Equivalent-layer technique for estimating magnetization direction

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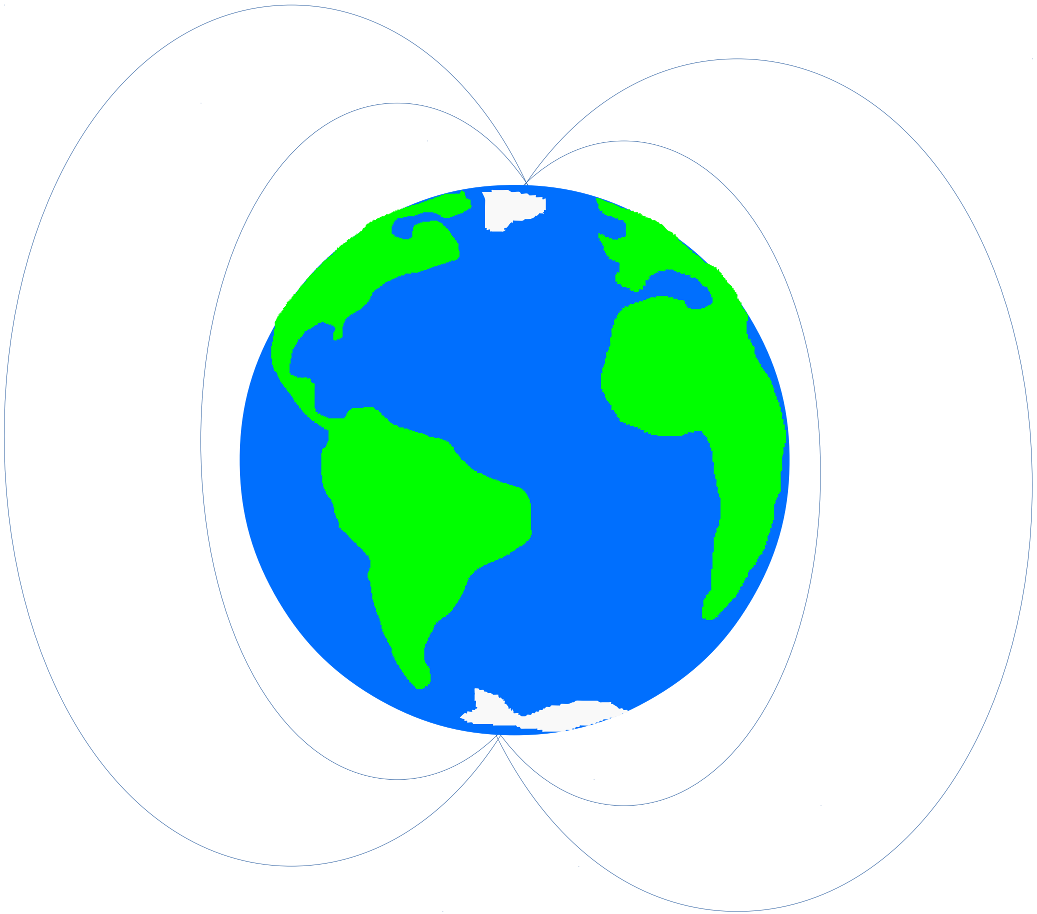
Observatório Nacional

SEG19
SAN ANTONIO, TX

Overview

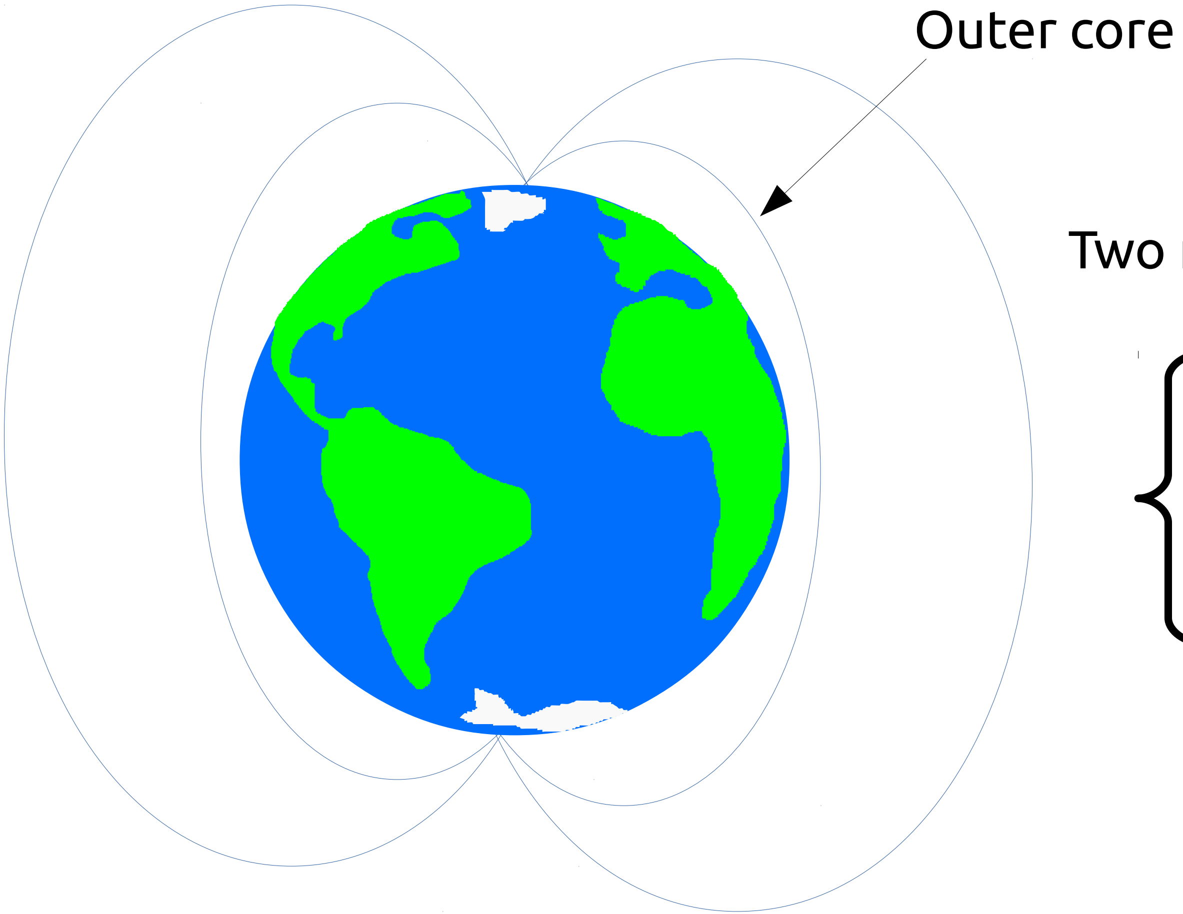
- Total-field anomaly and magnetization direction;
- Equivalent layer and the positivity;
- Forward and inverse problems;
- Numerical simulations;
- Field data application;
- Conclusion.



Two main components:

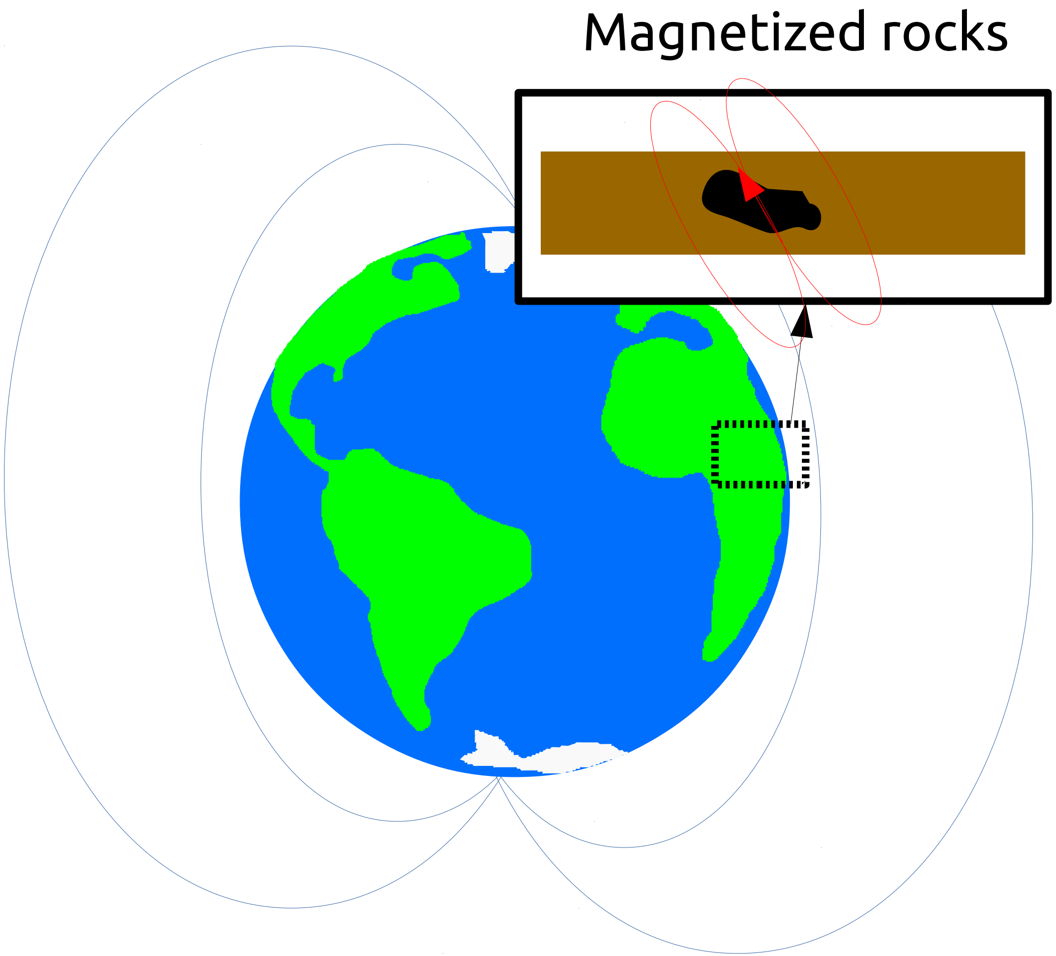
Main field

Crustal



Two main components:

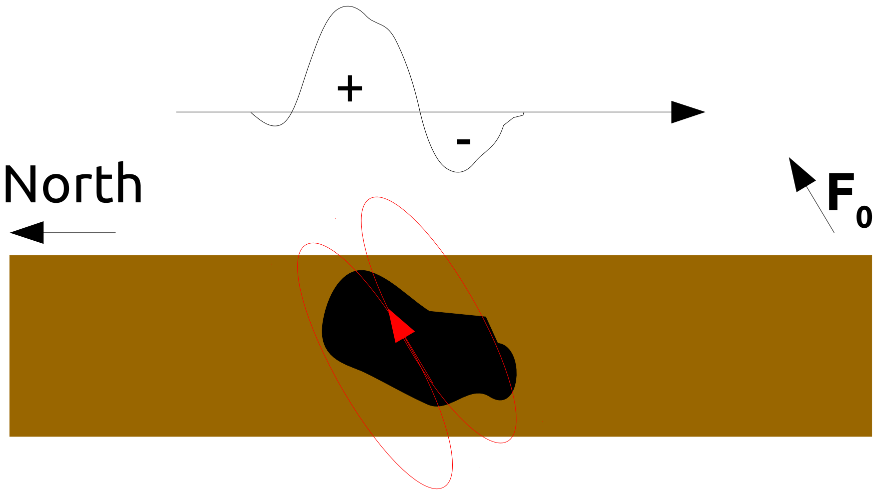
- Main field
- Crustal



Two main components:

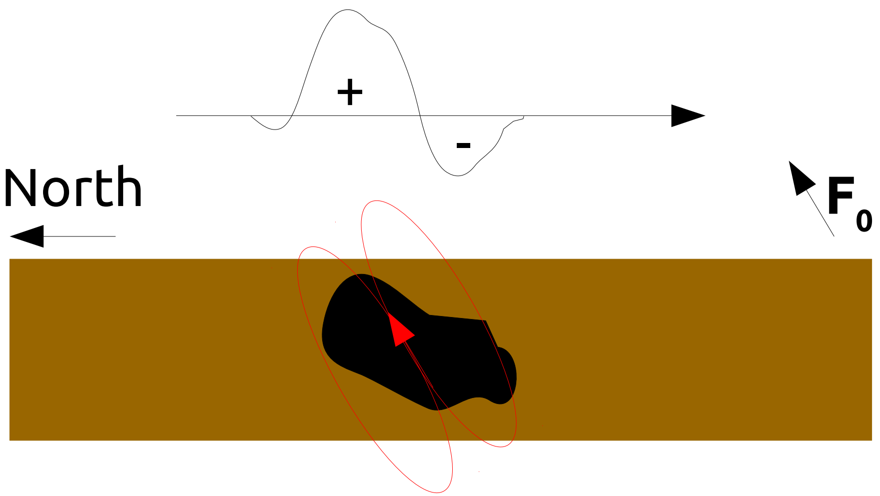
- Main field
- Crustal

Magnetized rocks



Magnetic field can be measured over the surface

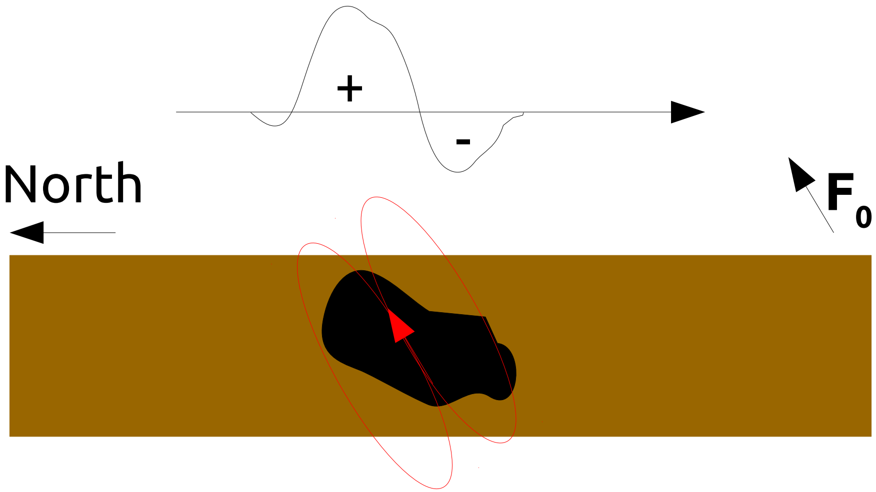
Magnetized rocks



Magnetic field can be measured over the surface

Depends on the magnetization direction of the magnetic source

Magnetized rocks



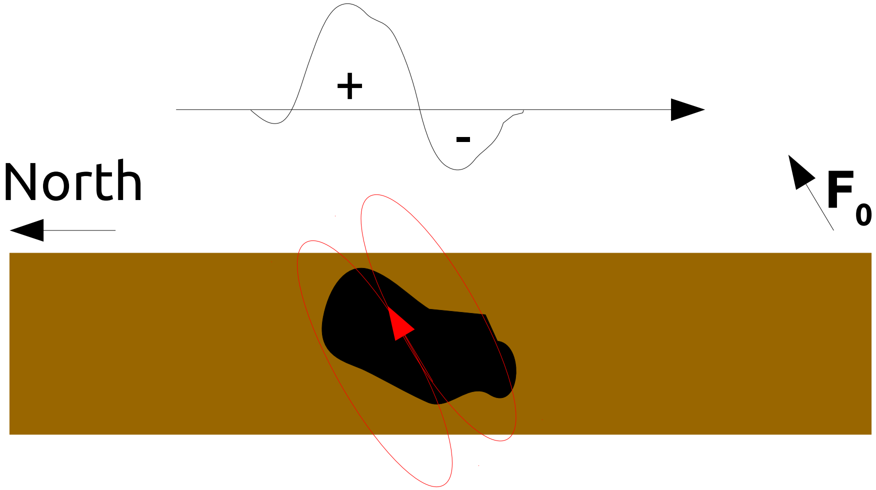
Magnetic field can be measured over the surface

Depends on the magnetization direction of the magnetic source

Exploration geophysics

Describing geological scenarios

Magnetized rocks



Magnetic field can be measured over the surface

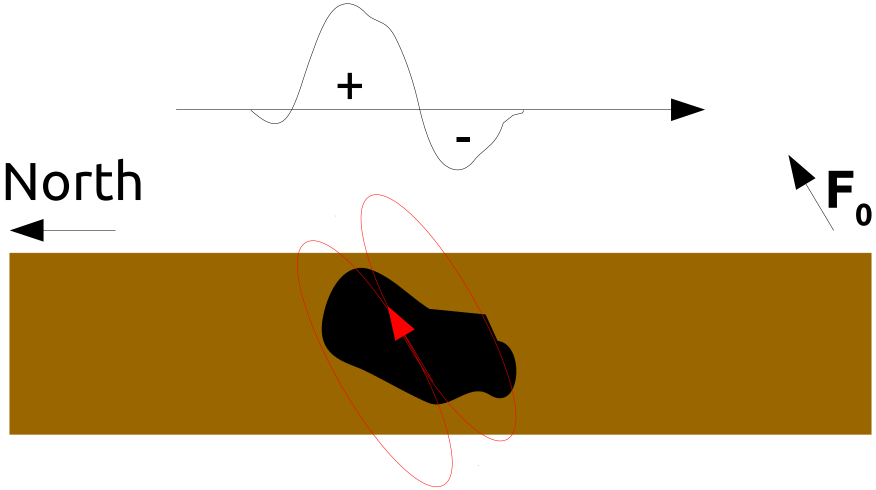
Depends on the magnetization direction of the magnetic source

Mathematically...

$$\boxed{\Delta T = \hat{\mathbf{F}}_0^T \mathbf{B}}$$

Total-field anomaly

Magnetized rocks



Magnetic field can be measured over the surface

↓

Depends on the magnetization direction of the magnetic source

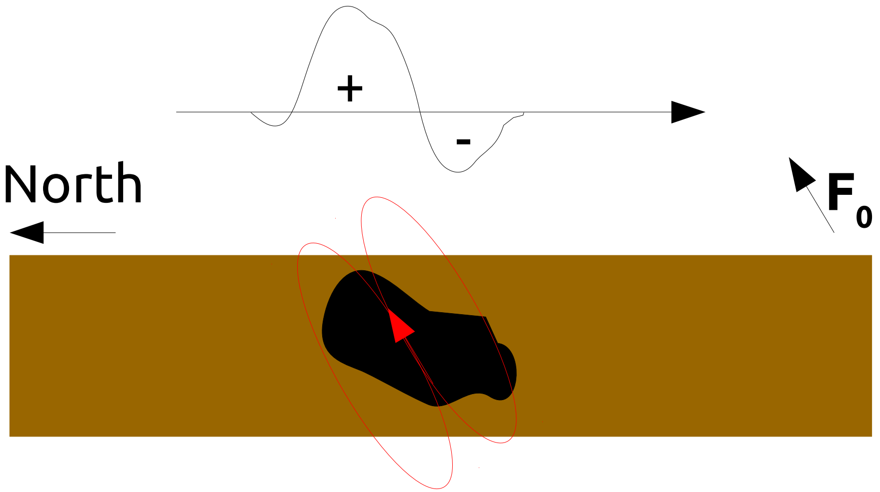
Mathematically...

$$\boxed{\Delta T = \hat{\mathbf{F}}_0^T \mathbf{B}}$$

Total-field anomaly

$$\Delta T = \gamma m \hat{\mathbf{F}}_0^T \mathbf{H}\,\hat{\mathbf{h}}$$

Magnetized rocks



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Constant with vacuum permeability

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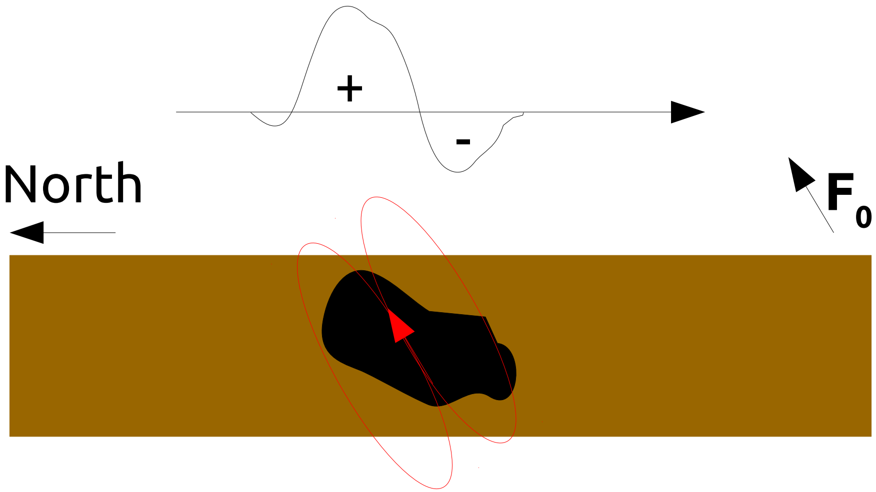
Magnetized rocks



Magnetic field can be measured over the surface

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Total-field anomaly

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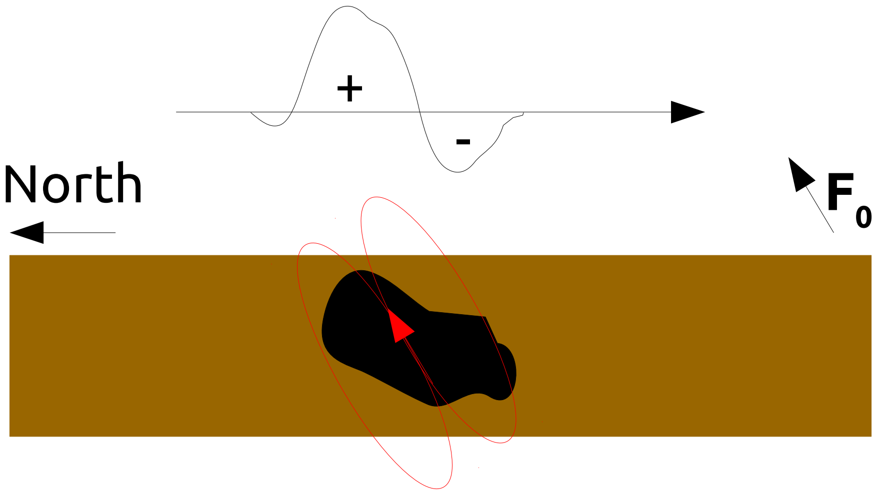
Magnetization intensity

Magnetized rocks



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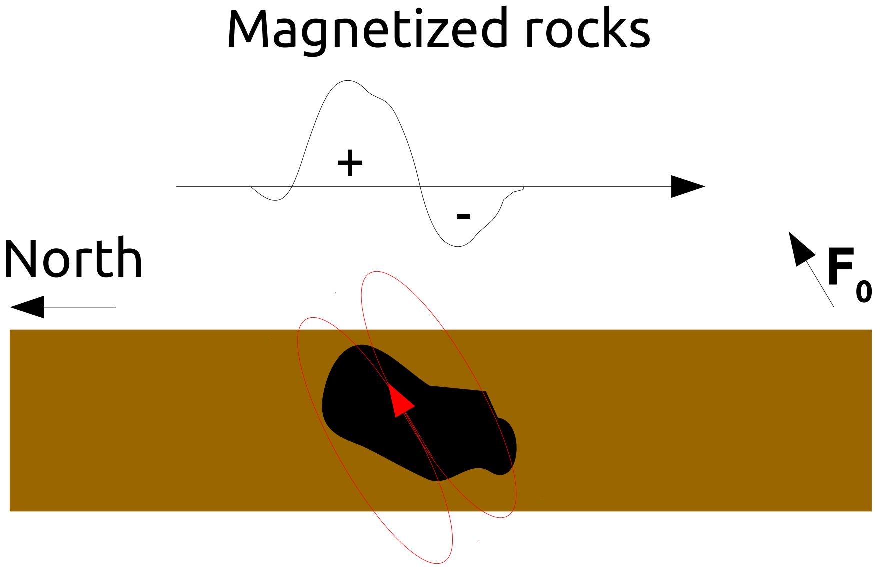
$$\boxed{\Delta T = \hat{\mathbf{F}}_0^T \mathbf{B}}$$

Total-field anomaly

$$\Delta T = \gamma m \hat{\mathbf{F}}_0^T \mathbf{H} \hat{\mathbf{h}}$$

Matrix that depends on the source geometry and observation coordinates



Magnetic field can be measured over the surface

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Magnetization direction of the source

How to estimate the magnetization direction?

1. Methods that presume some geometry for the source

Set of prisms or spherical geometries (e.g.,Battacharyya,1996; Emilia e Massey, 1974; Medeiros e Silva, 1995; Parker et al, 1987; Kubota e Uchiyama, 2005; Oliveira Jr et al, 2015)

2. Methods that not presume any information about the source

Analysis of the magnetic moment of sources (e.g., Tontini e Pedersen, 2008)

Correlating of potential quantities (e.g.,Roest e Pilkington,1993; Dannemiller e Li, 2006; Gerovska, 2009; Li et al, 2017; Zhang et al, 2018)

Succesive RTP (Fedi, 1994)

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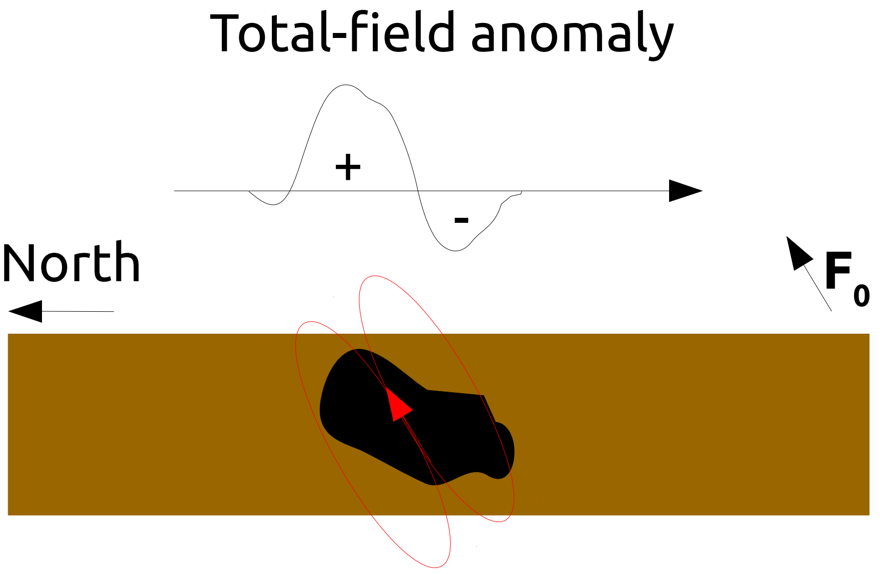
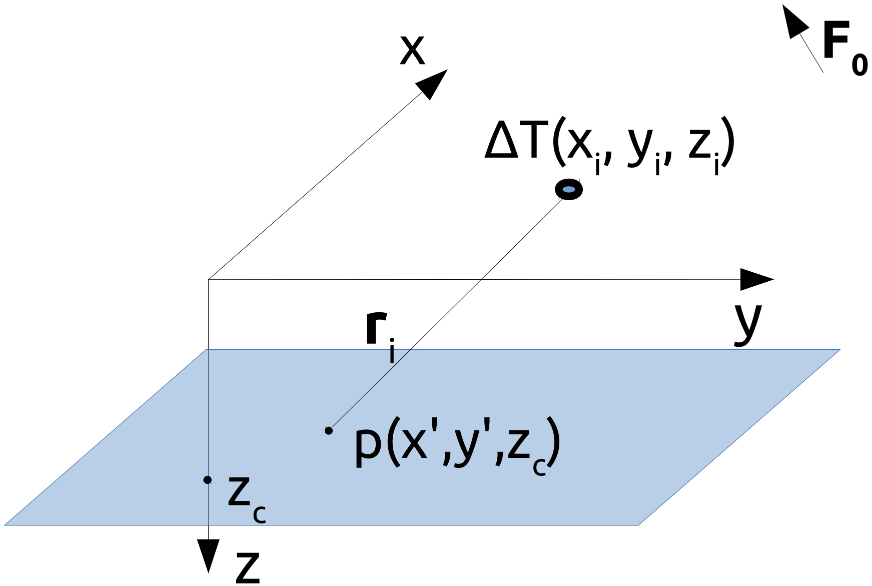


Here we use the **Equivalent-layer technique**

An interesting feature!

