal</td>
<td>Removing high frequency components of the data that are clearly not attributable to geological features.</td>
<td>Profile Editor (T17) &quot;Low Pass filter&quot; in Line Filtering (T31)</td>
</tr>
<tr>
<td></td>
<td>When you apply a vertical derivative, INTREPID may amplify low amplitude high frequency noise into the signal range of the Naudy Automatic Model tool. You can remove this with a low pass filter set to a wavelength 1–1.5 times the average flying height</td>
<td></td>
</tr>
<tr>
<td>Tie line levelling</td>
<td>Correcting for discrepancies between acquisition and tie line data</td>
<td>Line correction and tie levelling (T30)</td>
</tr>
<tr>
<td>Decorrugation and Microlevelling</td>
<td>Removal of corrugations using a grid of the data, then applying the corrections to the original line data</td>
<td>Decorrugation (T32) and Microlevelling (T33)</td>
</tr>
<tr>
<td>Reduction to the Pole (some processes only)</td>
<td>The inclination of the Earth’s magnetic field during data acquisition results in a displacement of the observed data with respect to the position of the magnetic body. This correction adjusts the location of magnetic sources.</td>
<td>Line Filtering (T31), Spectral domain grid filters tool (GridFFT) (T40) and Spectral domain grid filters (GridFFT) wizard (T39)</td>
</tr>
<tr>
<td>Gridding (some processes only)</td>
<td>Overlaying a grid on the survey area and using the line data to calculate a TMI value for each cell in the grid.</td>
<td>Old Gridding (T22)</td>
</tr>
</tbody>
</table>
Notes about reduction to the pole

Interpretation tools generally produce solutions that are correctly located. You will most likely want to compare the interpretation results with the original data (e.g., by overlaying them on a grid). The results will align with the original data more closely if the original data has had a reduction to the pole correction.

Reduction to the Pole (RTP) can sometimes introduce artifacts. Compare your RTP results with the uncorrected data to detect this problem. Once an algorithm is used to interpret your data, we compensate for the field inclination and declination, so leave the data as it was acquired, provided you know the date and survey height.

Euler/Werner Deconvolution automatically creates correctly located solutions and it is advised not to do an RTP.

The matched filter has no built-in RTP process. If you perform RTP on the data before or after using the matched filter parameters, the accuracy of source location will improve.

You should perform RTP before using the Phillips method.

Note about gridding

Gridding is required for the Euler, WormE methods and matched filter. Gridding removes some high frequency information. The very shallow Euler solutions (if retained) may become slightly deeper. Matched filter solutions will be unaffected because the high frequencies removed by gridding are a very small part of the full power spectrum.
Shapes of source bodies

The shape of the magnetic body you are seeking is a criterion for selecting the depth estimation technique. The following table lists some simple geological shapes and the depth tools that are most appropriate for these shapes. These shapes correspond both to real geological structures and to the assumptions of the mathematical models used for the depth estimations.

**Note:** The matched filter does not operate on the basis of shape and therefore may be generally useful for the whole range of shapes.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Description</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dyke-like structures^1</td>
<td>Relatively thin sheet-like bodies that are near-vertical (wall-like)</td>
<td>Naudy, Euler, Phillips</td>
</tr>
<tr>
<td>Vertical pipes</td>
<td>Near-vertical cylinder shaped structures (e.g., kimberlite pipes and small volcanic plugs)</td>
<td>Euler</td>
</tr>
<tr>
<td>Point sources</td>
<td>Sources that are not continuous in any direction, normally irregular in shape but nominally spherical in mathematical models (e.g., discrete magnetic base metal ore bodies, magnetite alteration zones in gold deposits)</td>
<td>Euler</td>
</tr>
<tr>
<td>Plates</td>
<td>Relatively thin sheet-like bodies that are near-horizontal. (e.g., mafic intrusive sills, faulted flat-lying sedimentary units containing a magnetic unit such as certain Pilbara iron ore deposits).</td>
<td>Naudy</td>
</tr>
<tr>
<td>Steps</td>
<td>Step-like structures show a sudden change of magnetic response. Examples: Contacts between large bodies, such as between granite and surrounding rocks, Uplifted blocks at the site of a fault, such as a Horst-Graben.</td>
<td>Naudy, Euler</td>
</tr>
</tbody>
</table>

^1 For INTREPID's current implementation of the Naudy tool, the thin dyke-like magnetic bodies are more precisely defined. Their width (thickness in the line direction) must be less than their depth to qualify as 'thin'. Their length (extent in the direction of their strike) must be at least five times their depth.
Depth ranges of interest

According to normal geophysical areas of interest and for the purposes of selecting INTREPID depth estimation tools you can divide depth into three ranges. For best results with some tools you must configure them according to the depth of the sources you are seeking.