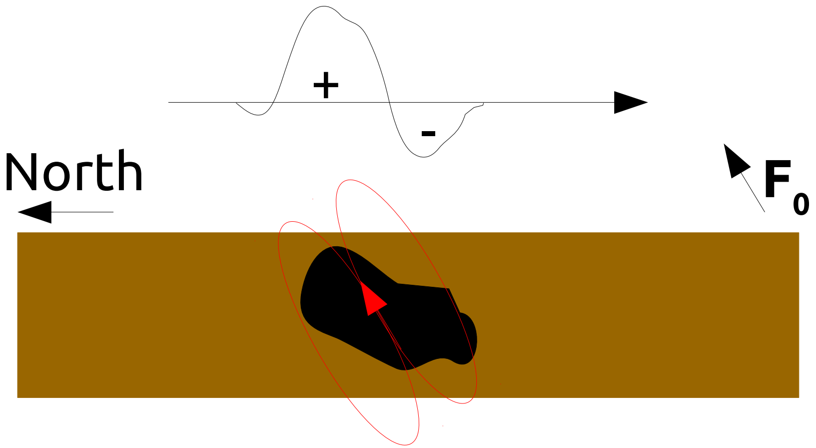
We can retrieve the data generated by a 3D source using a 2D physical-property distribution

Total-field anomaly (layer)



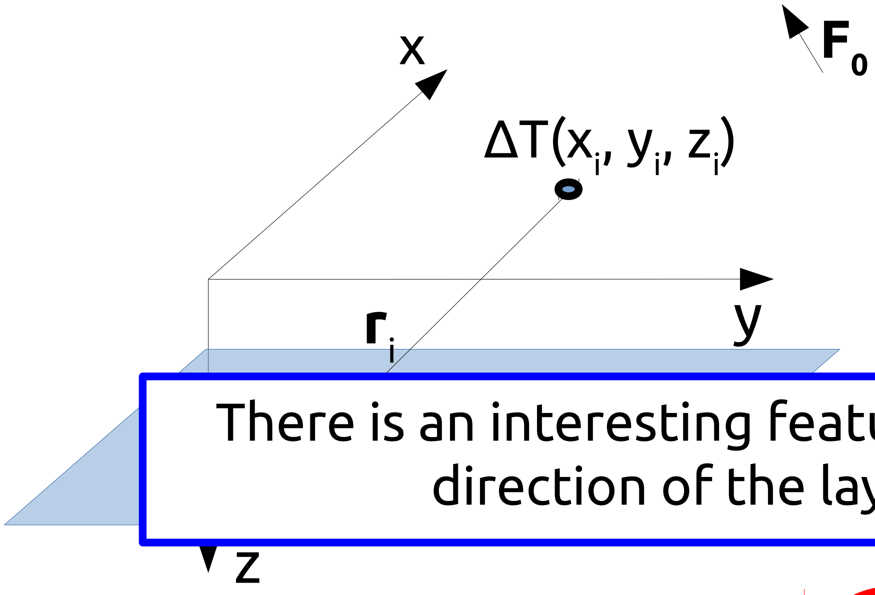
$$\Delta T_i = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} p(x', y', z_c)[\gamma \hat{\mathbf{F}}_0^T \mathbf{M}\,\hat{\mathbf{m}}(\mathbf{q})]dx'\,dy'$$

Total-field anomaly (source)

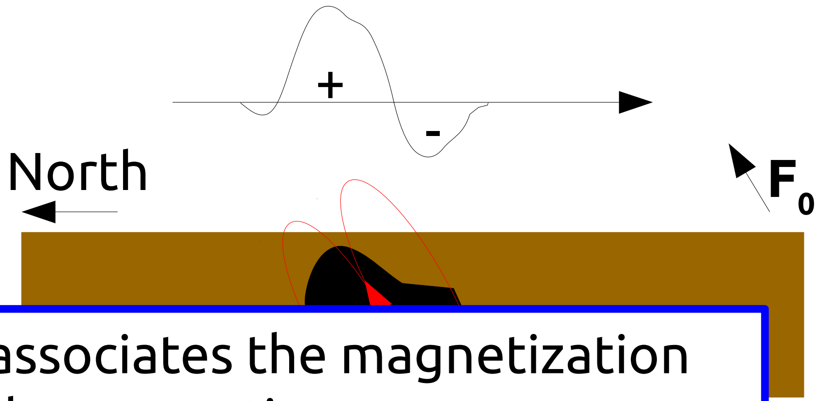


$$\Delta T = \gamma m \hat{\mathbf{F}}_0^T \mathbf{H}\,\hat{\mathbf{h}}$$

Total-field anomaly (layer)



Total-field anomaly (source)



There is an interesting feature that associates the magnetization direction of the layer with the magnetic source

$$\Delta T_i = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} p(x', y', z_c)[\gamma \hat{\mathbf{F}}_0^T \mathbf{M}\, \hat{\mathbf{m}}(\mathbf{q})]d$$

$$\mathbf{H}\,\hat{\mathbf{h}}$$

If...

$$\hat{\mathbf{m}}(\mathbf{q}) = \hat{\mathbf{h}}$$

The magnetic-moment distribution is all-positive over the layer.

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This feature was explored by Pedersen (1991) and Li et al (2014).

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The magnetic-moment distribution is all-positive over the layer.

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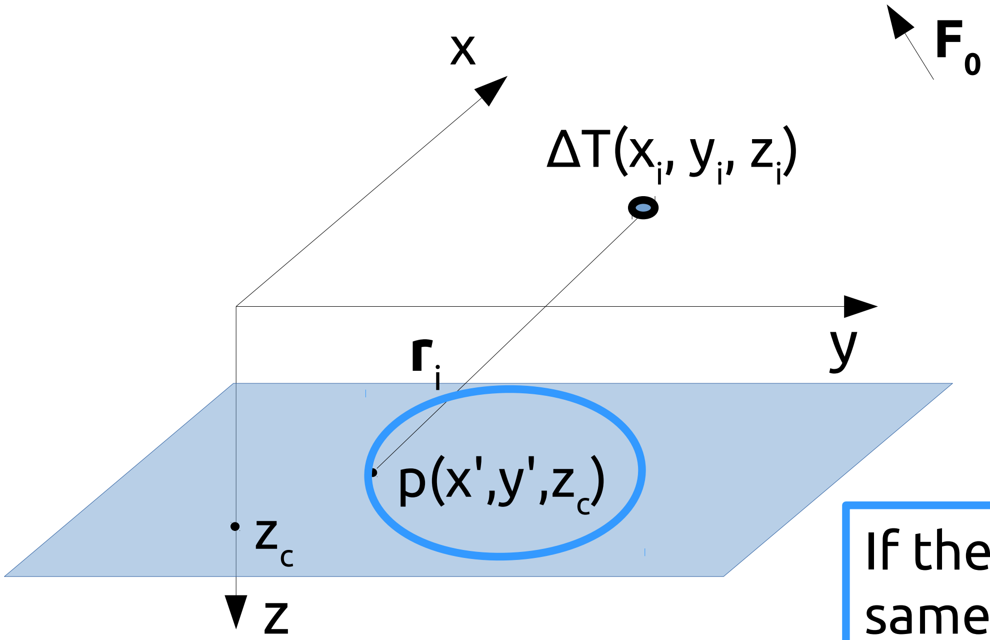
Lima and Weiss (2007) and Baratchart et al (2013) pointed out that uniqueness can be achieved by imposing an unidirectional solution.

Summary:

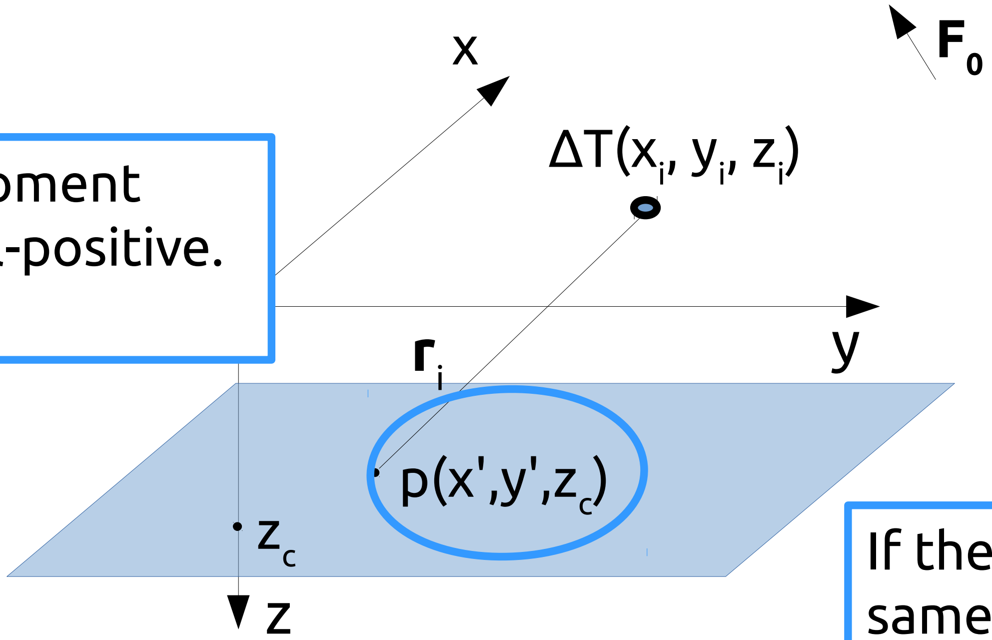


If the layer has the same direction of the true source

$$\Delta T_i = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} p(x', y', z_c)[\gamma \hat{\mathbf{F}}_0^T \mathbf{M}\, \hat{\mathbf{m}}(\mathbf{q})]\, dx'\, dy'$$

Summary:

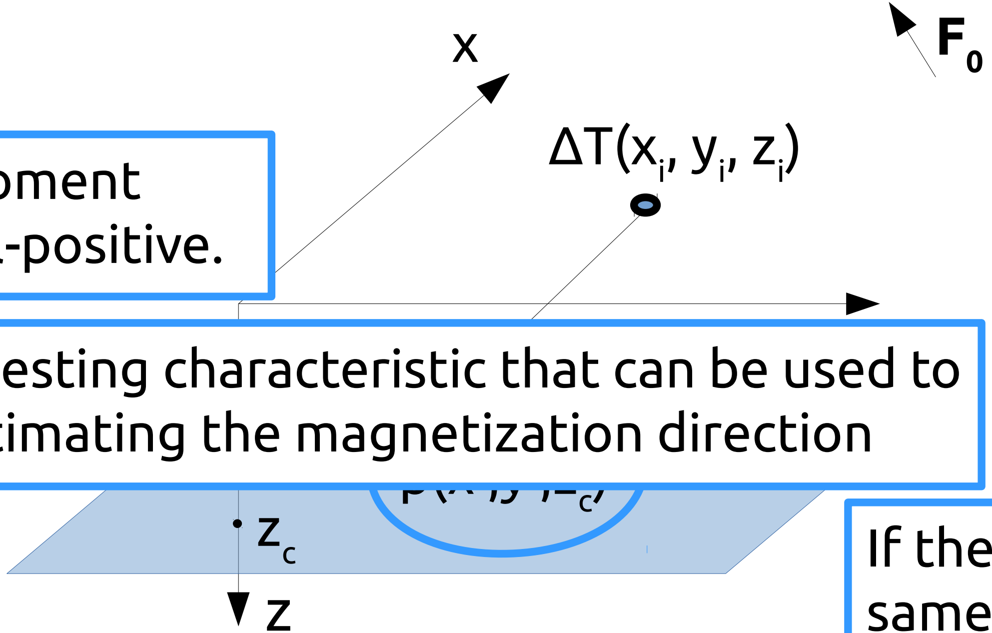
the magnetic-moment distribution is all-positive.



If the layer has the same direction of the true source

$$\Delta T_i = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} p(x', y', z_c)[\gamma \hat{\mathbf{F}}_0^T \mathbf{M}\, \hat{\mathbf{m}}(\mathbf{q})]\, dx'\, dy'$$

Summary:



the magnetic-moment distribution is all-positive.

This is an interesting characteristic that can be used to auxiliate in estimating the magnetization direction

If the layer has the same direction of the true source

$$\Delta T_i = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} p(x', y', z_c)[\gamma \hat{\mathbf{F}}_0^T \mathbf{M}\, \hat{\mathbf{m}}(\mathbf{q})]\, dx'\, dy'$$

How does it work in practice?

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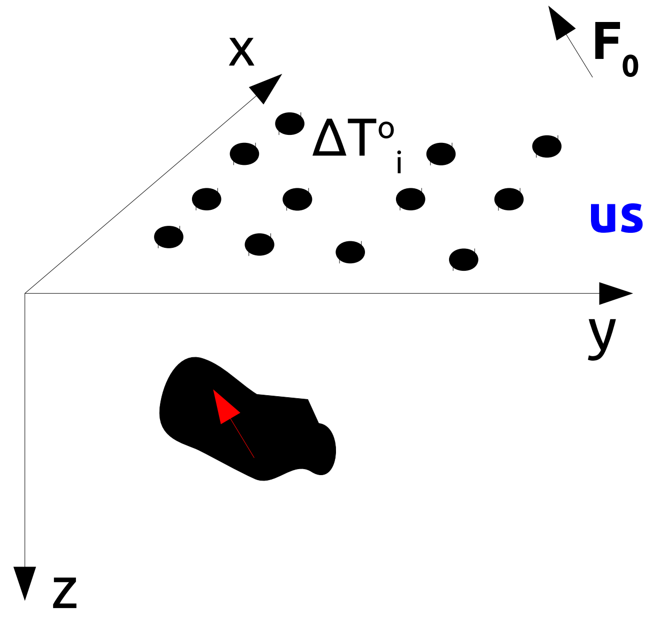
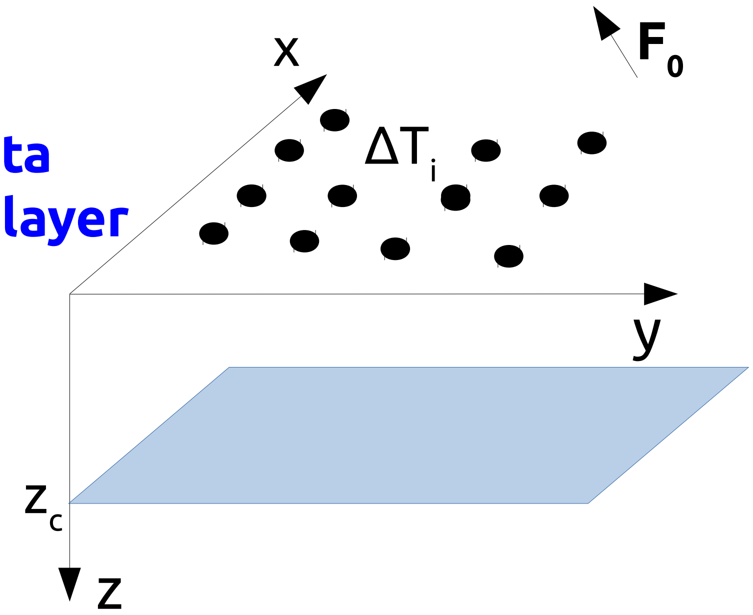
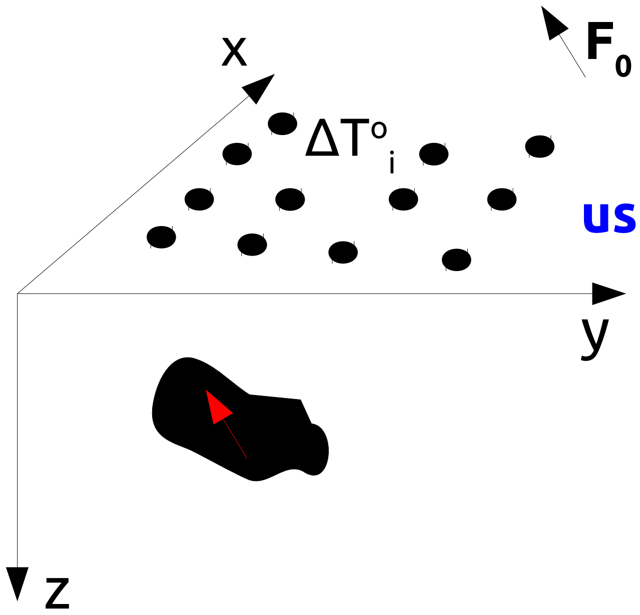
3D magnetization distribution



Reproduce the data using an equivalent-layer



3D magnetization distribution



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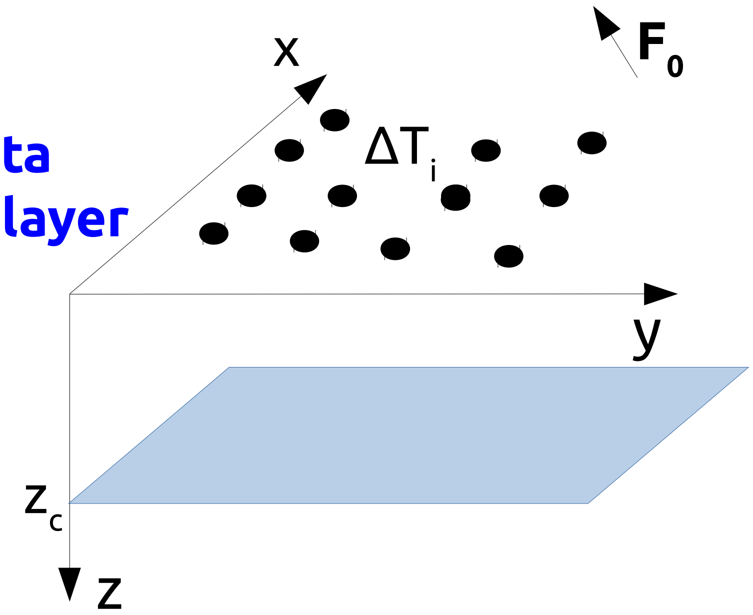
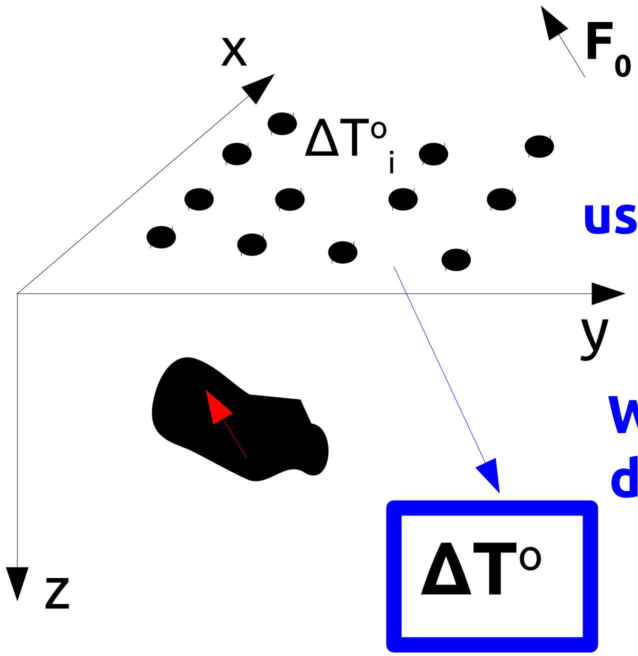


This is a discrete set of observations

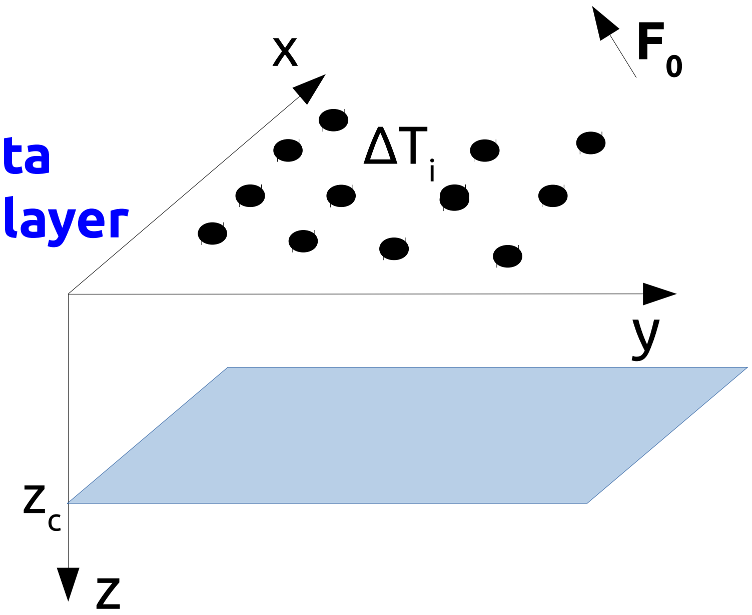
3D magnetization distribution



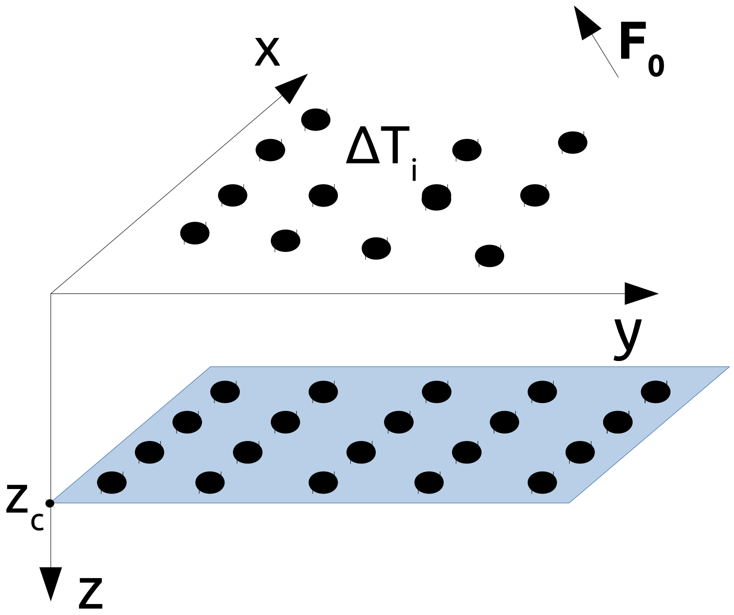
Reproduce the data using an equivalent-layer

We can group this data into a vector

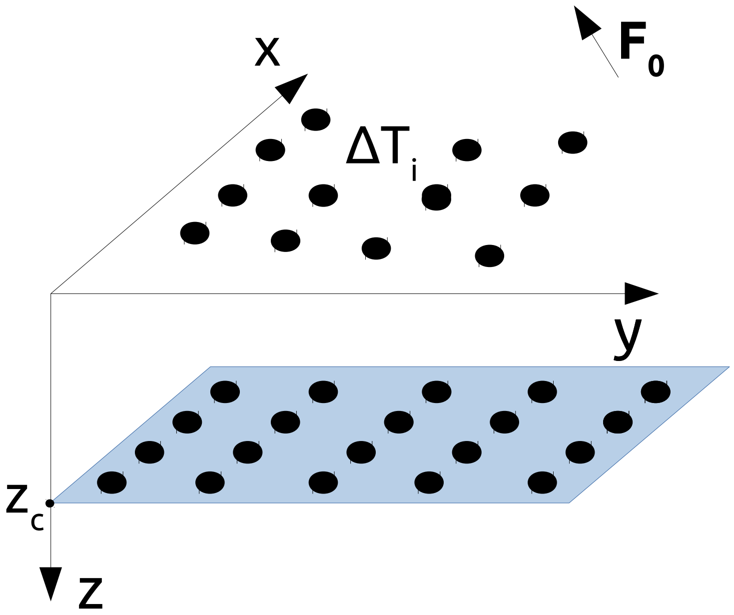
Observed data vector



Equivalent layer

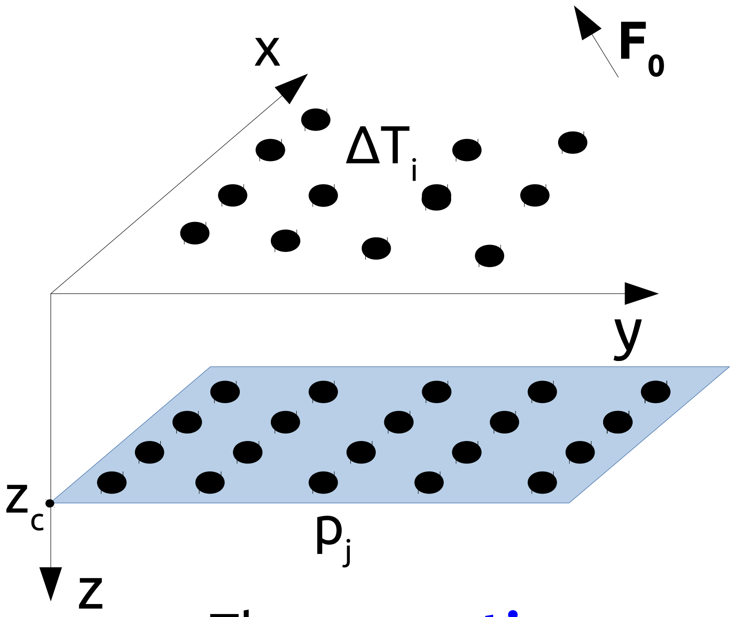


Equivalent layer



The equivalent layer can be approximated by a set of **equivalent sources** that, in this case, are **dipoles with unit volume**

Equivalent layer



The equivalent layer can be approximated by a set of **equivalent sources** that, in this case, are **dipoles with unit volume**

The **magnetic moment** of the jth dipole, j = 1, ..., M.

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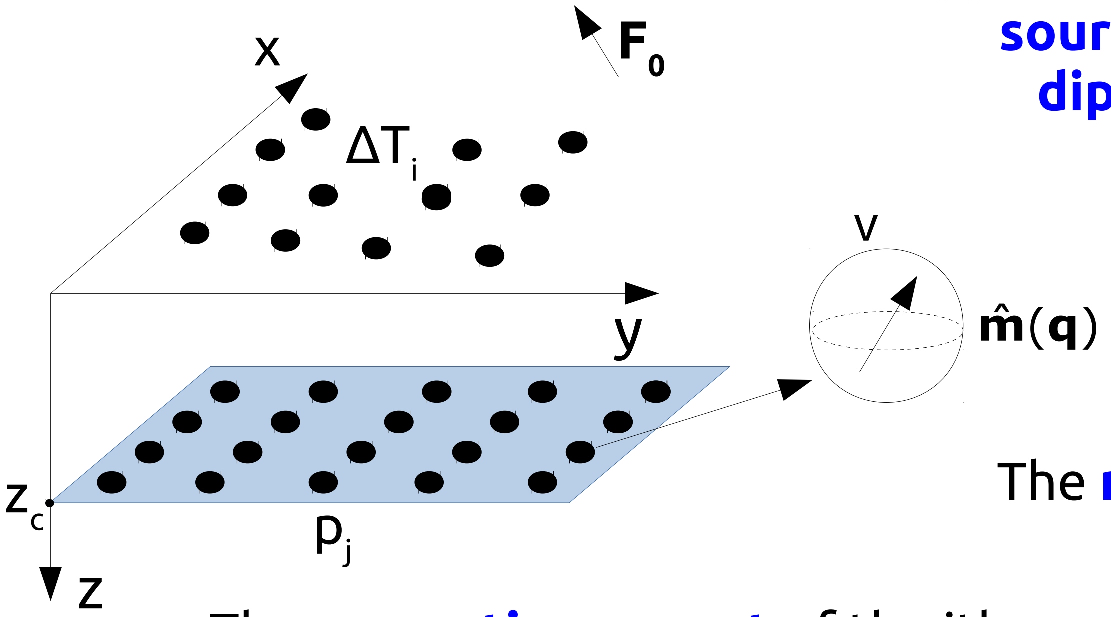
Equivalent layer



The equivalent layer can be approximated by a set of **equivalent sources** that, in this case, are **dipoles with unit volume**

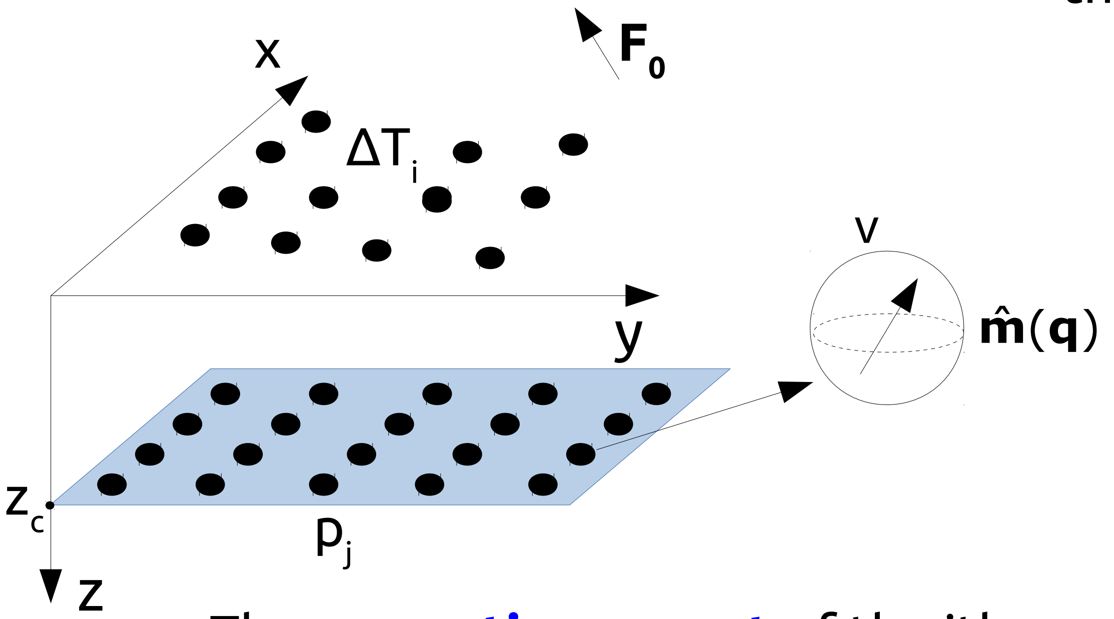
The **magnetization direction** is the same for all dipoles.

The **magnetic moment** of the jth dipole, j = 1, ..., M.

$$\mathbf{q} = \begin{bmatrix} I \\ D \end{bmatrix}$$

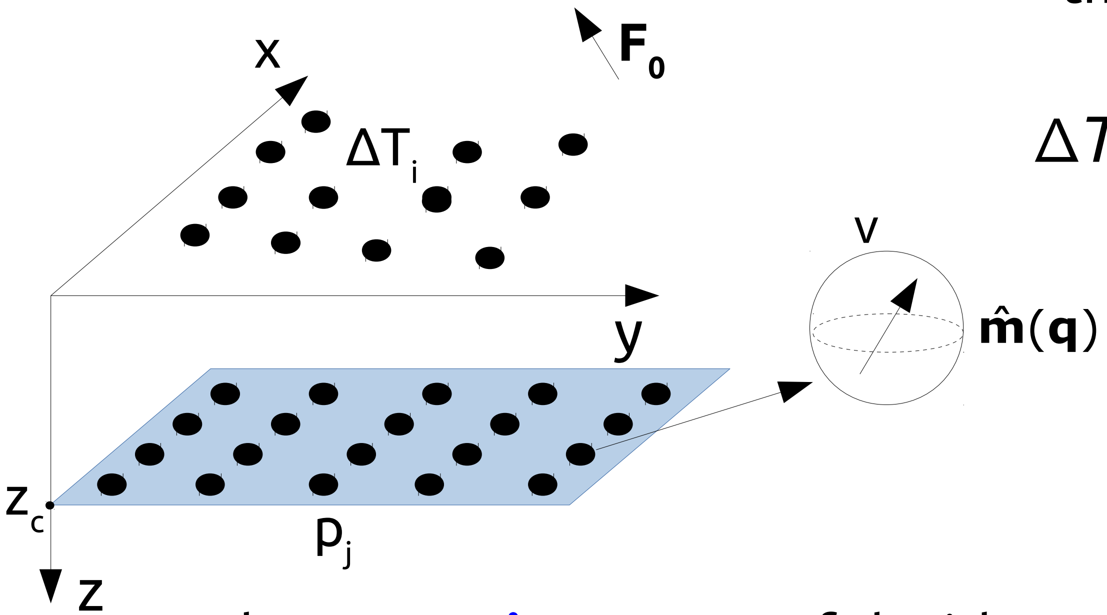
Equivalent layer

The effect produced by M dipoles at the ith observation point is



The **magnetic moment** of the jth dipole, j = 1, …, M.

Equivalent layer

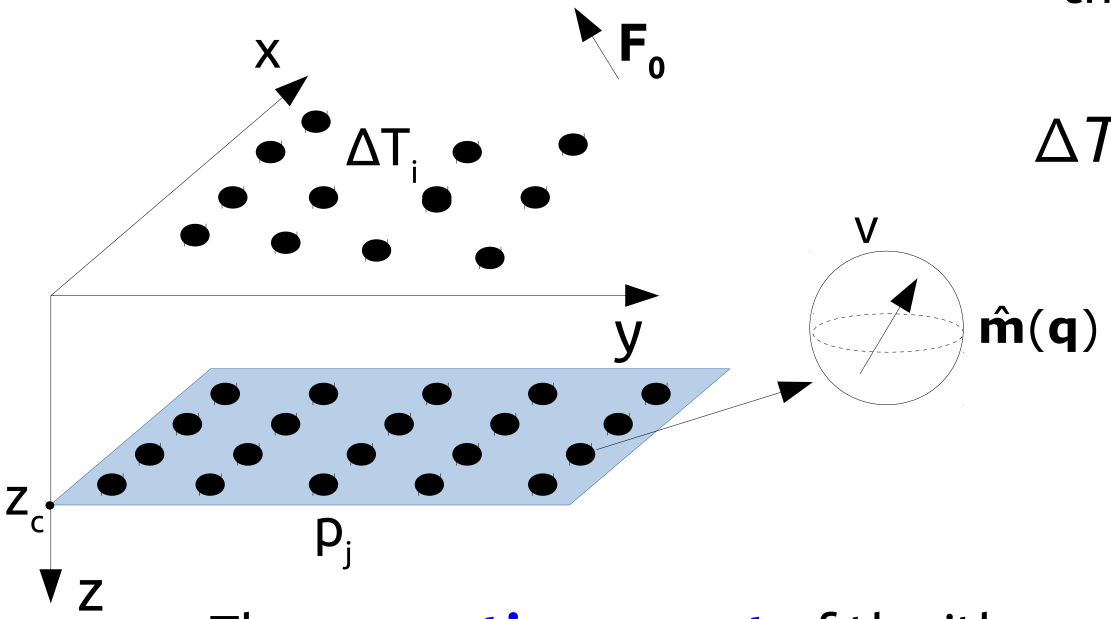


The effect produced by M dipoles at the ith observation point is

$$\Delta T_i(\mathbf{s}) = \sum_{j=1}^{M} g_{ij}(\mathbf{q}) p_j = \mathbf{g}_i^T \mathbf{p}$$

The **magnetic moment** of the jth dipole, j = 1, ..., M.

Equivalent layer



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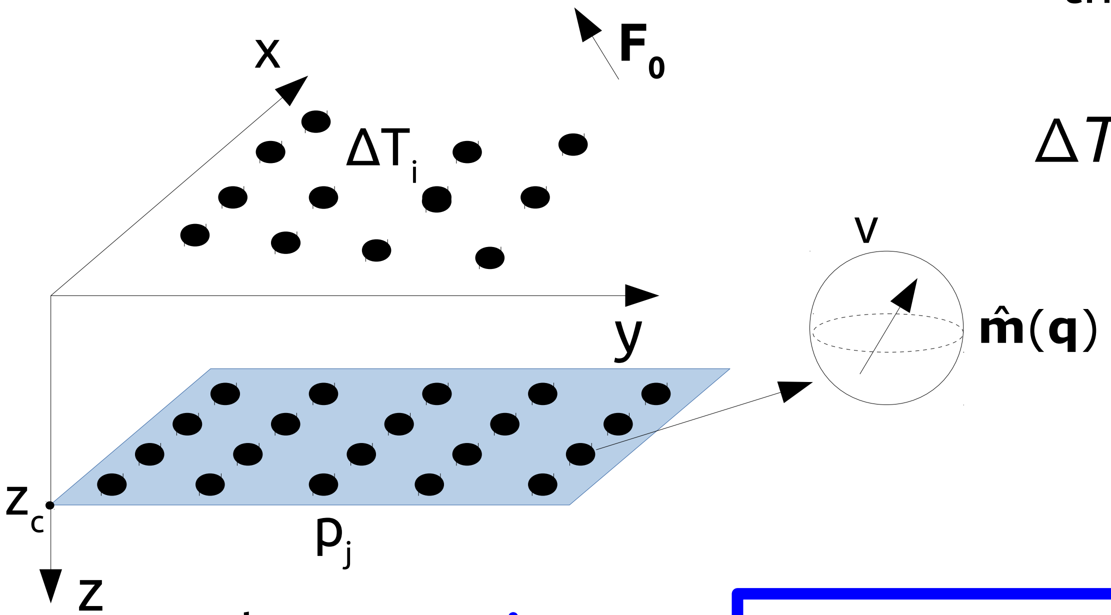
$$\mathbf{s} = \begin{bmatrix} \mathbf{p} \\ \mathbf{q} \end{bmatrix}$$

Parameter vector

The **magnetic moment** of the jth dipole, j = 1, ..., M.

Equivalent layer



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$$\mathbf{s} = \begin{bmatrix}\mathbf{p}\\ \mathbf{q}\end{bmatrix}$$

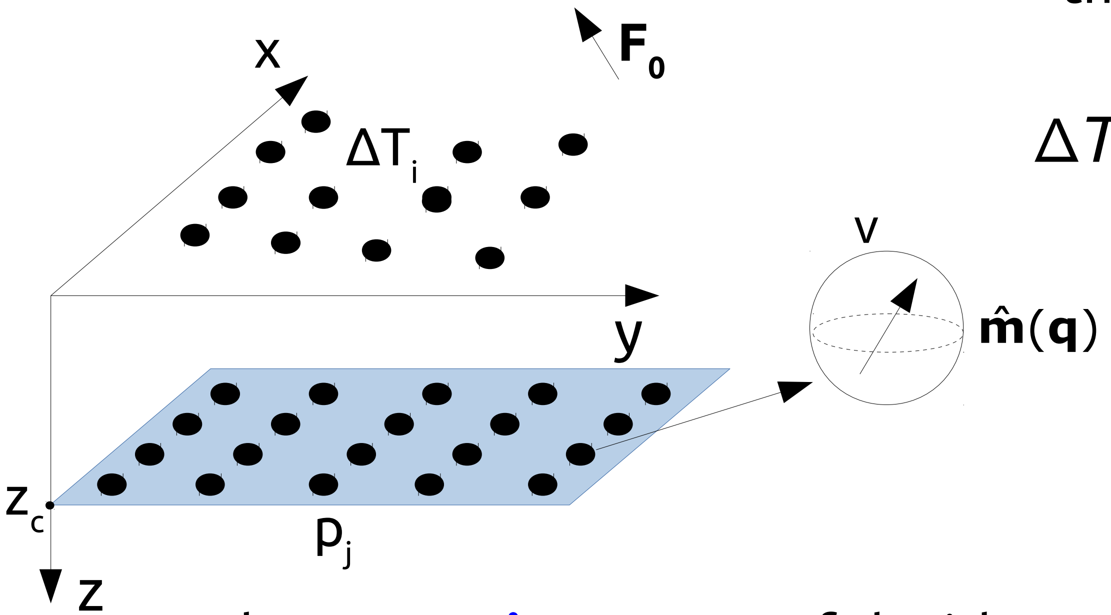
Parameter vector

The **magnetic momen**

dipole, j = 1, ...

This parameter vector is formed by the magnetic moment distribution and the magnetization direction

Equivalent layer



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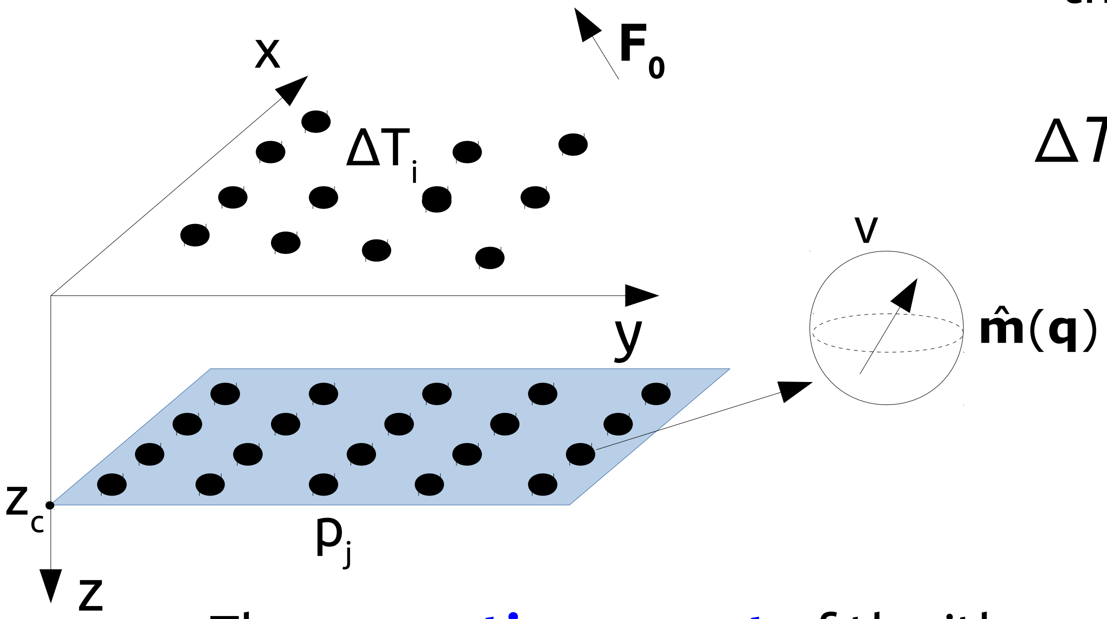
$$\Delta T_i(\mathbf{s}) = \sum_{j=1}^{M} g_{ij}(\mathbf{q}) p_j = \mathbf{g}_i^T \mathbf{p}$$

where

$$g_{ij}(\mathbf{q}) = \gamma \hat{\mathbf{F}}_0^T \mathbf{M}_{ij} \hat{\mathbf{m}}(\mathbf{q})$$

The **magnetic moment** of the jth dipole, j = 1, ..., M.

Equivalent layer



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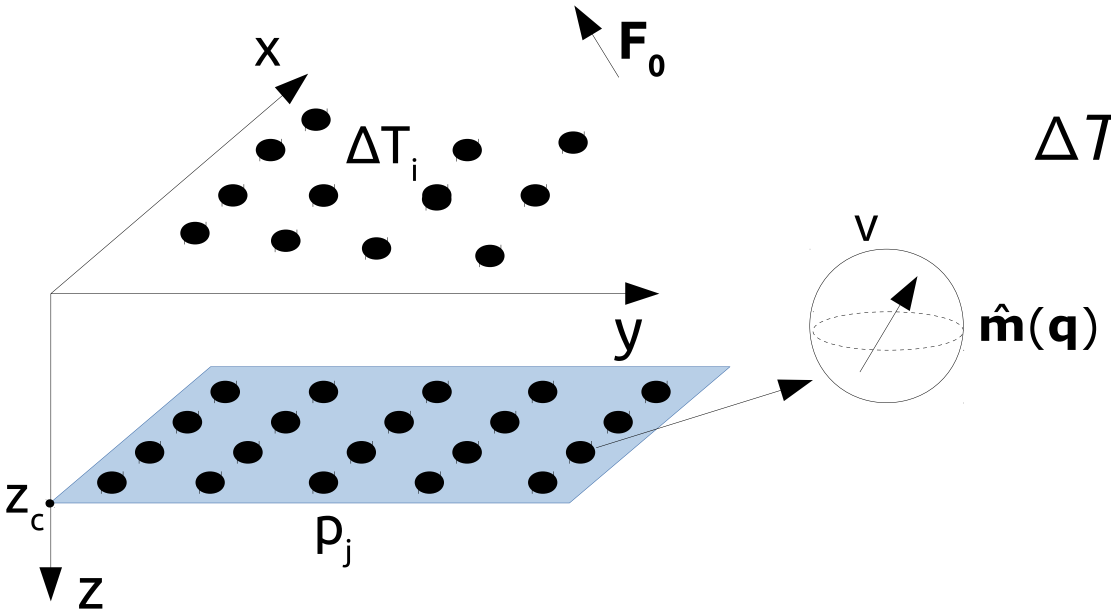
The **magnetic moment** of the jth dipole, j = 1, ..., M.

The task here is to estimate the magnetization direction!

The procedure for estimating magnetization direction

Equivalent layer



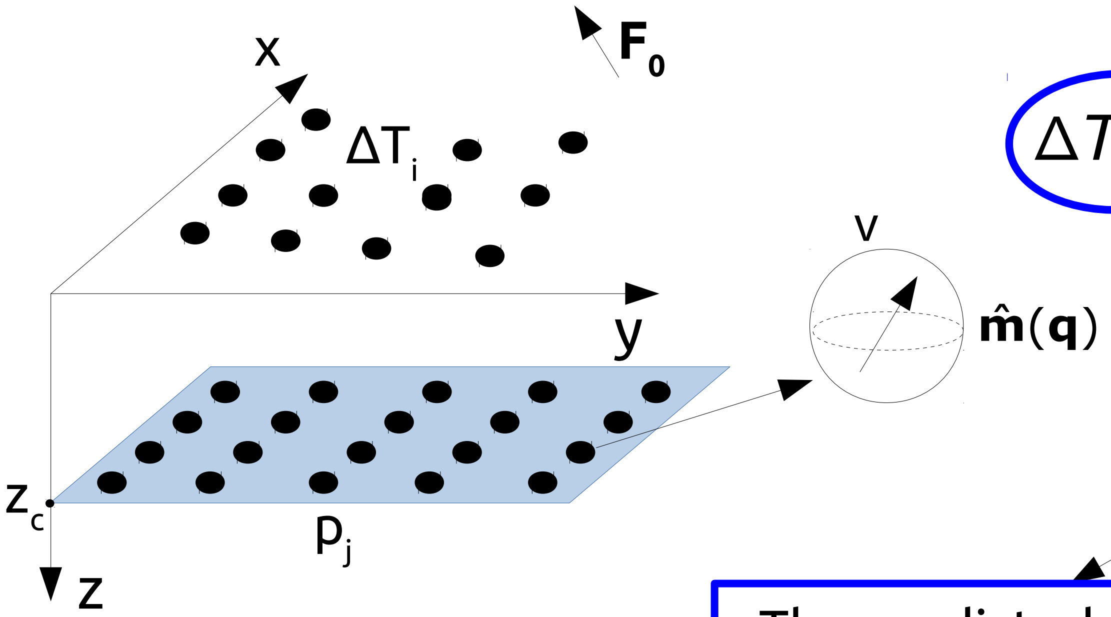
First, we must have to emphasize two issues

$$\Delta T_i(\mathbf{s}) = \sum_{j=1}^{M} g_{ij}(\mathbf{q}) p_j = \mathbf{g}_i^T \mathbf{p}$$

where

$$g_{ij}(\mathbf{q}) = \gamma \hat{\mathbf{F}}_0^T \mathbf{M}_{ij} \hat{\mathbf{m}}(\mathbf{q})$$

Equivalent layer



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The predicted data has a **linear relation** with magnetic moment distribution

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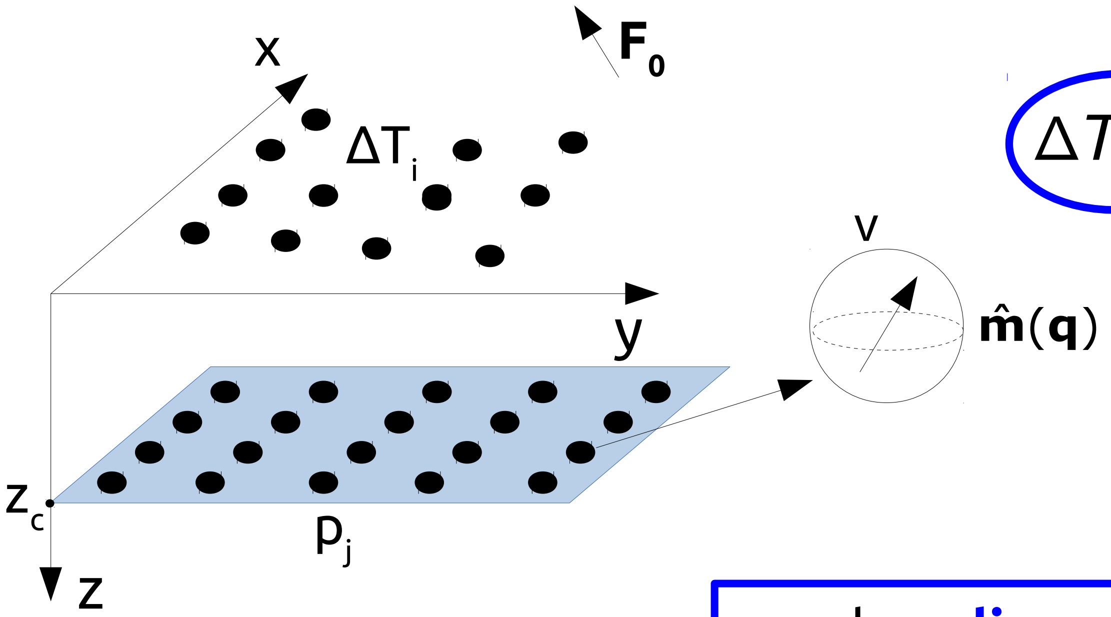
Equivalent layer



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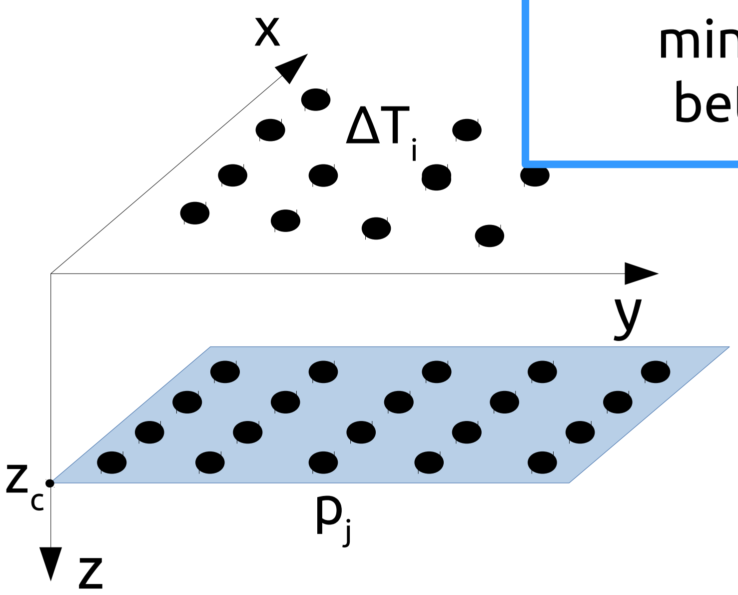
$$g_{ij}(\mathbf{q}) = \gamma \hat{\mathbf{F}}_0^T \mathbf{M}_{ij} \hat{\mathbf{m}}(\mathbf{q})$$

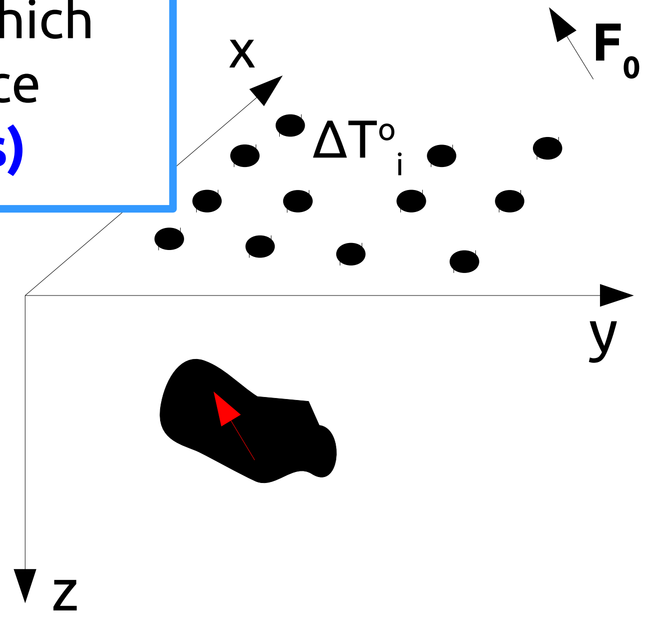
and **nonlinear relation** with the magnetization direction