<table>
<thead>
<tr>
<th>Depth Range</th>
<th>Description</th>
<th>Area of Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–200 m</td>
<td>Shallow</td>
<td>Mineral exploration, Water resources, Environmental studies</td>
</tr>
<tr>
<td>200–1000 m</td>
<td>Intermediate</td>
<td>Mineral exploration, Water resources</td>
</tr>
<tr>
<td>Deeper than 1000 m</td>
<td>Deep</td>
<td>Oil exploration, (increasingly) Mineral exploration</td>
</tr>
</tbody>
</table>

Preliminary examination of the data

It is important that you examine the magnetic data and note the range of frequencies. This will give you an appreciation of the likely depth range of the magnetic bodies. As a rule of thumb, for a well-defined peak, the depth of the corresponding source is approximately equal to the width of the peak at half of its amplitude.

All of the INTREPID depth tools examine the frequency content of data.

Examining line data

You can examine line data using the Profile Editor tool. Use the rule of thumb described above.
Examining grid data

You can examine grids using a visualisation tool. For dyke-like bodies use the rule of thumb described above to obtain an estimate of depths. For wide bodies a useful estimate is to measure the width of the steepest part of magnetic gradient (slope) at the southern edge of the wide body. This width will be roughly equal to 1.5 times the depth.

Selecting and configuring depth tools—summary

Selecting the depth tool

In order to select the best depth estimation tool for your purpose, you must ask:

- For which depth range do I require depth estimates?
- What is the shape of the geological structures I wish to locate?

The following table shows the INTREPID depth estimation tools you can use for the three depth ranges and the variety of inferred geological structure shapes.

The table gives a general indication only of tools that may be useful. Each tool gives results of a different nature. Tools shown as emphasised are normally the best choice. Tools shown as conditional format may be useful. You should read the detailed discussion in this chapter before selecting any tool.

<table>
<thead>
<tr>
<th>Depth range</th>
<th>Dyke-like</th>
<th>Other shapes</th>
<th>Edge of a plate</th>
<th>Edge of a step</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–200 m</td>
<td>Naudy Matched filter Euler Phillips</td>
<td>Matched filter Euler</td>
<td>Naudy Euler</td>
<td>Naudy* Euler</td>
</tr>
<tr>
<td>200–1000 m</td>
<td>Naudy Matched filter Euler Phillips</td>
<td>Matched filter Euler</td>
<td>Naudy Euler</td>
<td>Naudy* Euler</td>
</tr>
<tr>
<td>Deeper than 1000 m</td>
<td>Naudy Matched filter Euler Phillips</td>
<td>Matched filter Euler</td>
<td>Naudy Euler</td>
<td>Naudy* Matched filter Euler</td>
</tr>
</tbody>
</table>

* Future development

Configuring the depth tool

After selecting the tool, in most cases you can configure it for the required depth range and/or the shape of the inferred geological structures. See the following discussion for further instructions.
Notes about regional aeromagnetic datasets

Nature of the datasets
A regional aeromagnetic dataset usually covers a large area, perhaps > 5000 km². Examples are the AGSO 1 : 250 000 sheet areas and the Eastern Goldfields multiclient surveys. These surveys sacrifice some resolution, through wide line spacings and a greater flying height, in order to cover larger areas economically.

Using line vs grid data
Regional data can be of variable quality and may consist of several surveys stitched together. If the line data is available, use it in preference to the grid data unless the geology indicates a young terrain with few linear magnetic responses. The line data is the information with the highest resolution available and will give the best depth estimates for shallow sources.

Selecting a tool according to the type of geology
Different geological terrains have very different magnetic responses. In general, the older the terrain (eg Archean and Proterozoic), the more likely that linear magnetic trends will dominate the magnetic features. The Naudy method is the best depth estimation tool for the older terrains.

Magnetic bodies with more irregular features such as intrusives and volcanics tend to dominate the younger terrains. For these terrains, the Naudy and matched filter methods will give useful solutions. The Euler method may also give useful solutions.

Depth estimation references

Naudy method

Matched filter methods
Euler method


Phillips method


Magnetic (MagMage) coherence map


Complex Amplitude, Instantaneous Frequency


Strand line enhancement technique


Tensors


FitzGerald, D.J., Holstein, H., 2006, *Innovative Data Processing Methods for Gradient*
Airborne Geophysical Data Sets, The Leading Edge pp 87-94