Equivalent layer

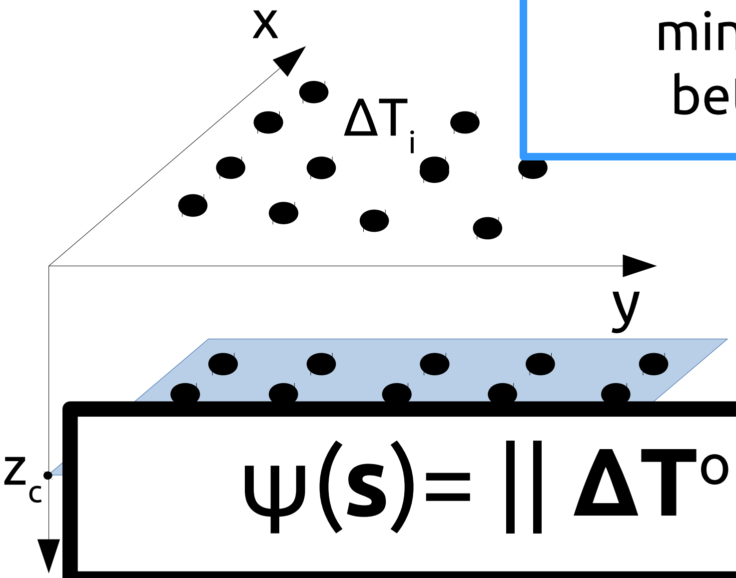
Magnetic source

Estimate the **p*** and **q*** which minimizes the difference between **ΔT°** and **ΔT(s)**

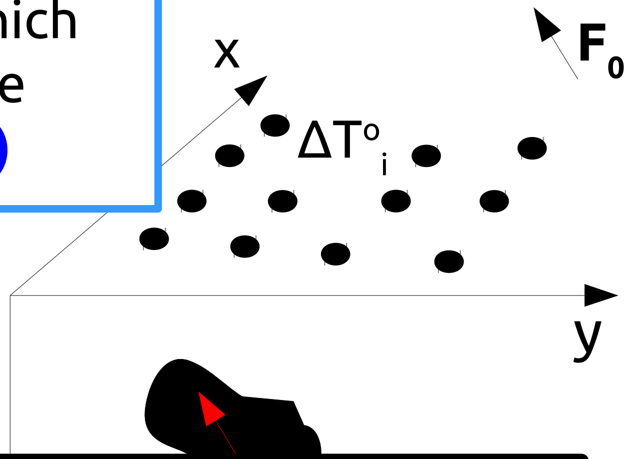




Equivalent layer



Magnetic source



Estimate the **p*** and **q*** which minimizes the difference between **ΔT^o** and **$\Delta T(s)$**

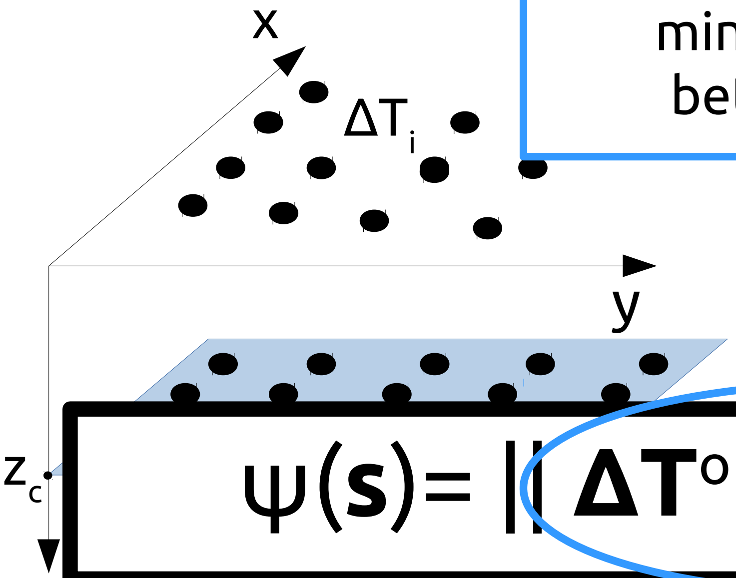
Minimize

$$\psi(\mathbf{s}) = \|\, \boldsymbol{\Delta} \mathbf{T}^o - \boldsymbol{\Delta} \mathbf{T}(\mathbf{s}) \|_2 + \mu f_0 \|\mathbf{p}\|_2$$

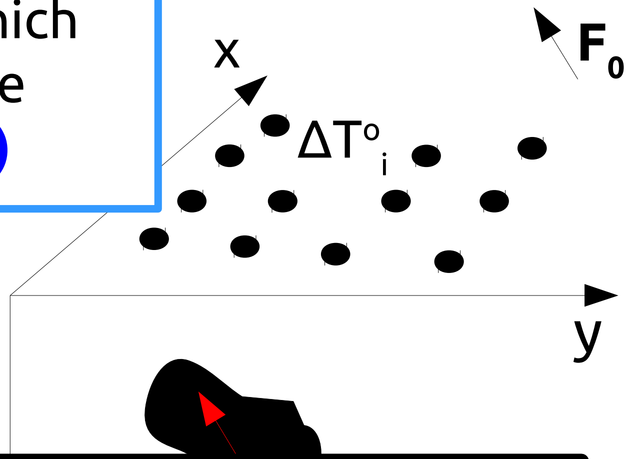
Subject to

$$\mathbf{p} \geq 0$$

Equivalent layer



Magnetic source



Estimate the **p*** and **q*** which minimizes the difference between **ΔT^o** and **ΔT(s)**

Minimize

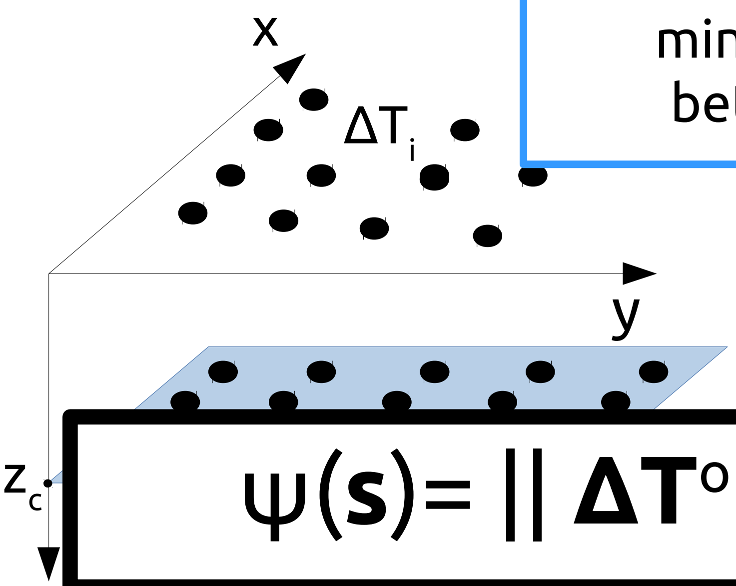
$$\psi(\mathbf{s}) = \|\Delta T^o - \Delta T(\mathbf{s})\|_2 + \mu f_0 \|\mathbf{p}\|_2$$

Data misfit

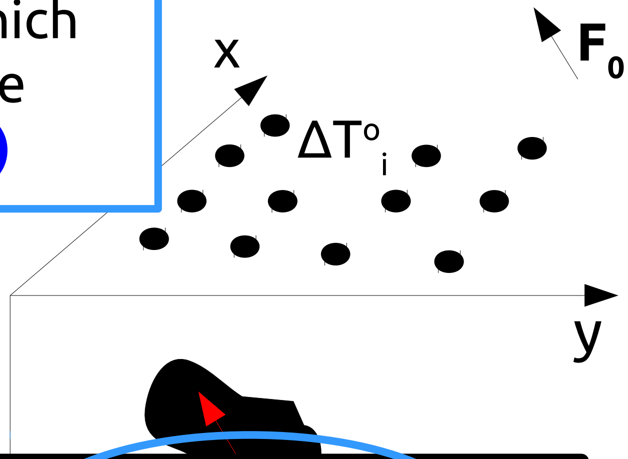
Subject to

$$\mathbf{p} \geq 0$$

Equivalent layer



Magnetic source



Estimate the **p*** and **q*** which minimizes the difference between **ΔT°** and **ΔT(s)**

Minimize

$$\psi(\mathbf{s}) = \| \Delta \mathbf{T}^o - \Delta \mathbf{T}(\mathbf{s}) \|_2 + \mu f_0 \|\mathbf{p}\|_2$$

Tik-0 reg.

Subject to

$$\mathbf{p} \geq 0$$

How to solve this inverse problem?

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We propose a nested algorithm that solves the problem in two steps

Given an initial guess $\mathbf{q}_0$ for magnetization direction

We propose a nested algorithm that solves the problem in two steps

1 $$\left(\mathbf{G}_p^{k^T}\mathbf{G}_p^k + \mu f_0^k \mathbf{I}\right)\mathbf{p}^{*^k} = \mathbf{G}_p^{k^T}\boldsymbol{\Delta}\mathbf{T}^o$$

2 $$\left(\mathbf{G}_q^{k^T}\mathbf{G}_q^k + \lambda \mathbf{I}\right)\boldsymbol{\Delta}\mathbf{q}^{*^k} = \mathbf{G}_q^{k^T}\left[\boldsymbol{\Delta}\mathbf{T}^o - \boldsymbol{\Delta}\mathbf{T}(\mathbf{s})\right]$$

Given an initial guess $\mathbf{q}_0$ for magnetization direction

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1 $$(\mathbf{G}_p^{k^T}\mathbf{G}_p^k + \mu f_0^k\mathbf{I})\mathbf{p}^{*^k} = \mathbf{G}_p^{k^T}\mathbf{\Delta T}^o$$

Nonnegative least squares (NNLS) by Lawson and Hanson (1974)

2 $$(\mathbf{G}_q^{k^T}\mathbf{G}_q^k + \lambda\mathbf{I})\mathbf{\Delta q}^{*^k} = \mathbf{G}_q^{k^T}[\mathbf{\Delta T}^o - \mathbf{\Delta T}(\mathbf{s})]$$

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Levenberg-Marquardt method

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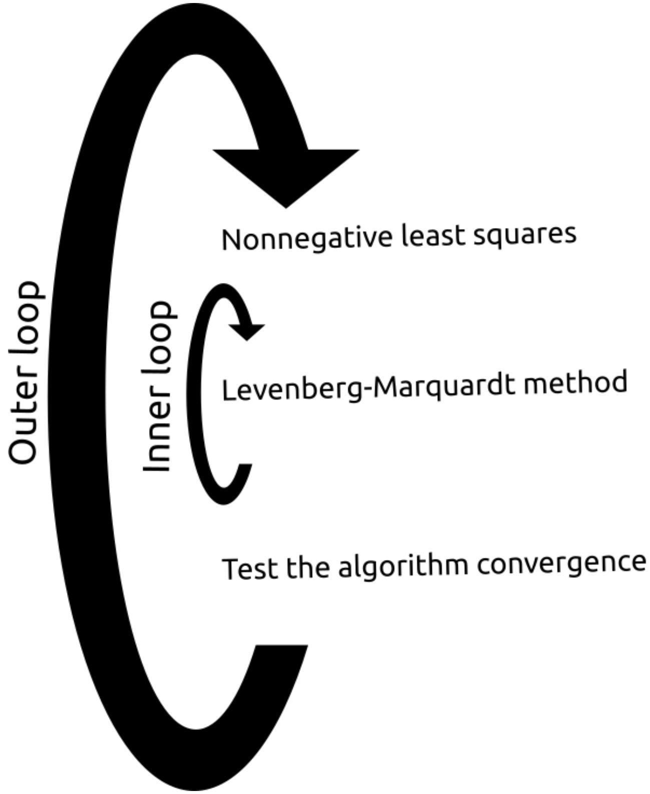
An overview of the algorithm

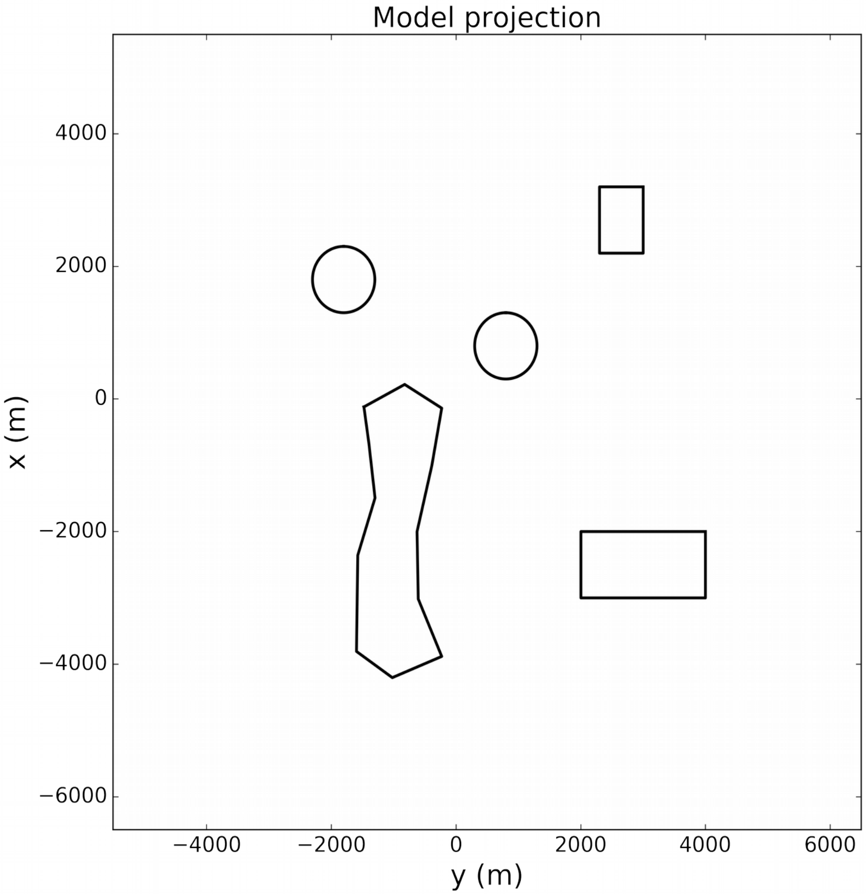


Numerical simulations

1. Unidirectional magnetization sources
2. Unidirectional with shallow-seated source
3. Shallow-seated source with different direction

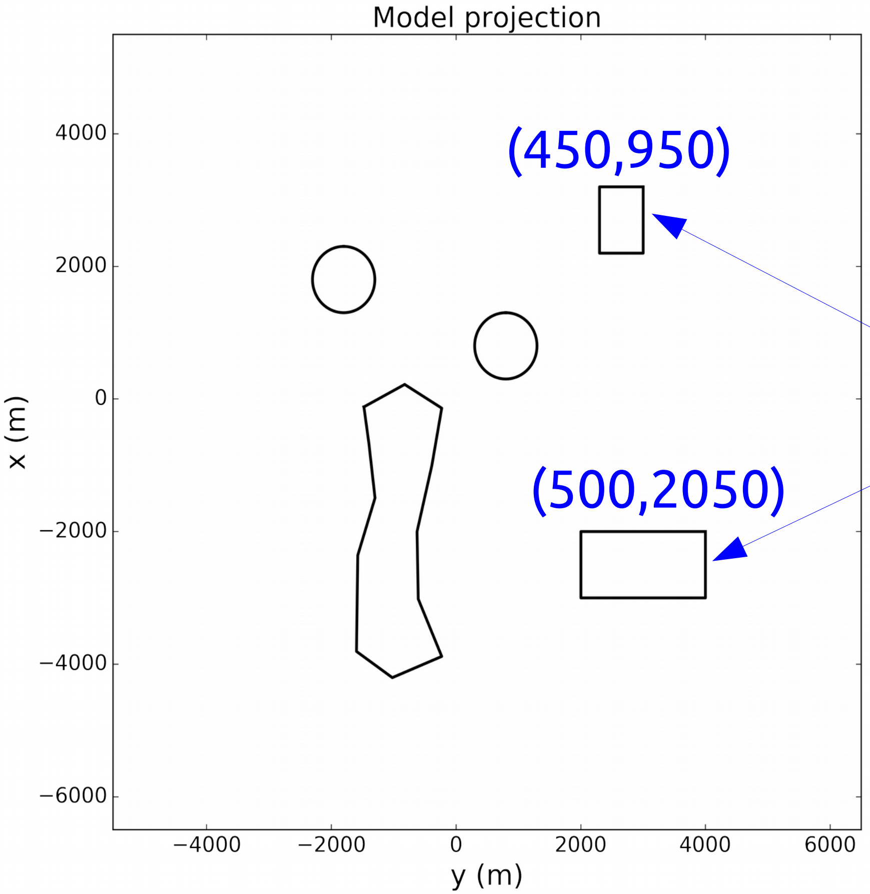
For all simulations

*(top, bottom) in meters



A model composed by five magnetic sources :

For all simulations *(top, bottom) in meters

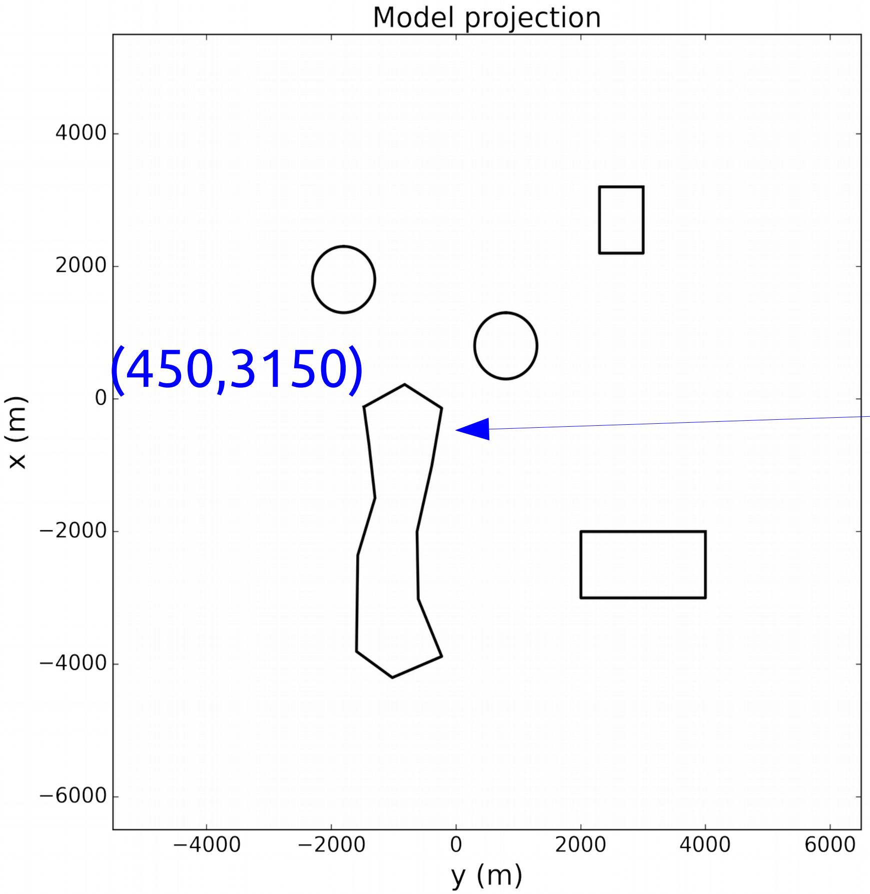


A model composed by five magnetic sources :

Two rectangular prisms

For all simulations

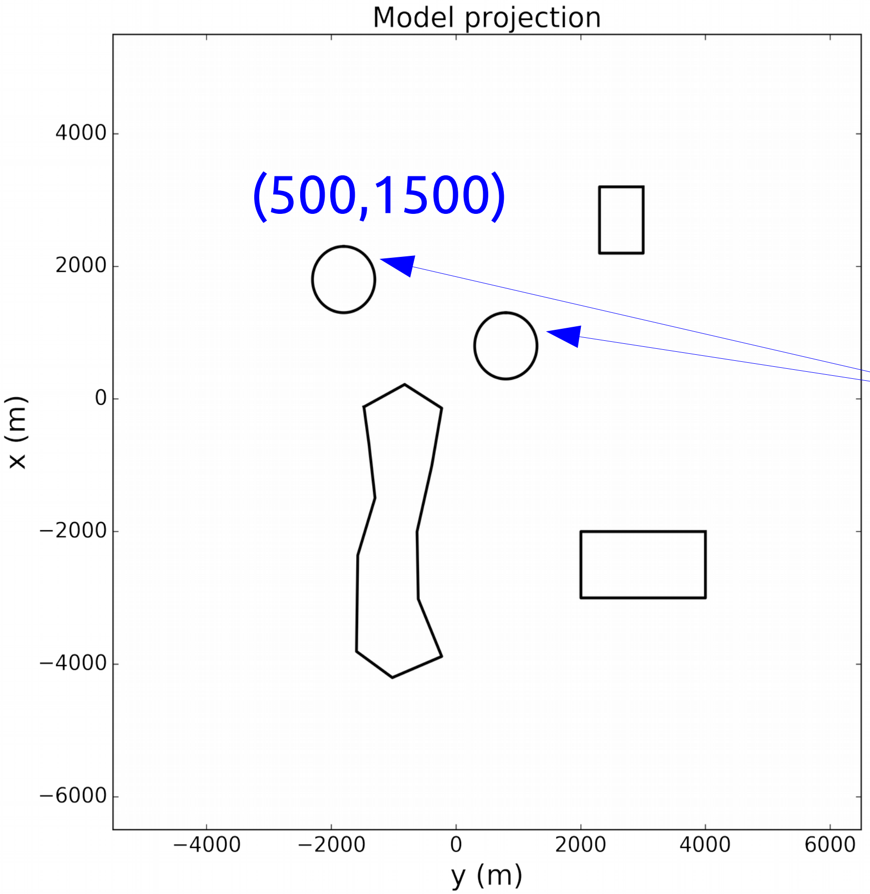
*(top, bottom) in meters



A model composed by five magnetic sources :

Prism with
polygonal cross-section

For all simulations *(top, bottom) in meters



A model composed by five magnetic sources :

Two spheres

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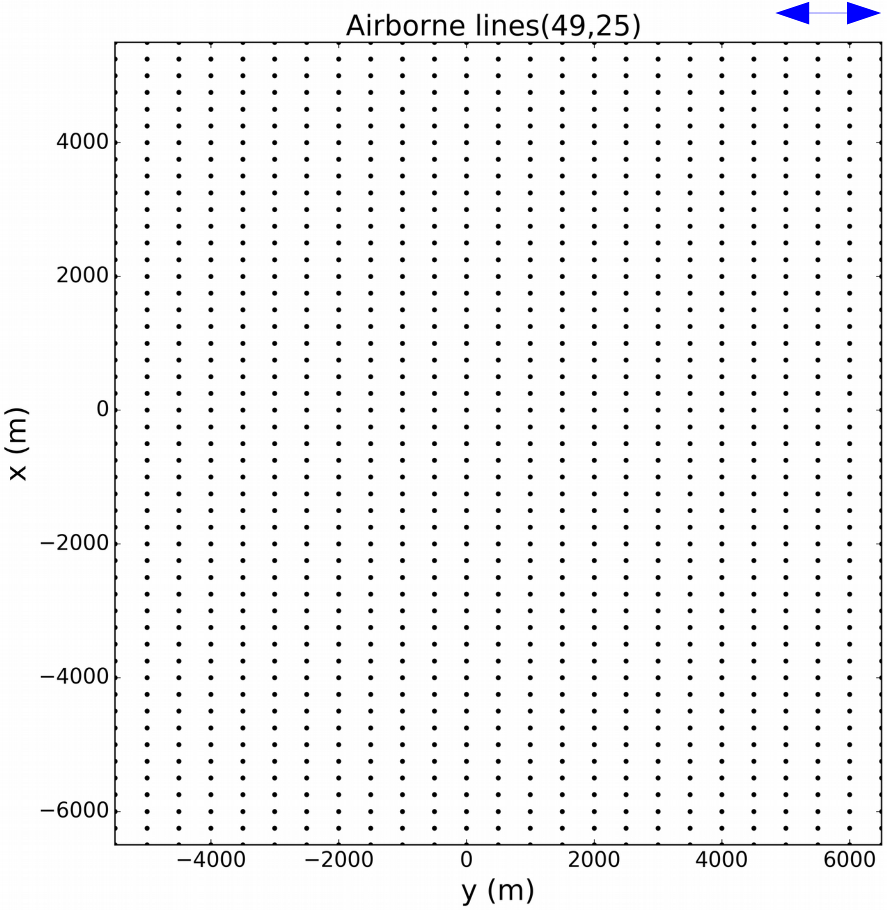
For all simulations

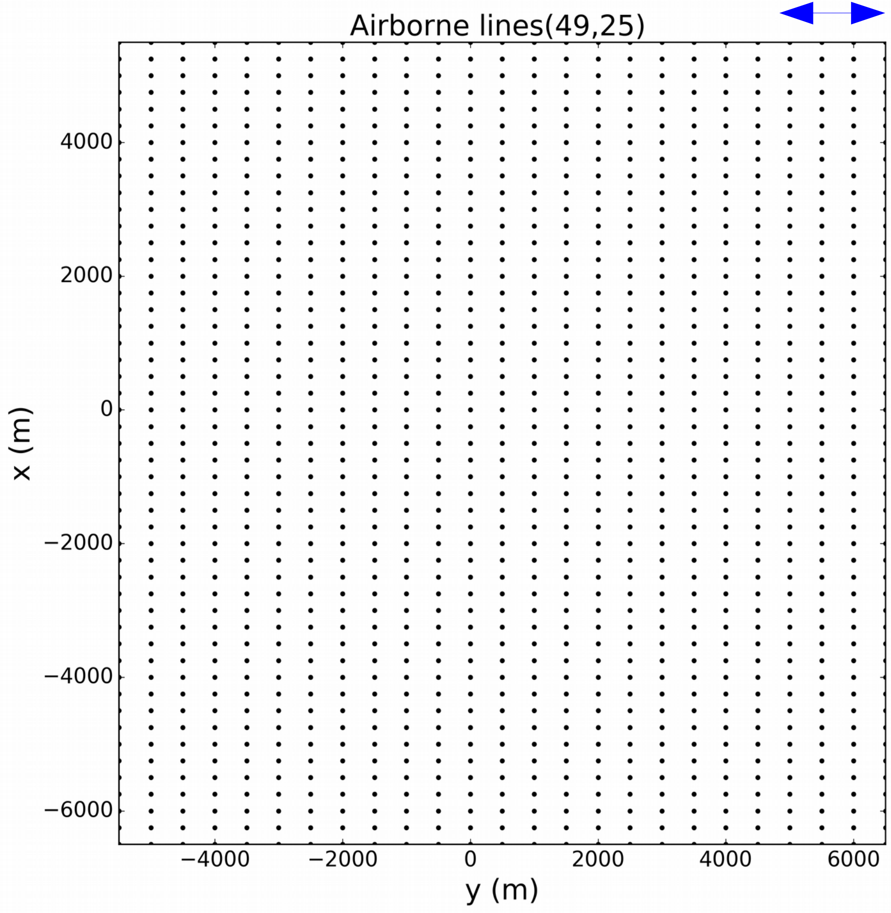


dy= 500 m

dx= 250 m

Grid spacing

For all simulations



dy= 500 m

Grid spacing

dx= 250 m

z = 100 m **Height**

N = 1225 points

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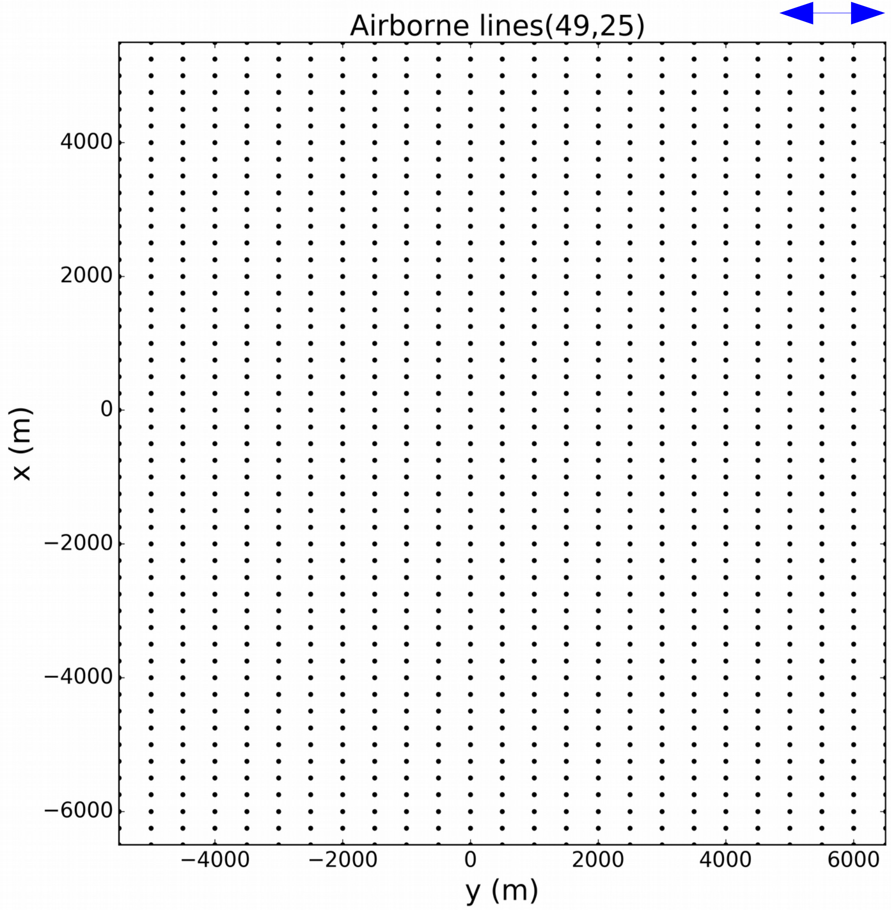
For all simulations



dy= 500 m

dx= 250 m

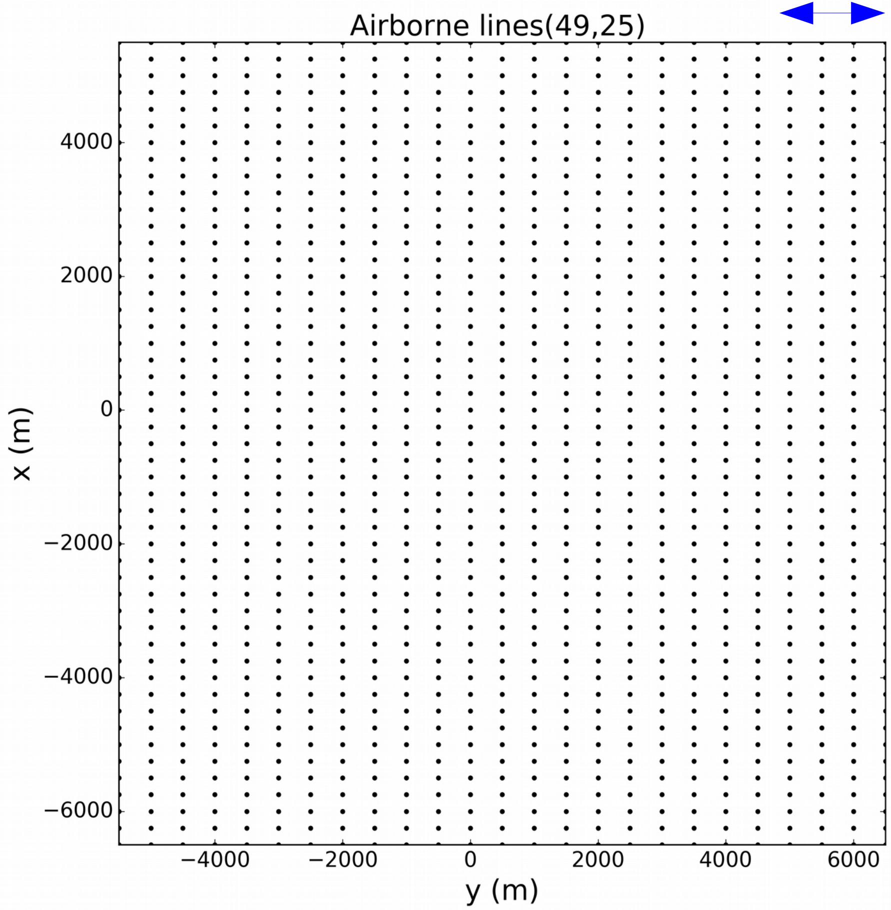
Grid spacing

z = 100 m **Height**

N = 1225 points

(I_0, D_0) = -40°,-22° **Simulated main field direction**

For all simulations



dy= 500 m

dx= 250 m

Grid spacing

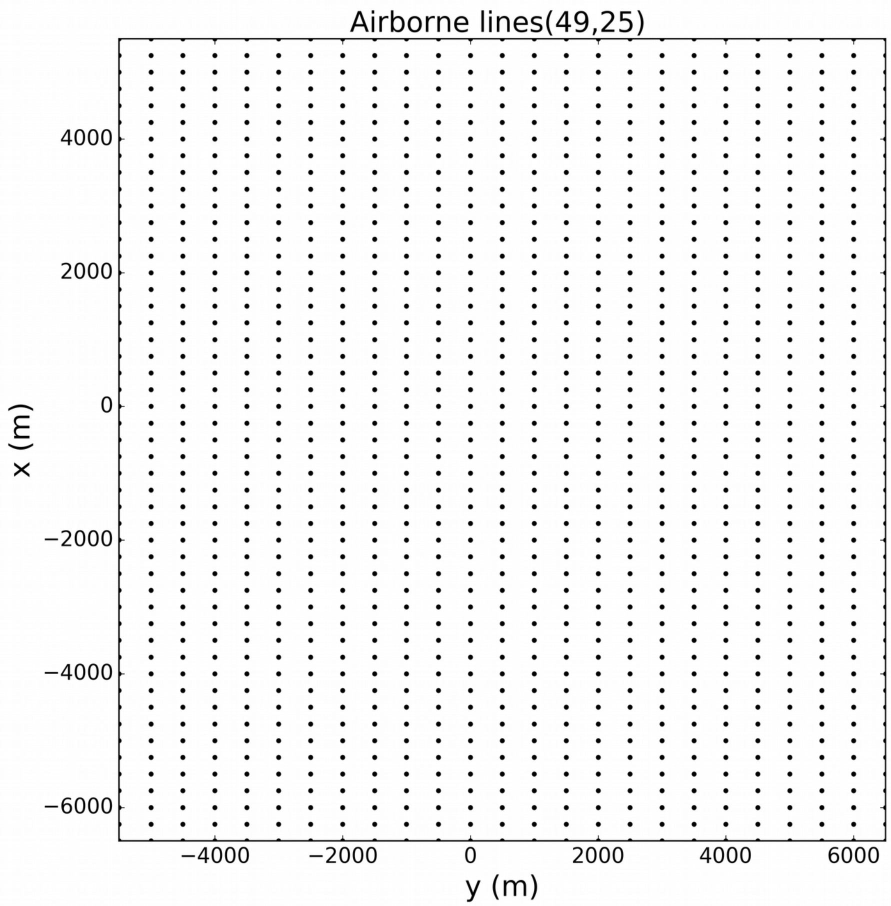
$z = 100$ m **Height**

$N = 1225$ points

$(I_0, D_0) = -40°, -22°$ **Simulated main field direction**

Gaussian noise with zero mean and standard deviation 10 nT

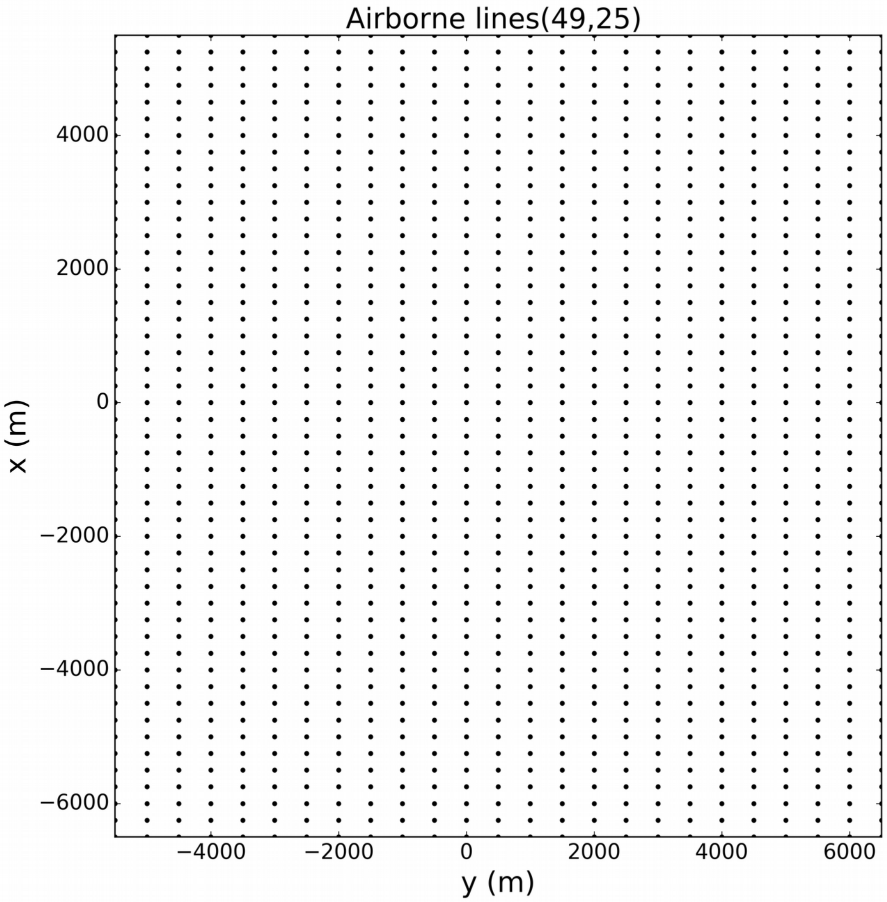
For all simulations



For the inversion

M = 1225 equivalent sources
(same number of observations)

For all simulations



For the inversion

M = 1225 equivalent sources
(same number of observations)

Depth of z = 1150 m

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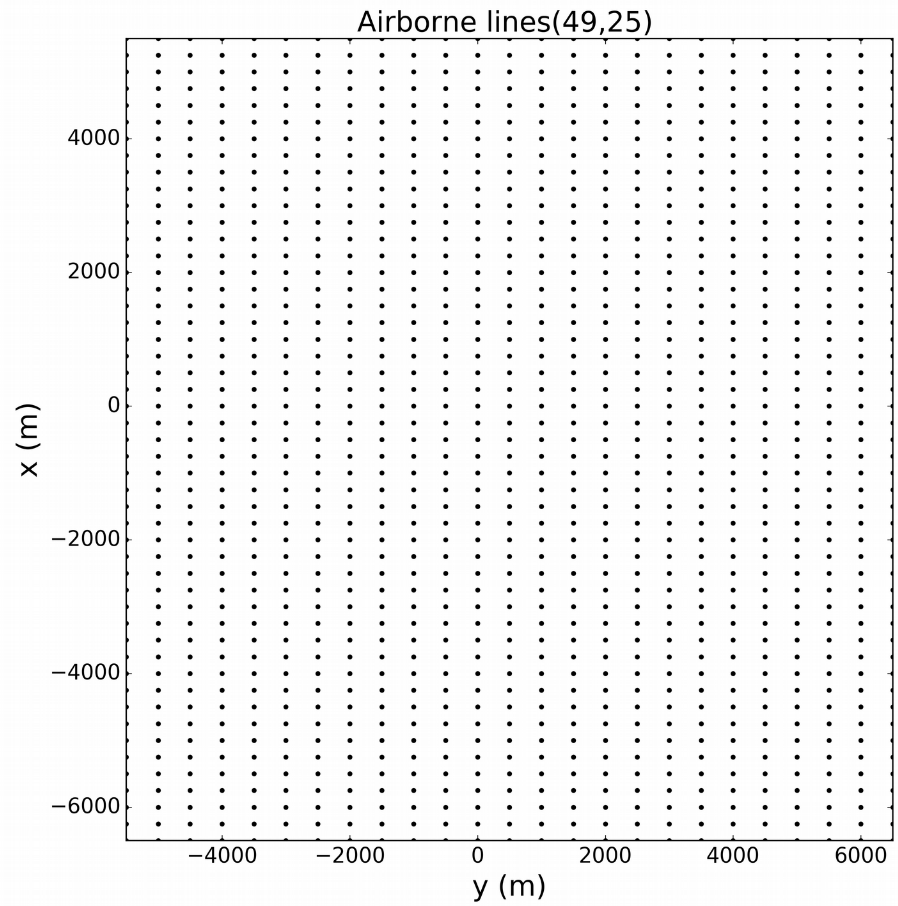
For all simulations



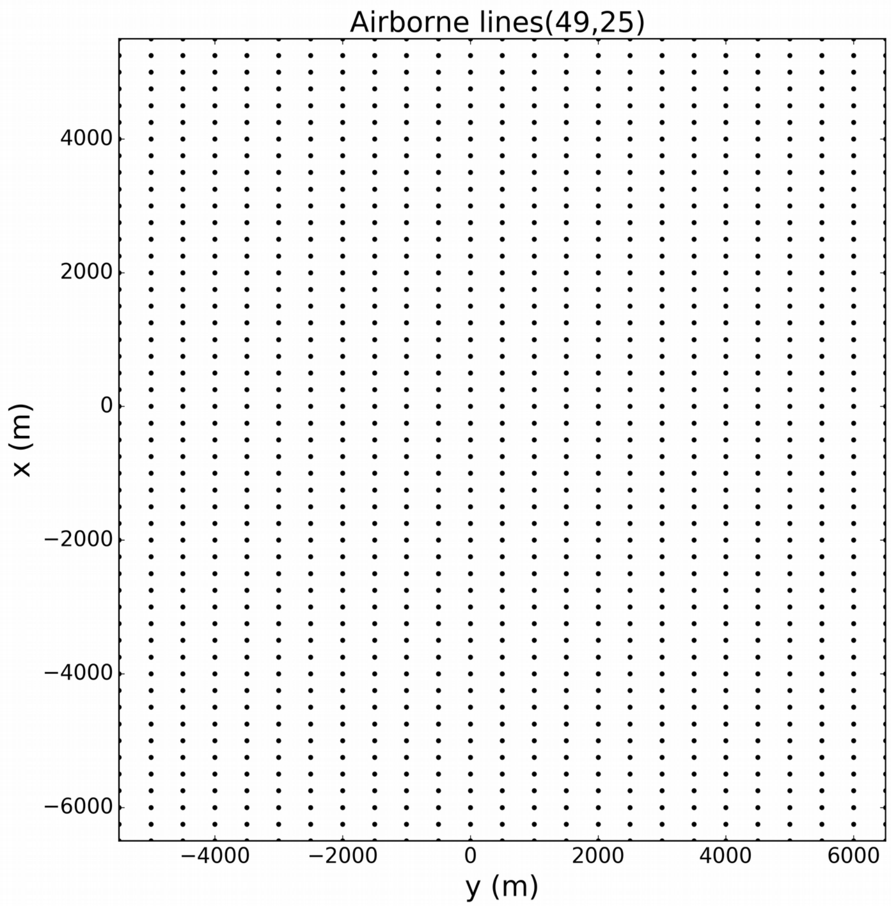
For the inversion

M = 1225 equivalent sources
(same number of observations)

Depth of z = 1150 m

L-curve for choosing the regularization parameter proposed by Hansen (1992).

For all simulations



For the inversion

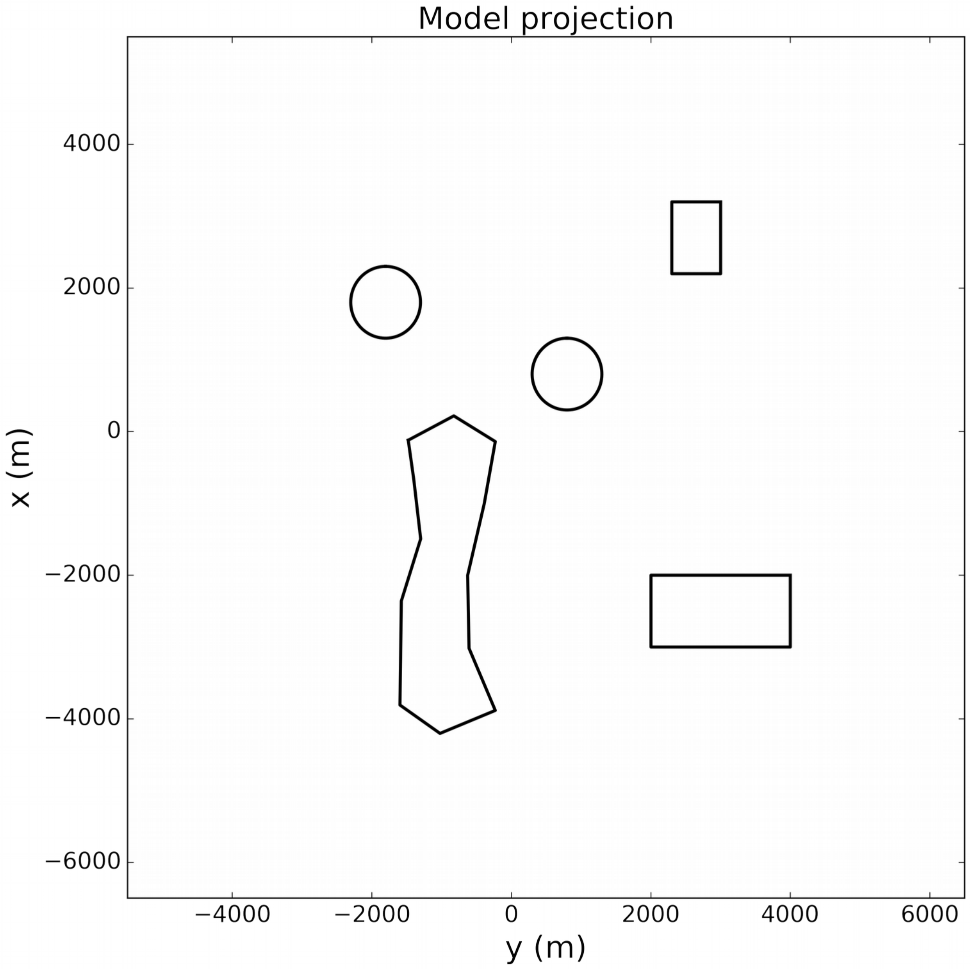
M = 1225 equivalent sources (same number of observations)

Depth of z = 1150 m

L-curve for choosing the regularization parameter proposed by Hansen (1992).

The initial guess of $\mathbf{q}_0$ = (-10°,-10°)

1. Unidirectional magnetization sources



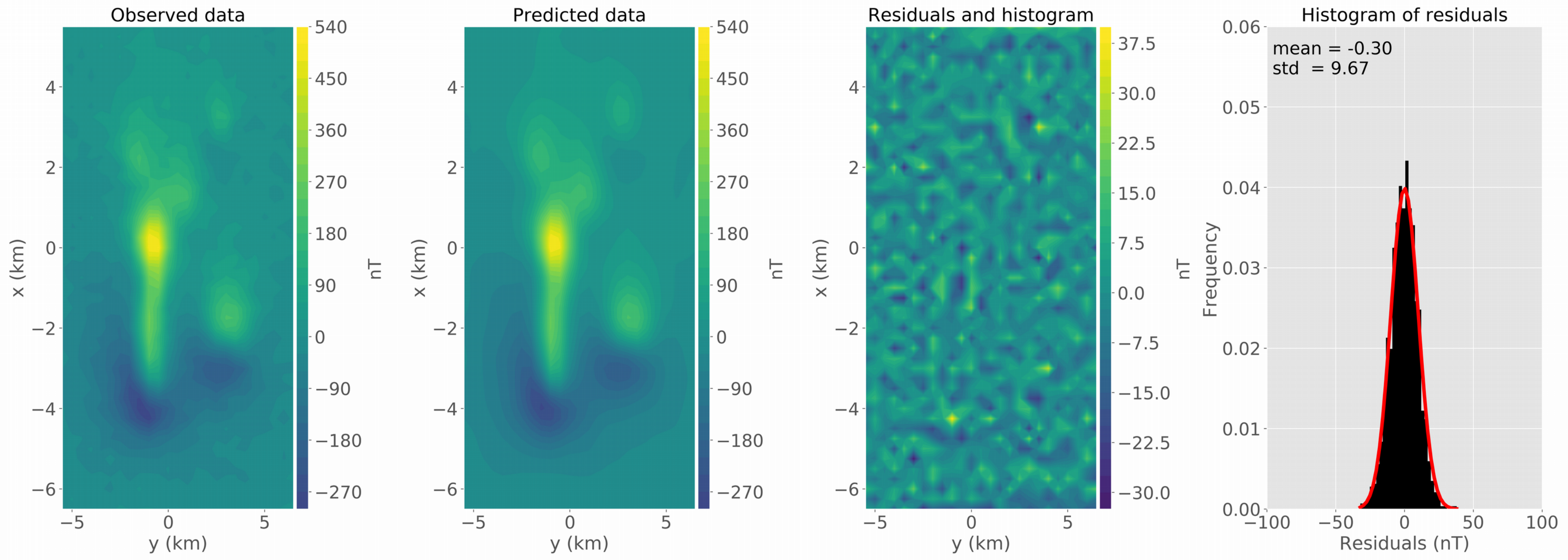
The magnetization direction for all sources:

(I,D) = (-25°,30°)

Data Fitting

(I,D) = (-25º,30º)

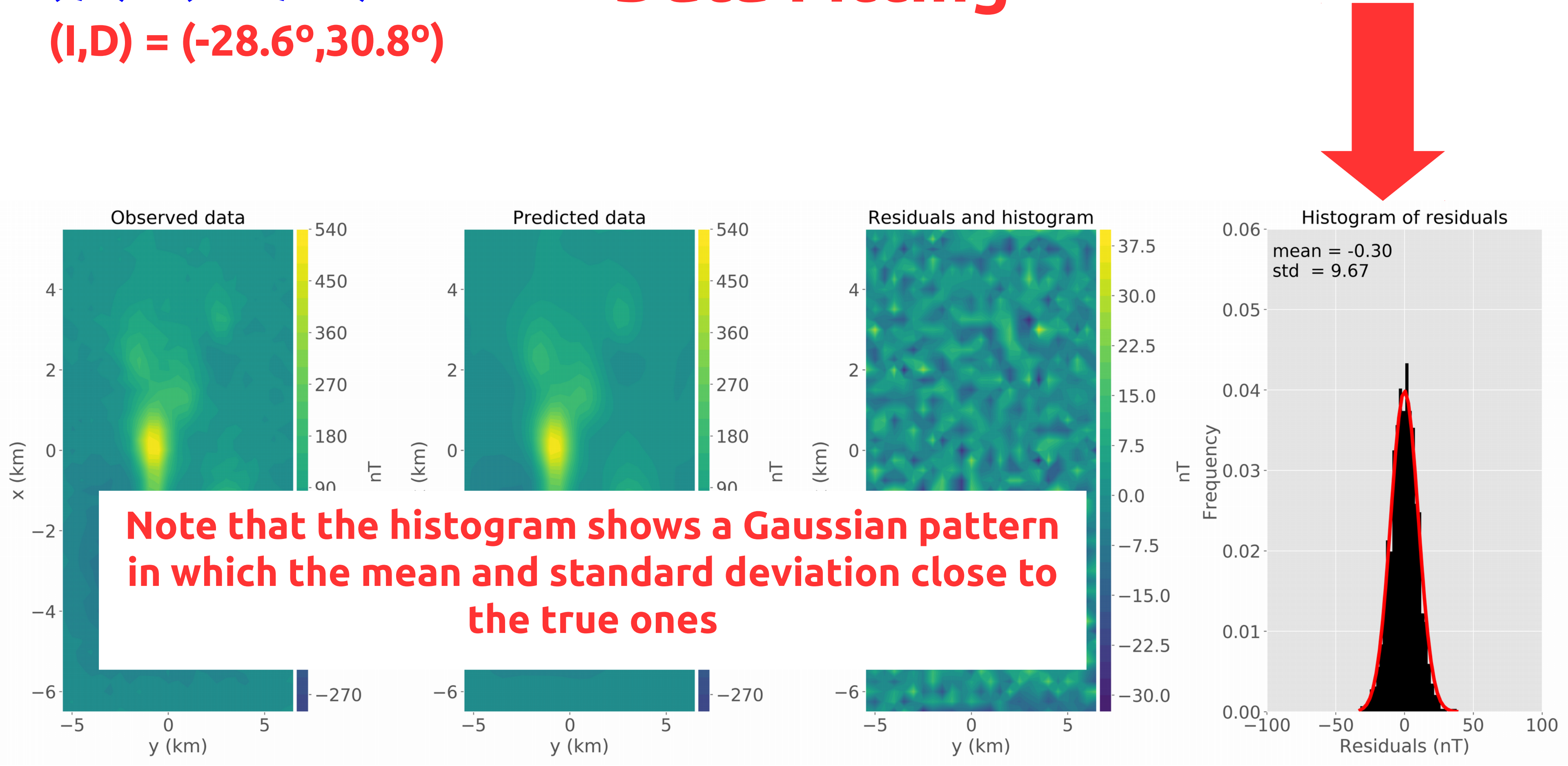
(I,D) = (-28.6º,30.8º)



(I,D) = (-25º,30º)

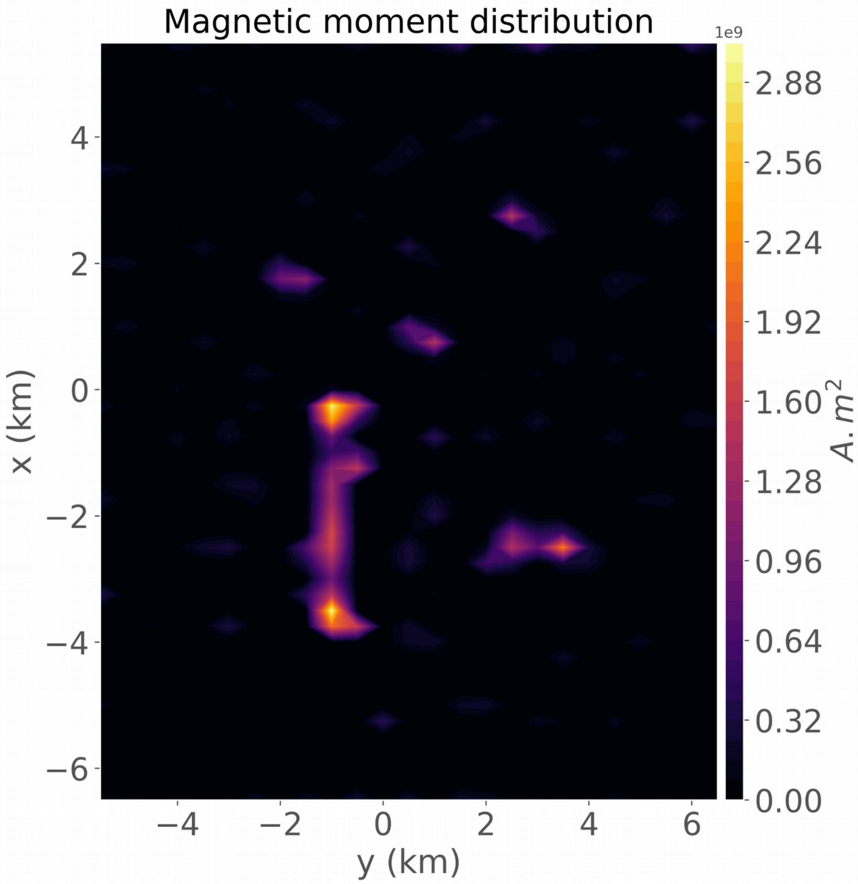
(I,D) = (-28.6º,30.8º)

Data Fitting



Note that the histogram shows a Gaussian pattern in which the mean and standard deviation close to the true ones

Magnetic moment distribution

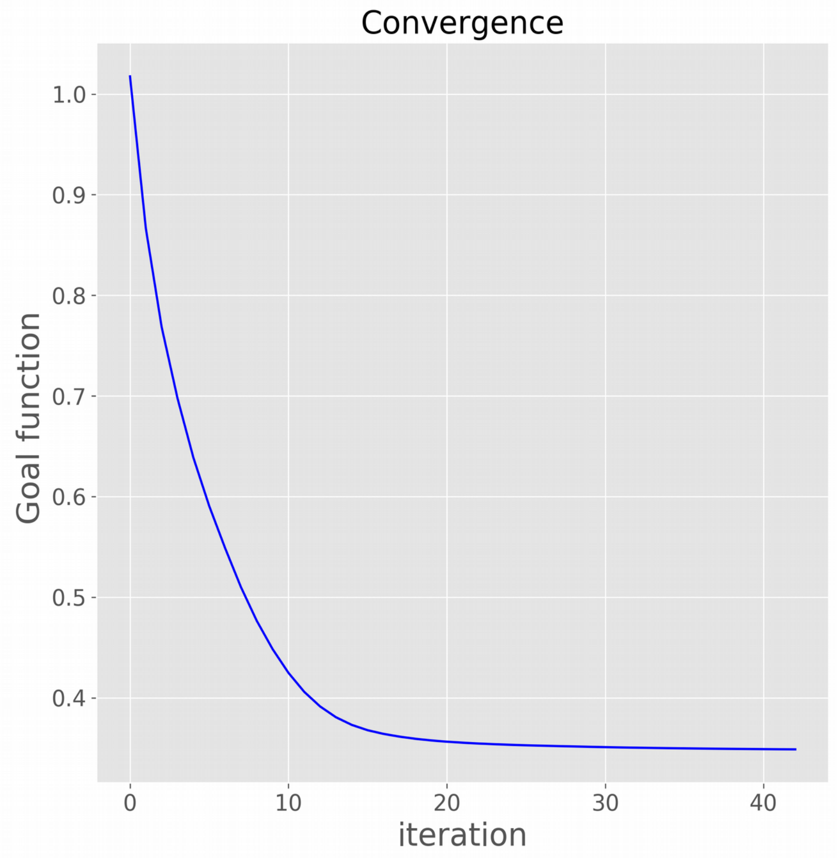


(I,D) = (-25°,30°)

(I,D) = (-28.6°,30.8°)

Note the positive magnetic moment distribution!

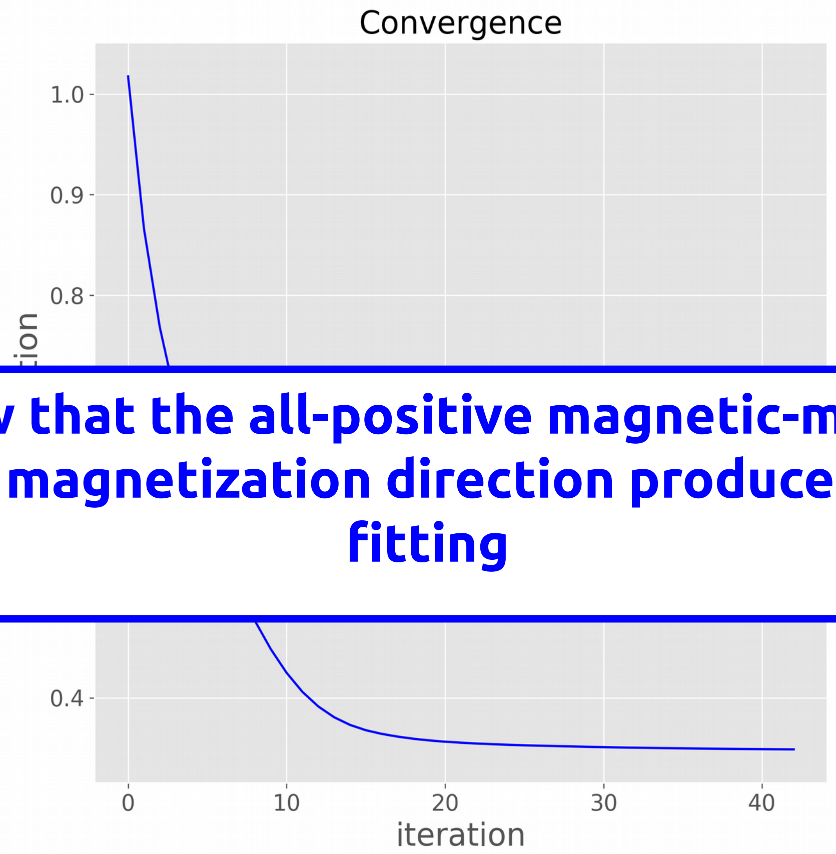
The algorithm convergence



(I,D) = (-25°,30°)

(I,D) = (-28.6°,30.8°)

The algorithm convergence



(I,D) = (-25°,30°)

(I,D) = (-28.6°,30.8°)

These results show that the all-positive magnetic-moment distribution and the estimated magnetization direction produce an acceptable data fitting

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2. Unidirectional with shallow-seated source

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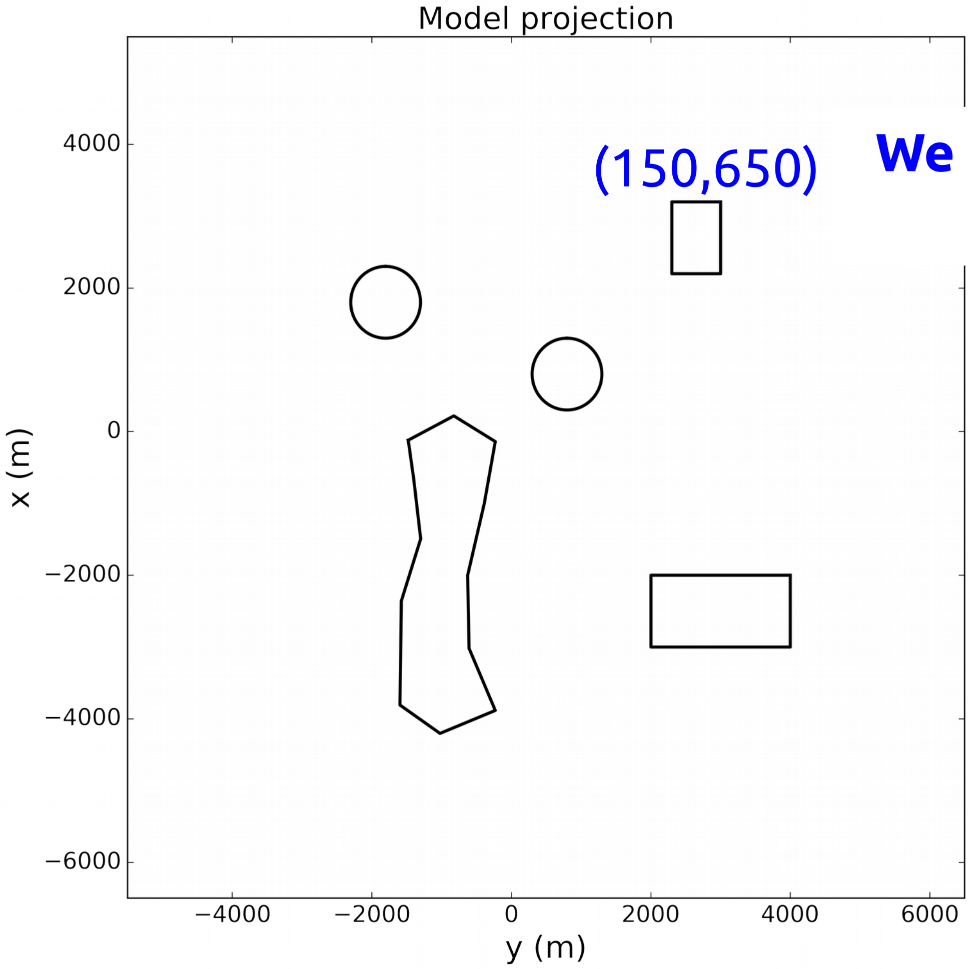
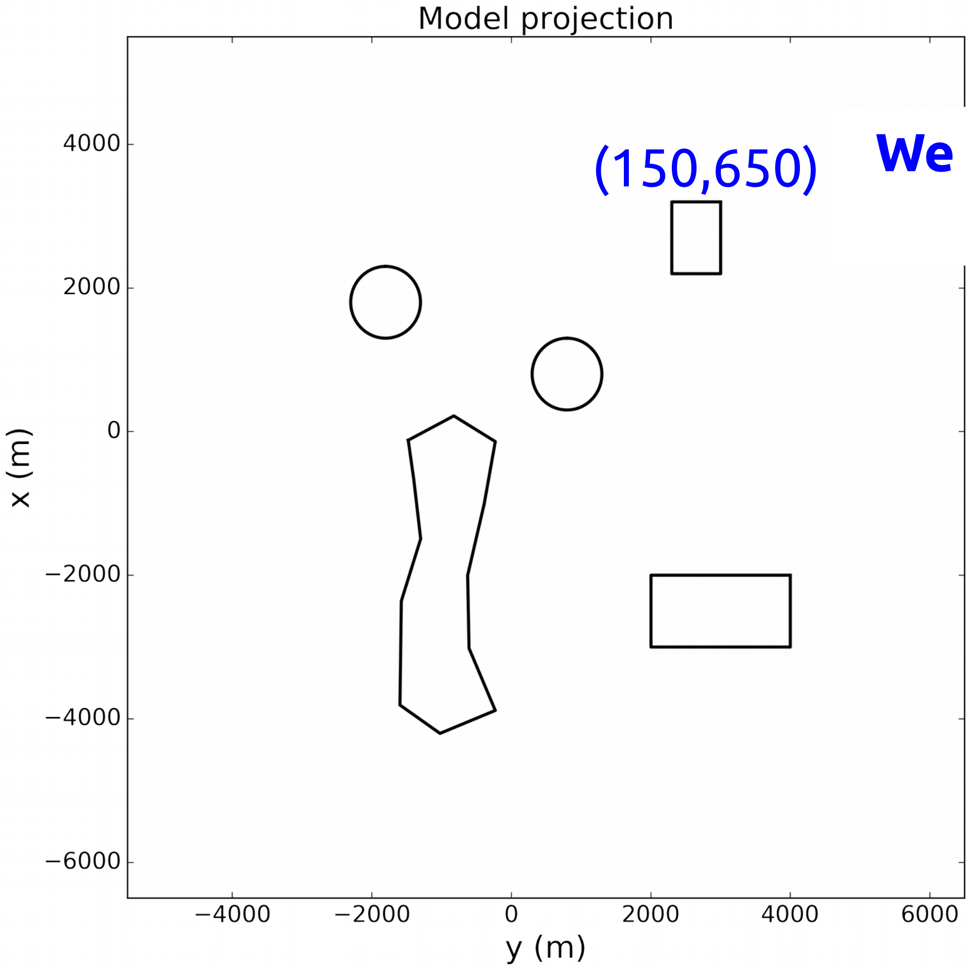


We brought this prism to a shallower depth



We brought this prism to a shallower depth

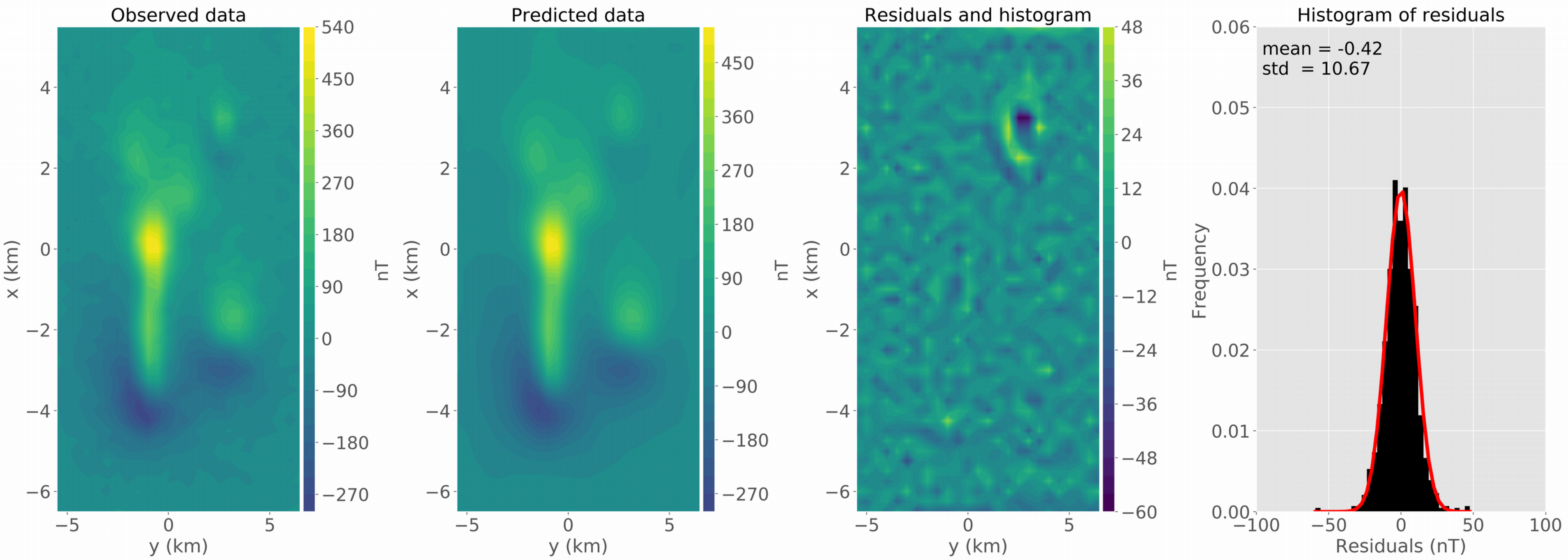
The magnetization direction for all sources:

(I,D) = (-25º,30º)

Data Fitting

(I,D) = (-25°,30°)

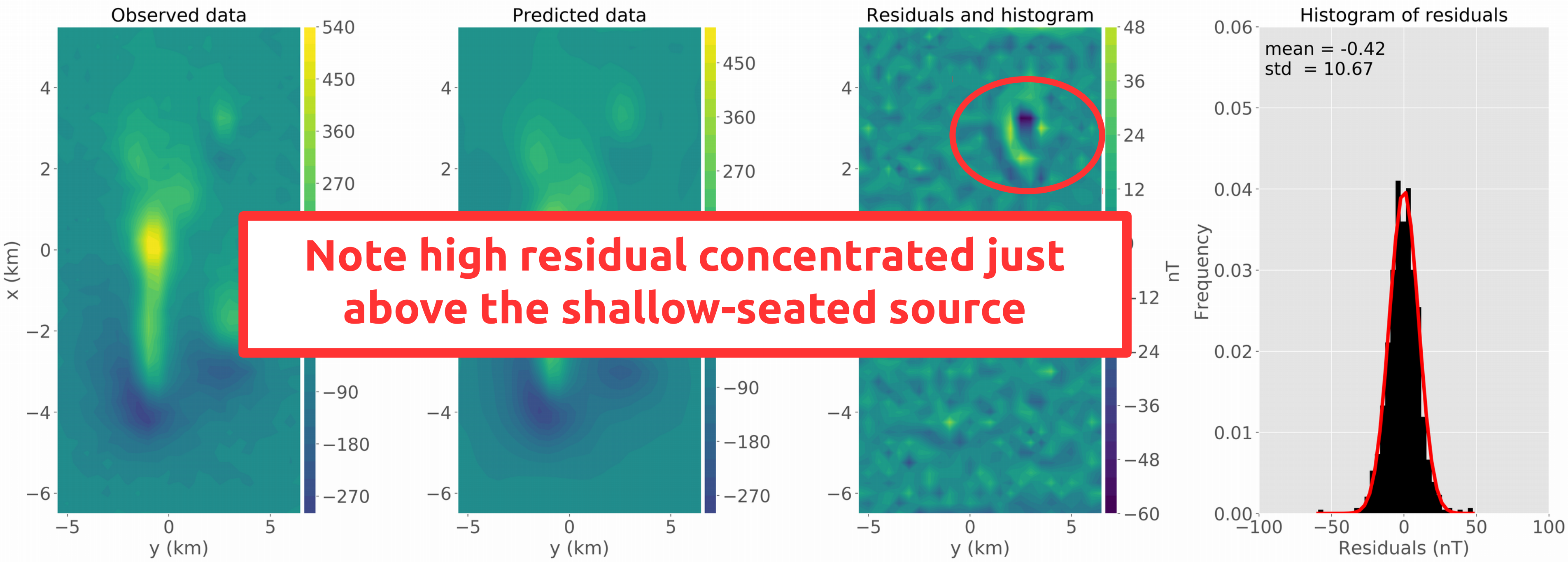
(I,D) = (-28.7°,31.7°)



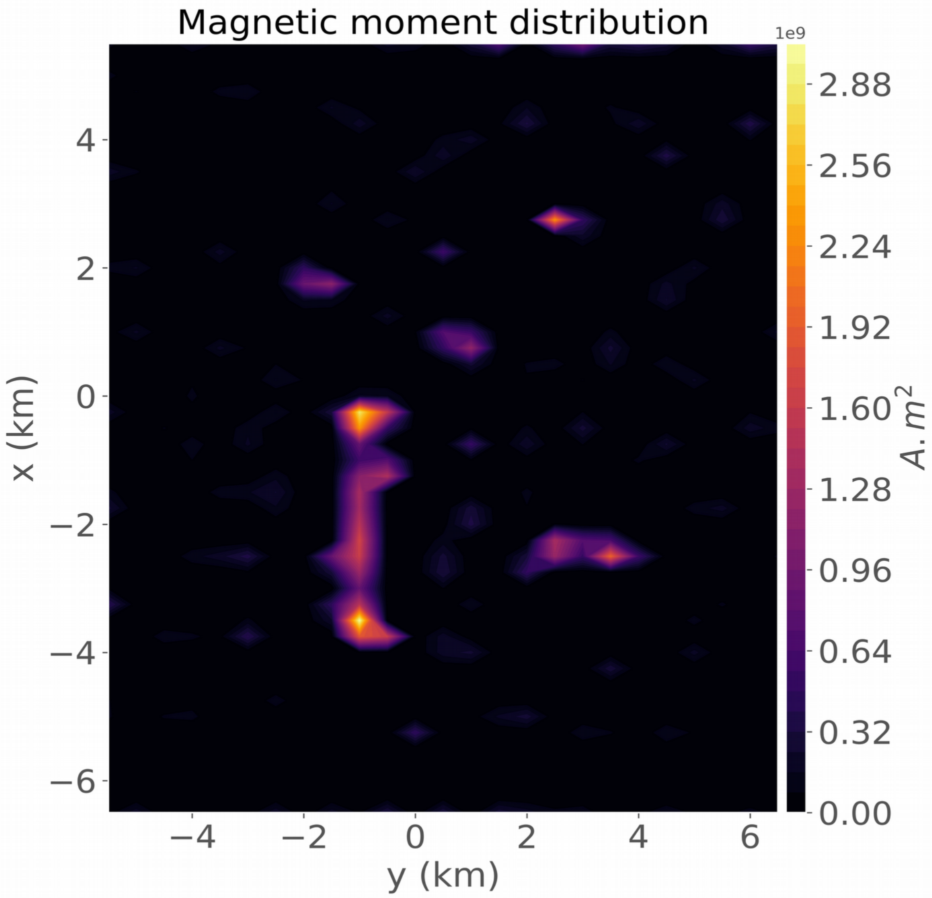
(I,D) = (-25°,30°)

(I,D) = (-28.7°,31.7°)

Data Fitting



Magnetic moment distribution



(I,D) = (-25º,30º)

(I,D) = (-28.7º,31.7º)

Note the positive magnetic moment distribution!

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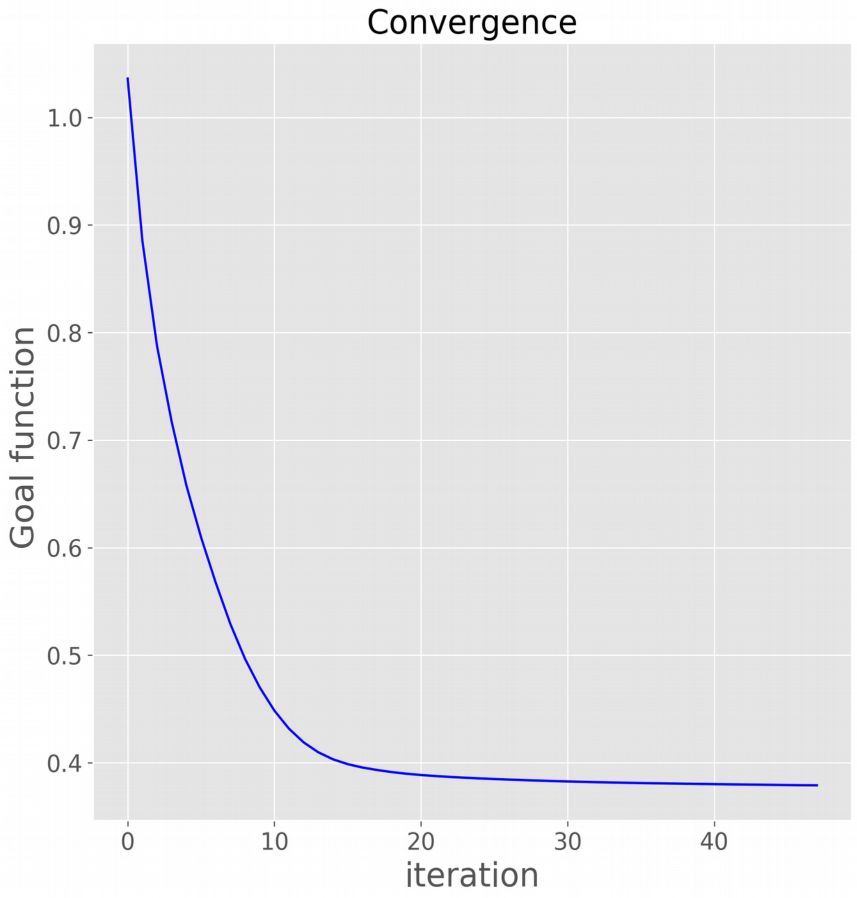
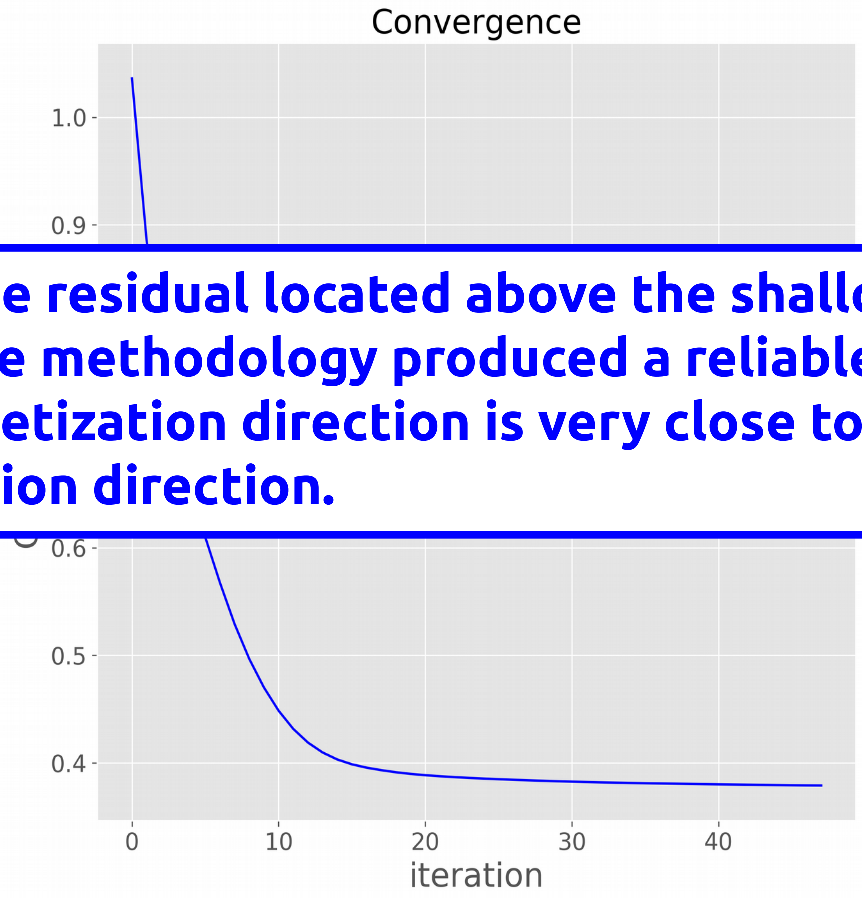
The algorithm convergence



(I,D) = (-25°,30°)

(I,D) = (-28.7°,31.7°)

The algorithm convergence



(I,D) = (-25º,30º)

(I,D) = (-28.7º,31.7º)

Despite the large residual located above the shallow-seated source, we consider that the methodology produced a reliable result because the estimated magnetization direction is very close to the corresponding true magnetization direction.

3. Shallow-seated source with different direction

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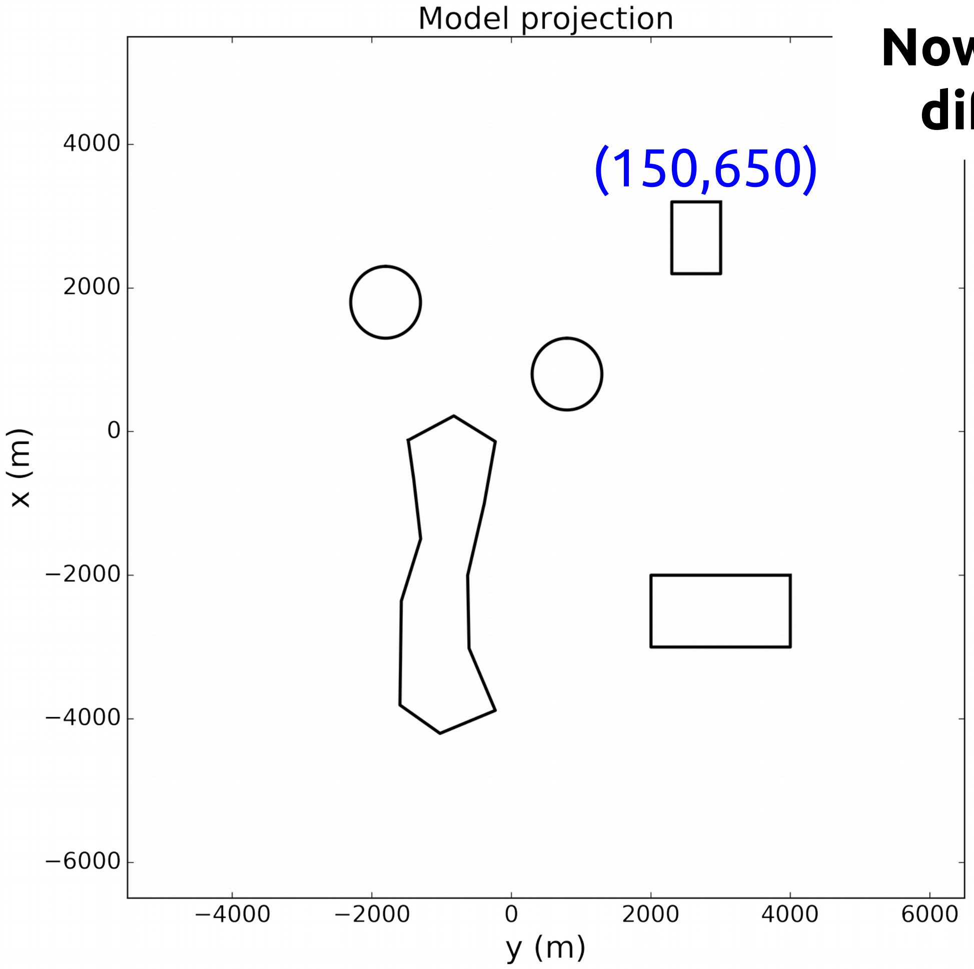
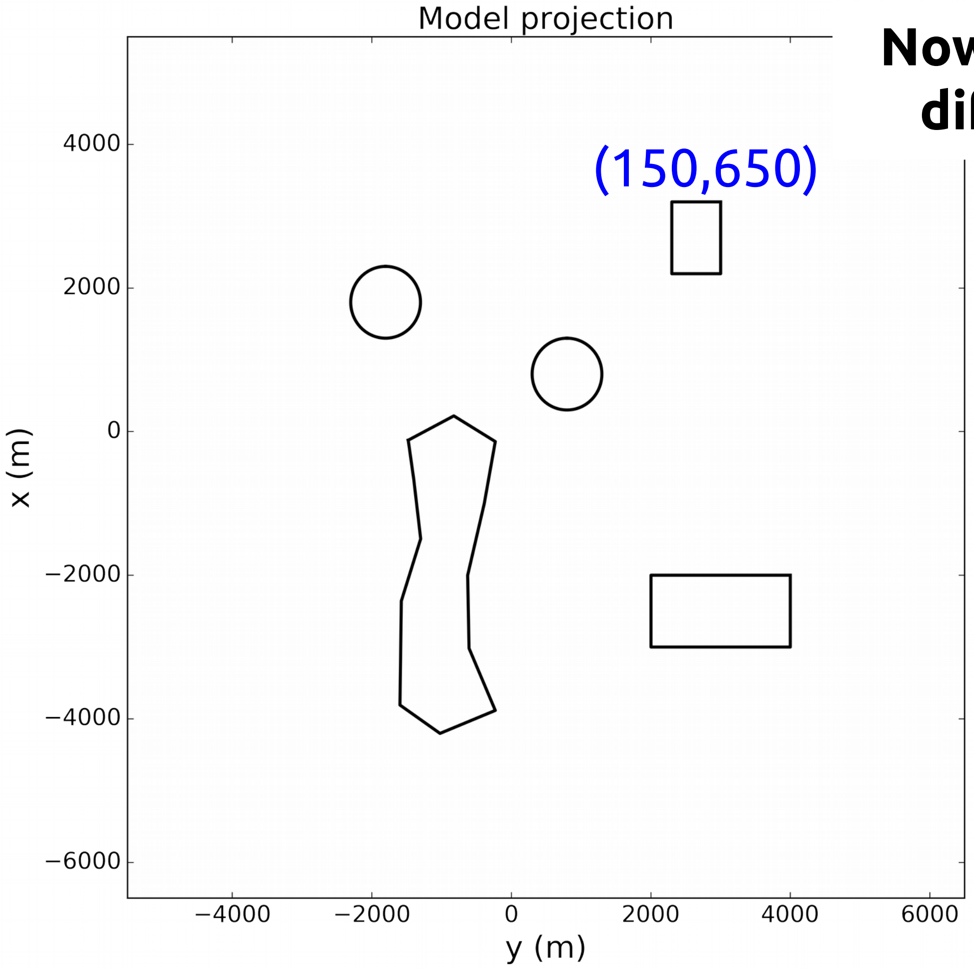


Now the shallow-seated source has a different magnetization direction

(I,D) = (20°,-30°)



Now the shallow-seated source has a different magnetization direction

(I,D) = (20°,-30°)

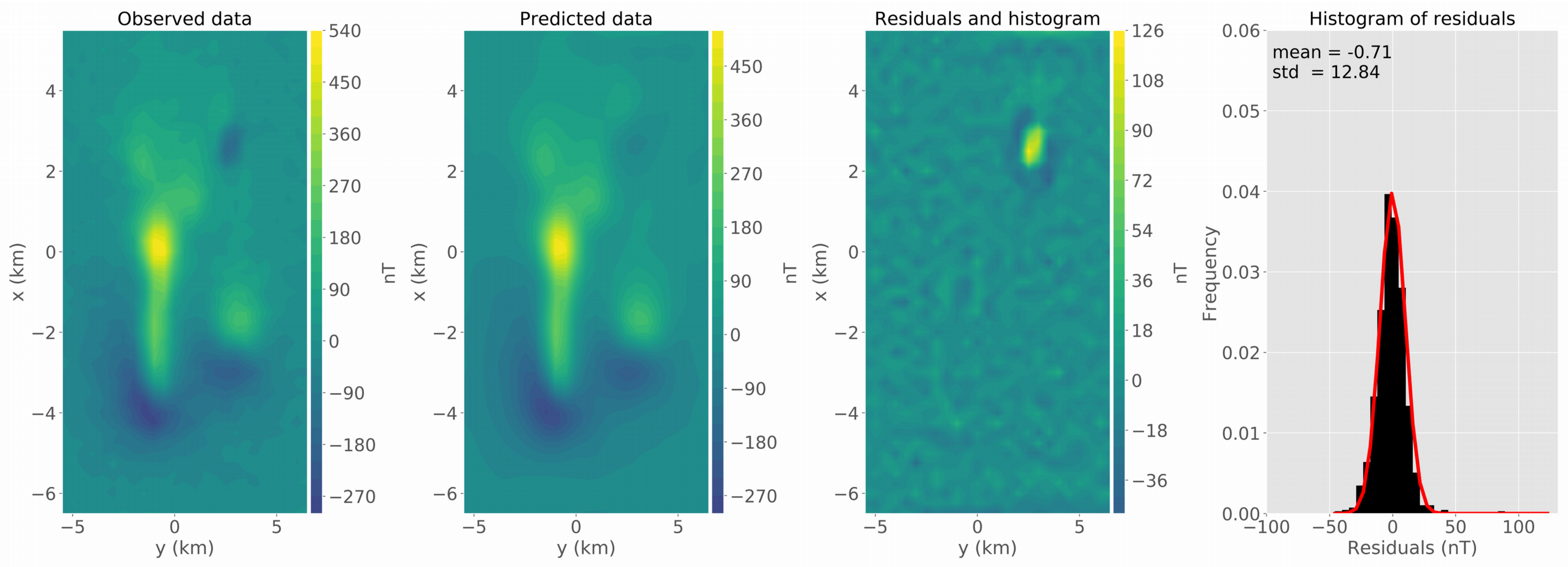
while the other sources:

(I,D) = (-25°,30°)

Data Fitting

(I,D) = (-25º,30º)

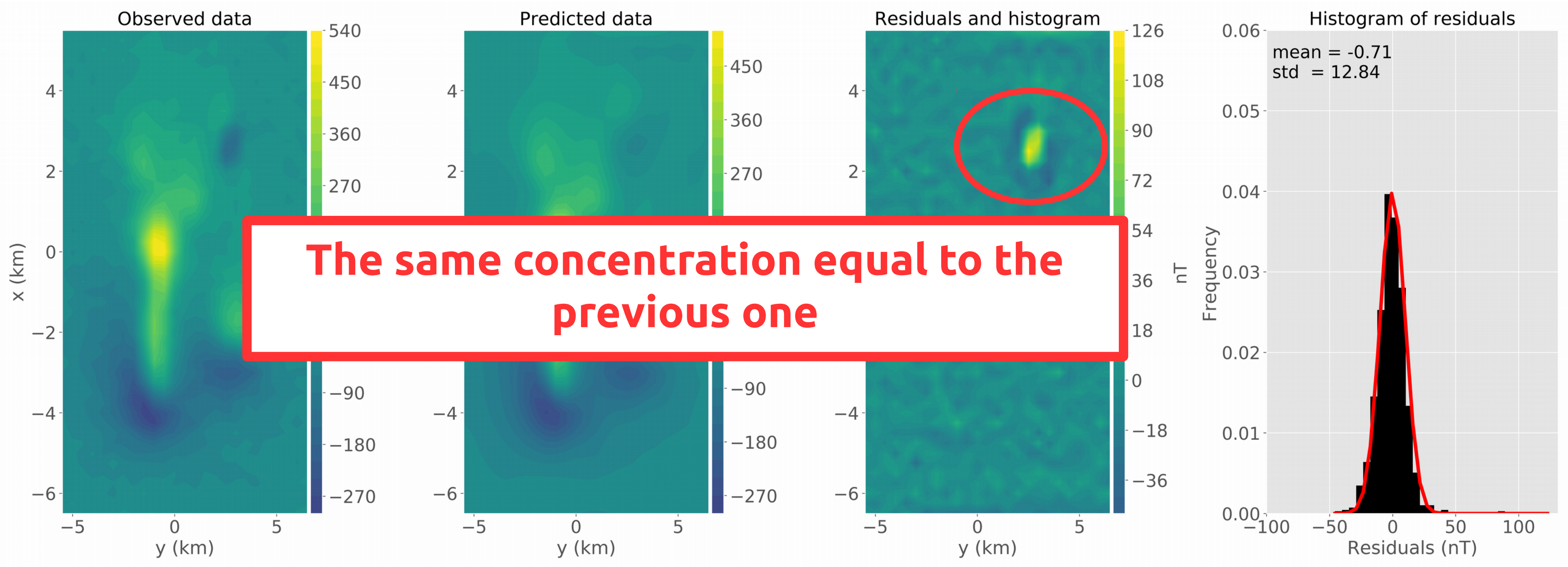
(I,D) = (-30.4º,27.6º)



Data Fitting

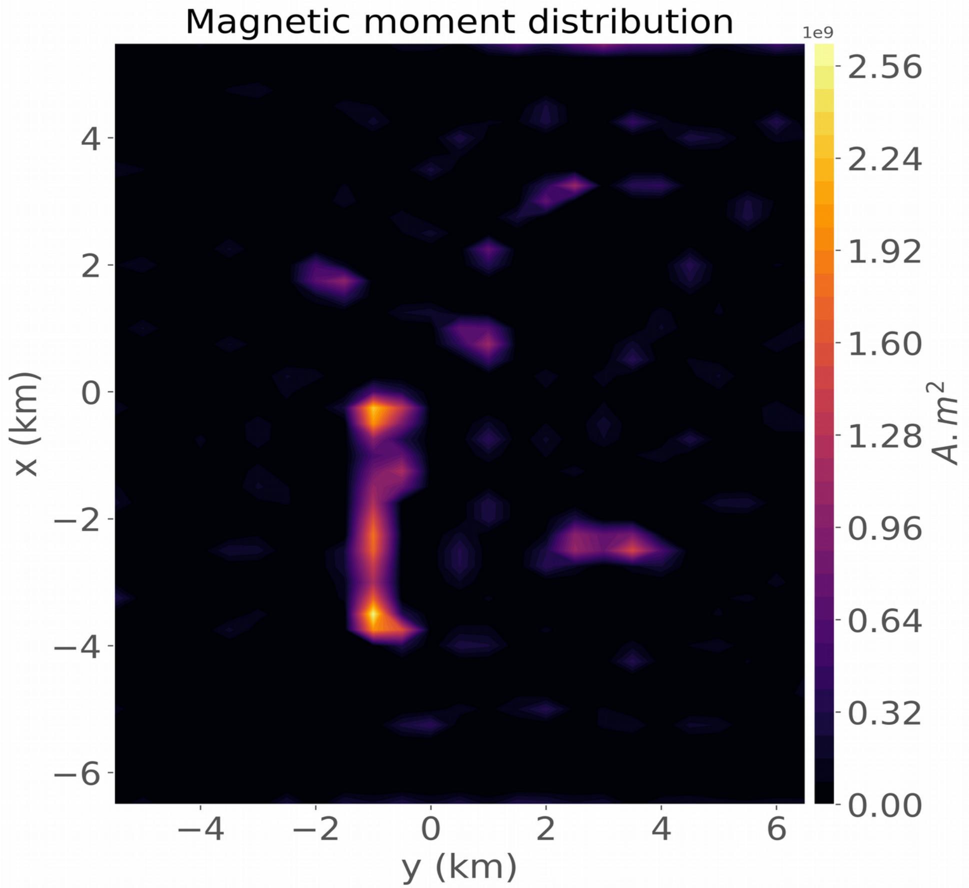
(I,D) = (-25º,30º)

(I,D) = (-30.4º,27.6º)



The same concentration equal to the previous one

Magnetic moment distribution



(I,D) = (-25°,30°)

(I,D) = (-30.4°,27.6°)

Note the positive magnetic moment distribution!

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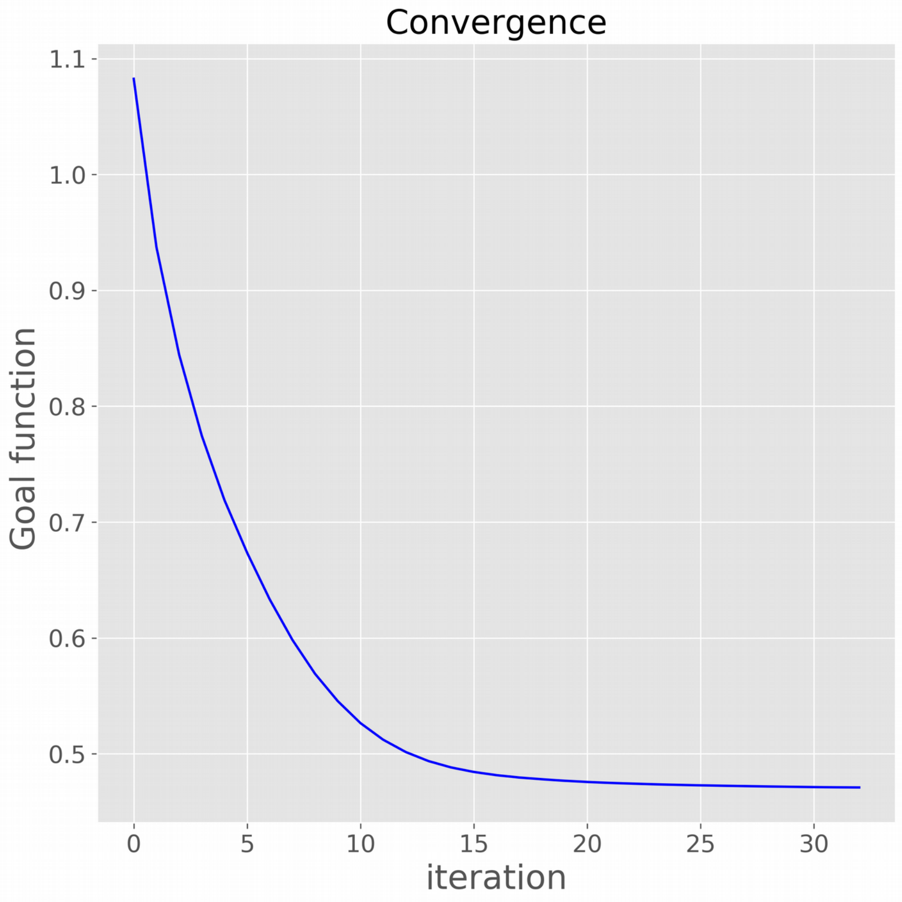
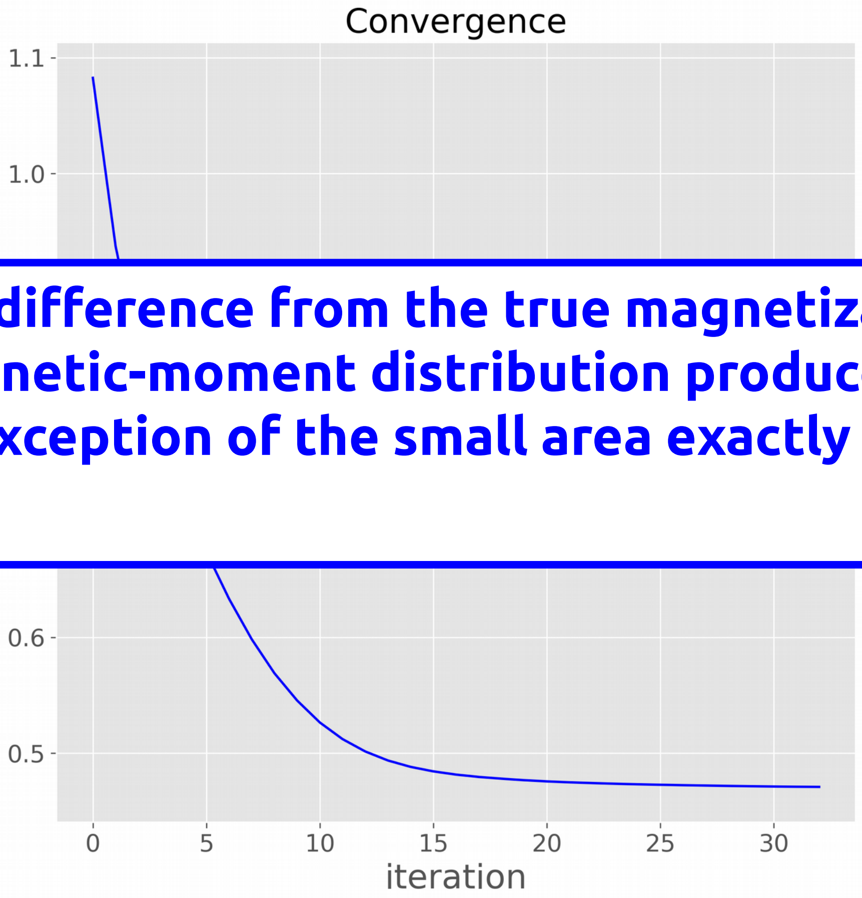
The algorithm convergence



(I,D) = (-25°,30°)

(I,D) = (-30.4°,27.6°)

The algorithm convergence



(I,D) = (-25º,30º)

(I,D) = (-30.4º,27.6º)

Despite the slight difference from the true magnetization direction, the estimated magnetic-moment distribution produces an acceptable data fit, with the exception of the small area exactly above the small-seated prism.

Field data application

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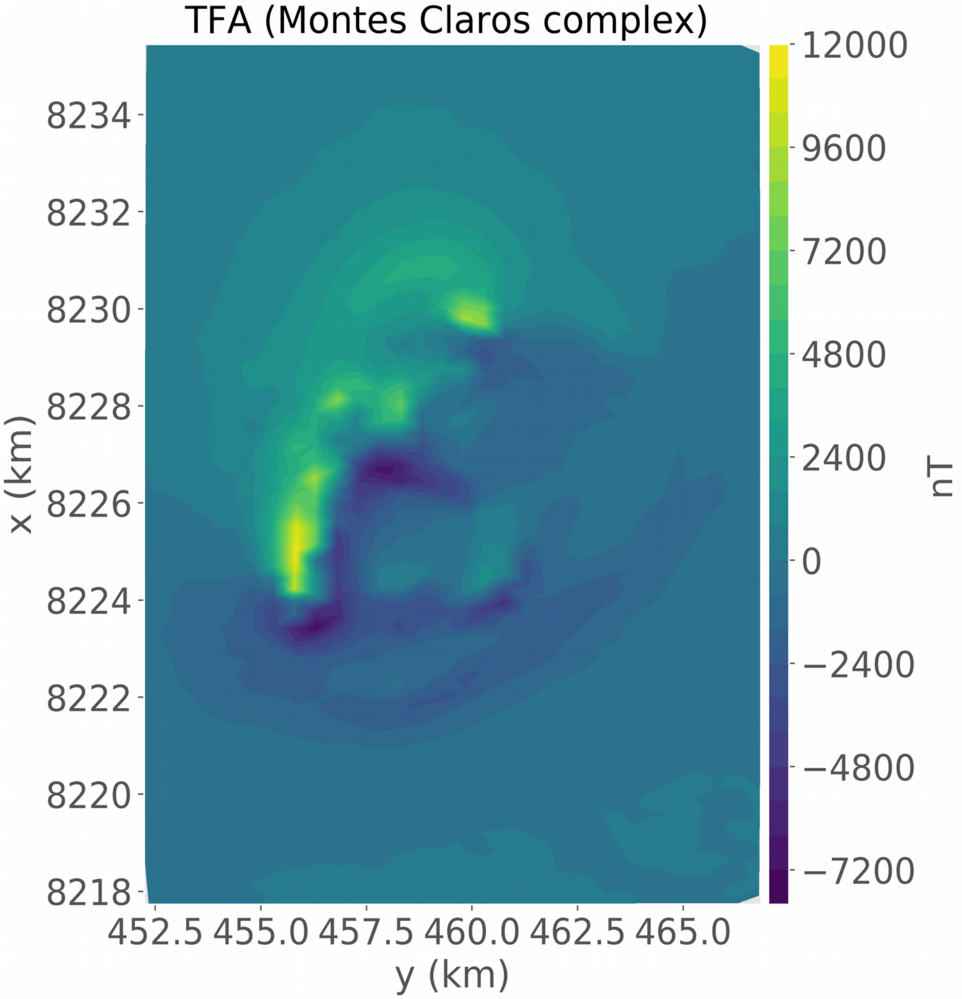
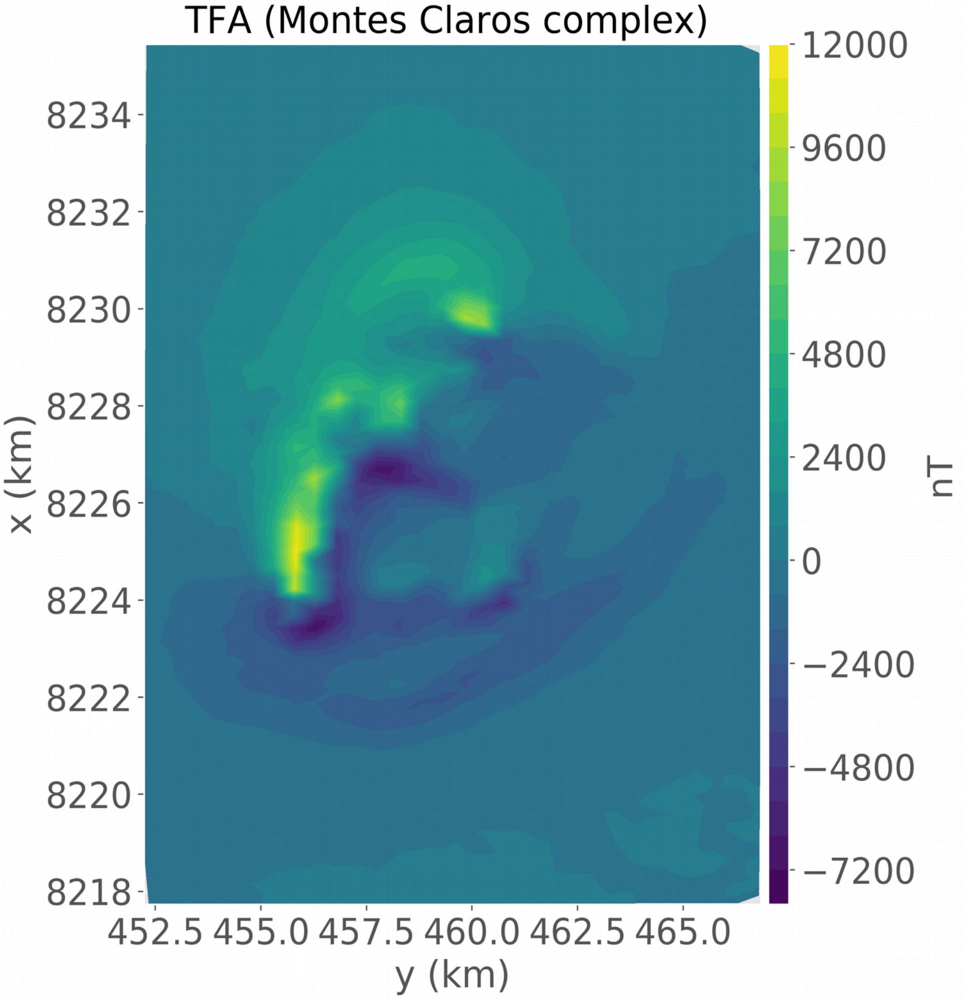
Goiás Alkaline Province (GAP):
Complex of Montes Claros de Goiás





Goiás Alkaline Province (GAP):
Complex of Montes Claros de Goiás

This area was flown with an aeromagnetic survey

The flight height of **100 m**

A total of N=1787 observations

$(I_0, D_0) = -19°, -18°$

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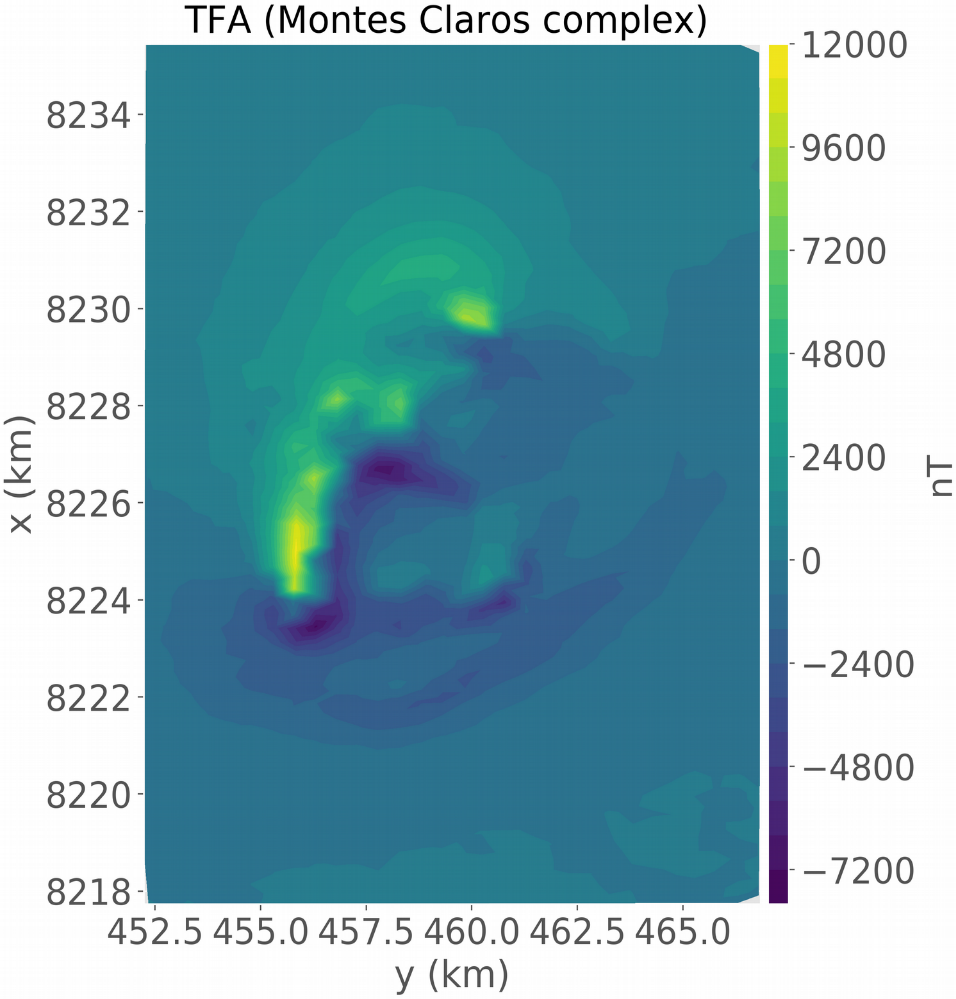


For the inversion

M = 1787 equivalent sources (same number of observations)

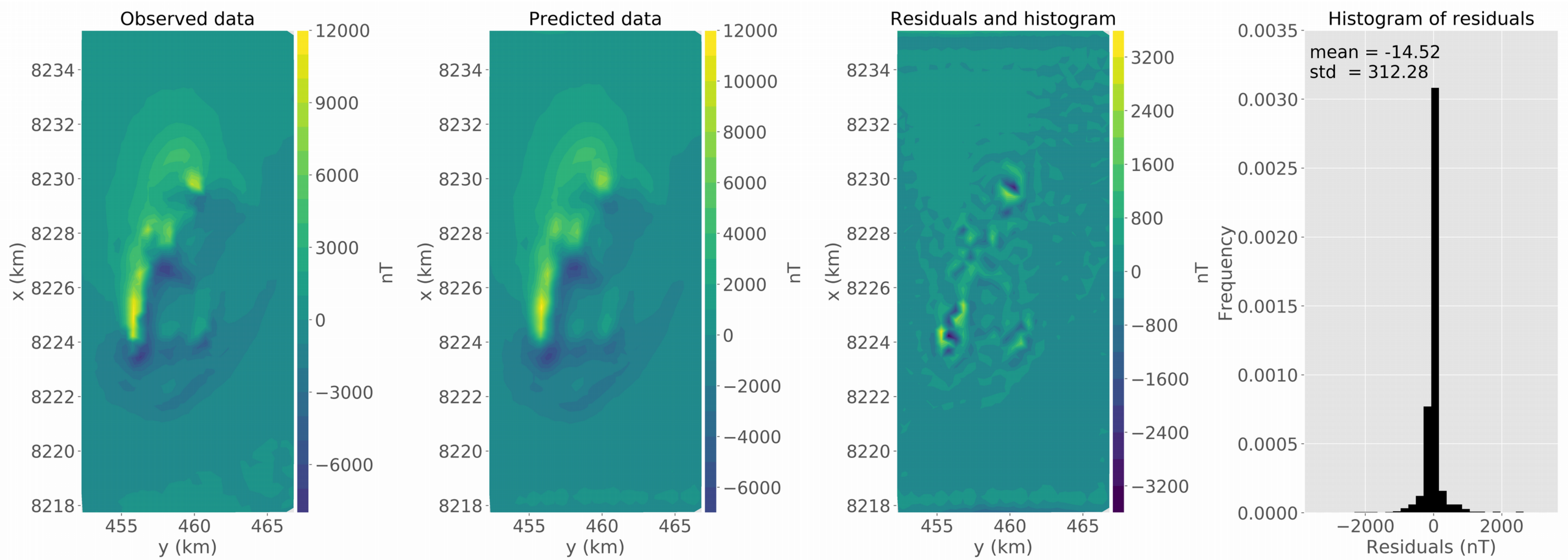
Depth of z = 840 m

L-curve for choosing the regularization parameter proposed by Hansen (1992).

The initial guess of $\mathbf{q}_0$ = (-70°,50°)

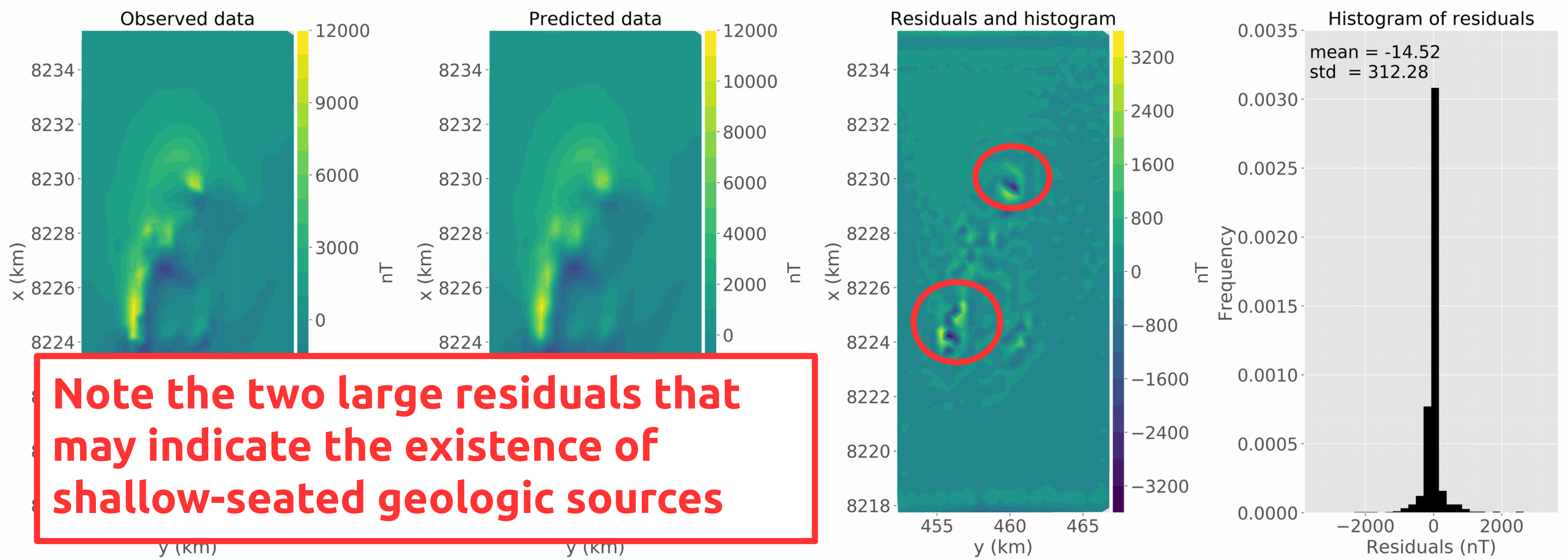
Data Fitting

(I,D) = (-50.2º,34.9º)



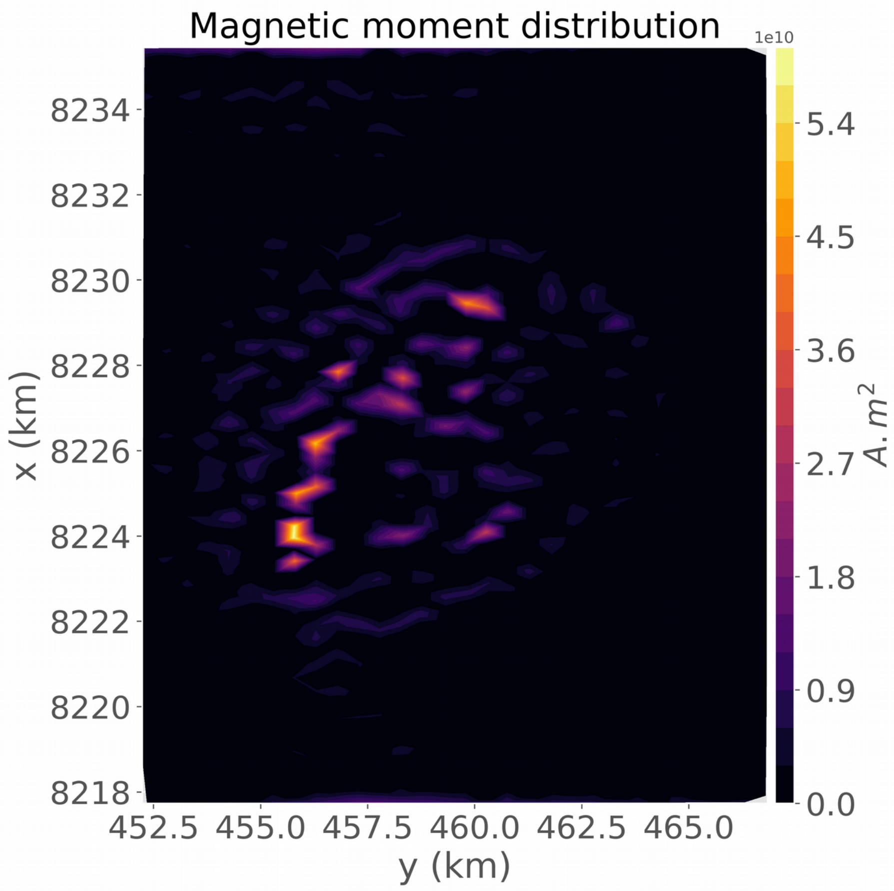
Data Fitting

(I,D) = (-50.2º,34.9º)



Note the two large residuals that may indicate the existence of shallow-seated geologic sources

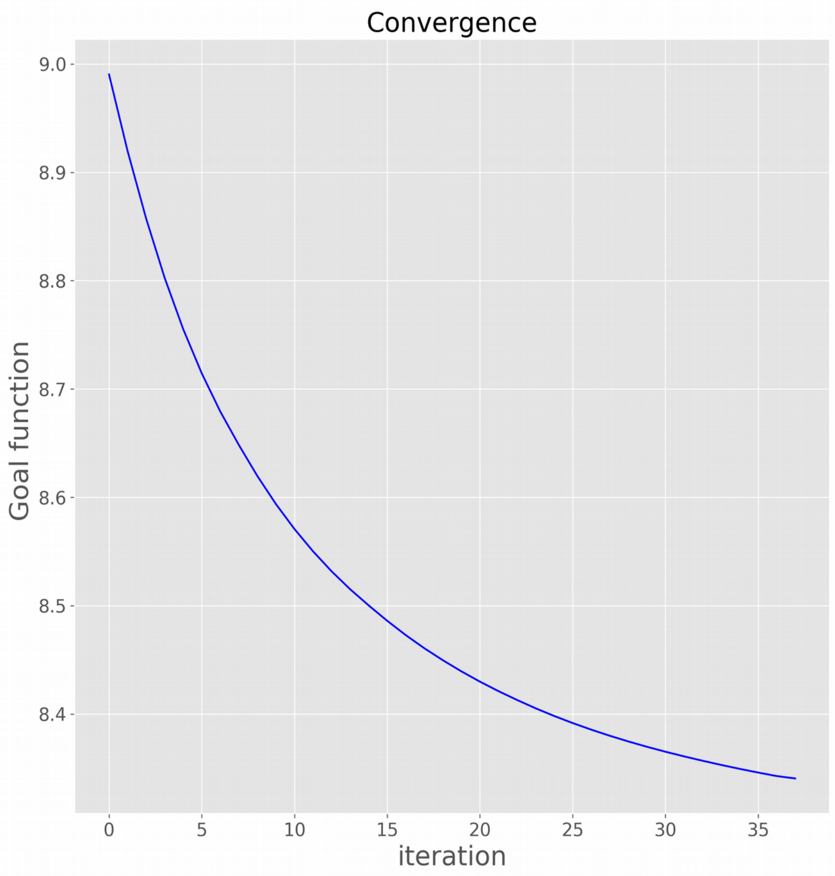
Magnetic moment distribution



(I,D) = (-50.2º,34.9º)

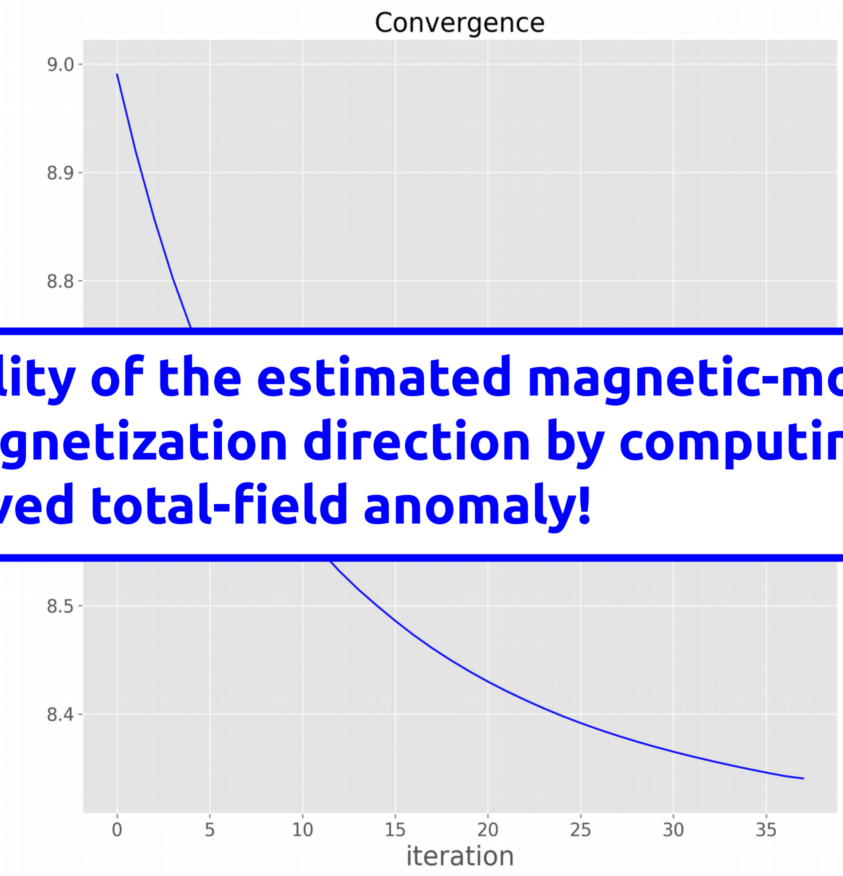
Note the positive magnetic moment distribution!

The algorithm convergence



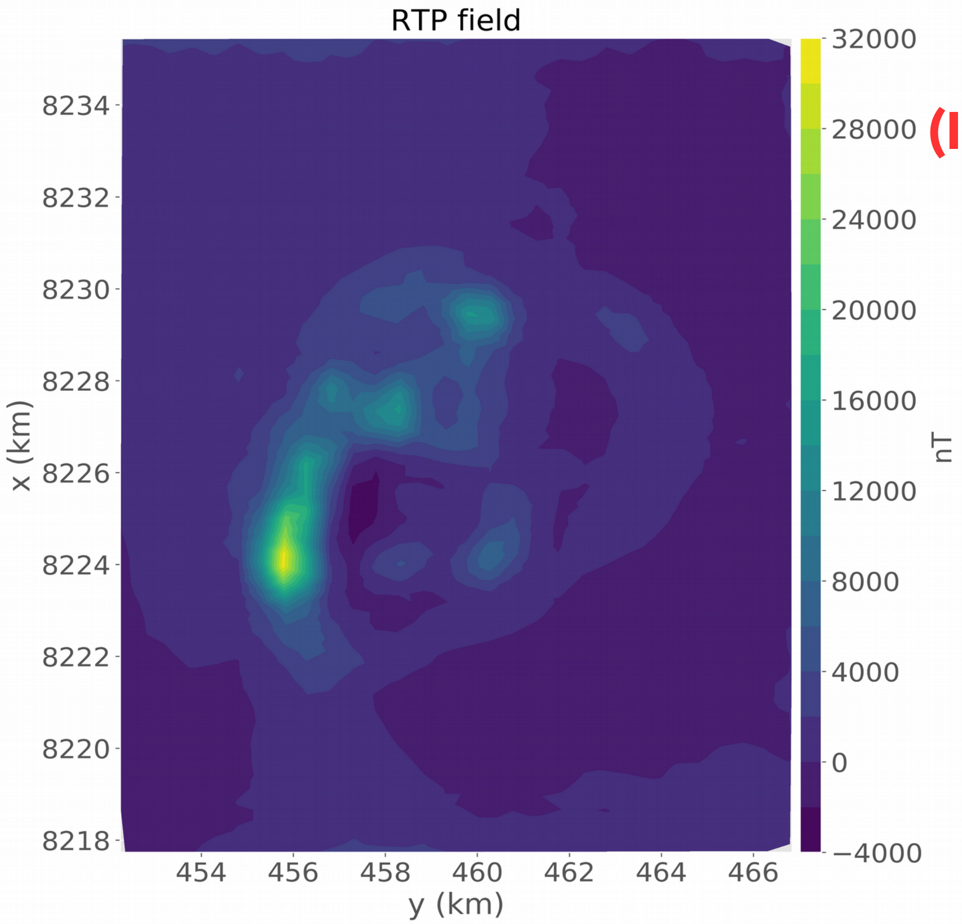
(I,D) = (-50.2°,34.9°)

The algorithm convergence



We check the quality of the estimated magnetic-moment distribution and estimated magnetization direction by computing the reduction-to-pole of the observed total-field anomaly!

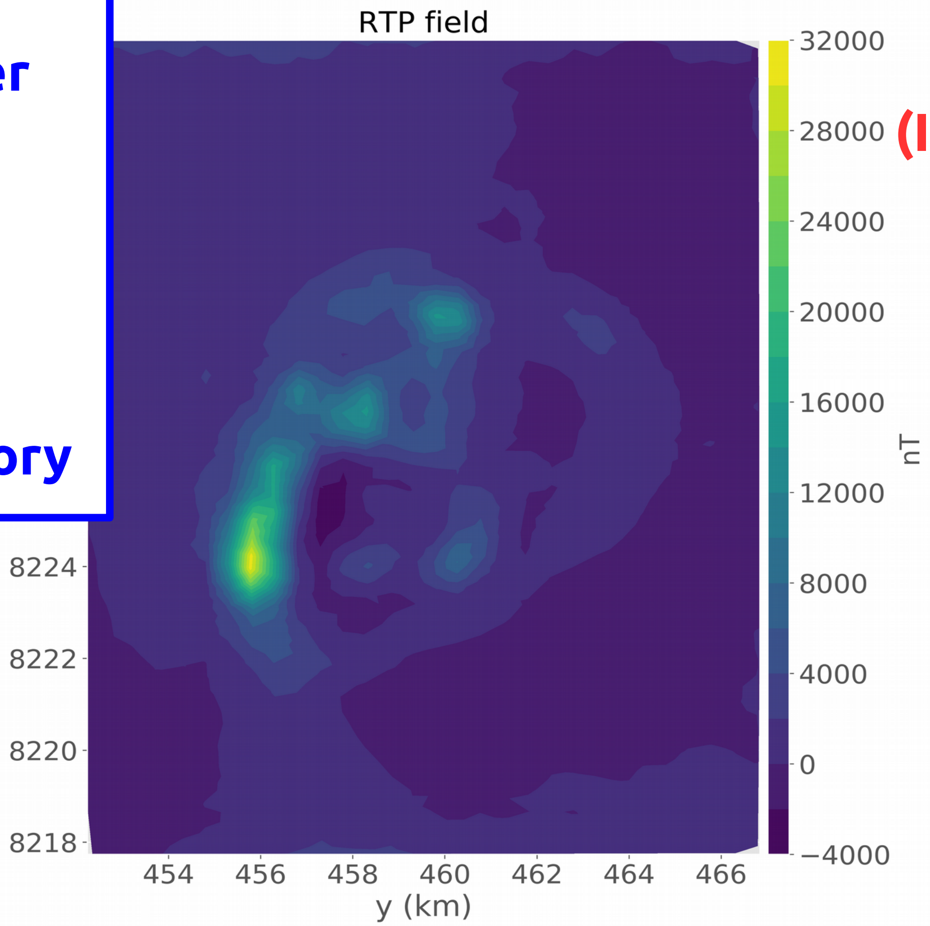
The reduction-to-pole



(I,D) = (-50.2°,34.9°)

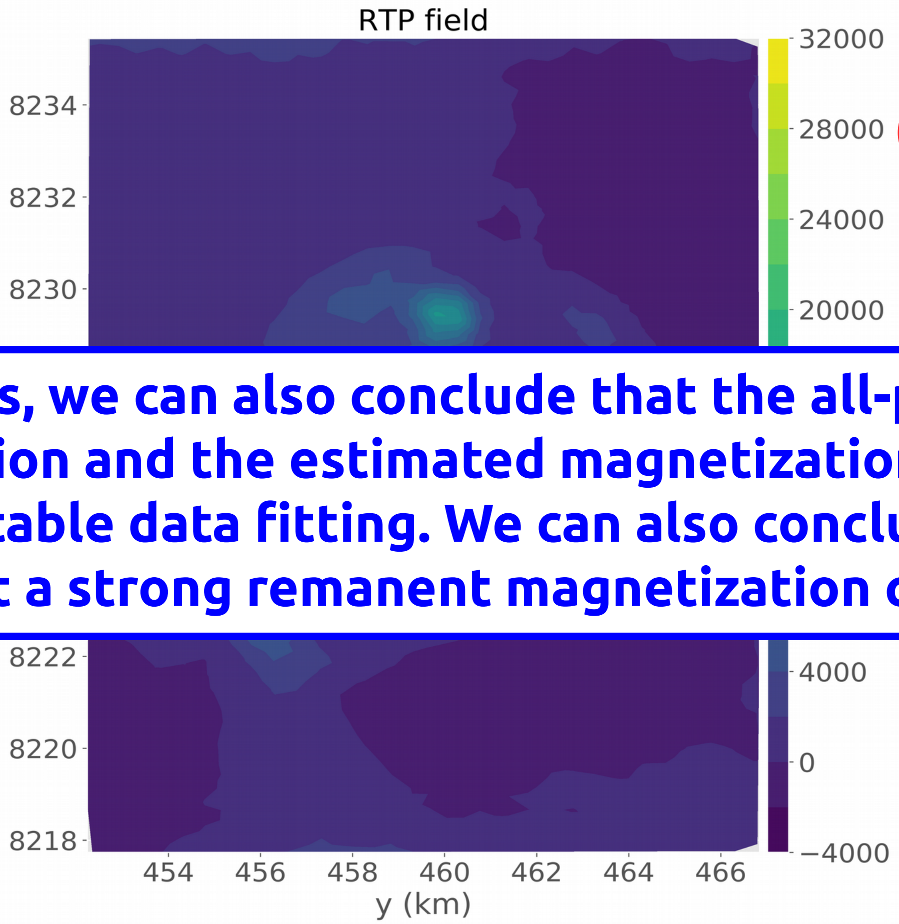
We can note predominantly positive values over the study area. For this reason, we consider the estimated magnetization direction satisfactory

...e reduction-to-pole



(I,D) = (-50.2°,34.9°)

The reduction-to-pole



$(I,D) = (-50.2°,34.9°)$

From these results, we can also conclude that the all-positive magnetic moment distribution and the estimated magnetization direction produce an acceptable data fitting. We can also conclude that these intrusions present a strong remanent magnetization component.

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Conclusions

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- We presented a method for estimating the total magnetization direction with equivalent-layer technique;

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- We presented a method for estimating the total magnetization direction with equivalent-layer technique;

- We propose a nested algorithm for solving the inverse problem in two steps;

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- This method can be applied to estimate the total magnetization direction of multiple sources;

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- We propose a nested algorithm for solving the inverse problem in two steps;

- This method can be applied to estimate the total magnetization direction of multiple sources;

- We show that the positive magnetic-moment distribution can auxiliate the magnetization estimation;

- We presented a method for estimating the total magnetization direction with equivalent-layer technique;

- We propose a nested algorithm for solving the inverse problem in two steps;

- This method can be applied to estimate the total magnetization direction of multiple sources;

- We show that the positive magnetic-moment distribution can auxiliate the magnetization estimation;

- After synthetic tests, we conclude that the method is capable to retrieve the magnetization direction of magnetic sources;

- We presented a method for estimating the total magnetization direction with equivalent-layer technique;
- We propose a nested algorithm for solving the inverse problem in two steps;
- This method can be applied to estimate the total magnetization direction of multiple sources;
- We show that the positive magnetic-moment distribution can auxiliate the magnetization estimation;
- After synthetic tests, we conclude that the method is capable to retrieve the magnetization direction of magnetic sources;
- The field data application confirms that our method can be a reliable tool for interpreting geological scenarios

- We presented a method for estimating the total magnetization direction with equivalent-layer technique;

- We propose a nested algorithm for solving the inverse problem in two steps;

- This method can be applied to estimate the total magnetization direction of multiple sources;

- We show that the positive magnetic-moment distribution can auxiliate the magnetization estimation;

- After synthetic tests, we conclude that the method is capable to retrieve the magnetization direction of magnetic sources;

- The field data application confirms that our method can be a reliable tool for interpreting geological scenarios

- However, despite the reliable magnetization estimate, we cannot infer if shallow sources has the same direction of the final solution.

Acknowledgments:

CAPES

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modeling and inversion | fatiando.org

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PINGA
Grupo de problemas inversos em geofísica
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Thank you!