The ArchaeoMag Project

Ver. 3.3.2 – December 2020

ArchaeoMag 3.3.2 User's Manual

by

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I Introduction

ArchaeoMag is a free computer program for the forward modelling of archaeological magnetic anomalies (Schettino et al., 2018 ; Ghezzi et al., 2018 ; Schettino & Ghezzi, 2020), based on classical algorithms of forward modelling and a new interactive user–friendly GUI. The programme allows to determine geometry, physical properties, and location of buried archaeological features, as well as the occurrence of fires or other historical events that may have affected the observed magnetic signal. The objective is to reconstruct the 3D arrangement of buried features and possibly obtain some information about their history. The *ArchaeoMag* user interface is shown in Fig. 1.

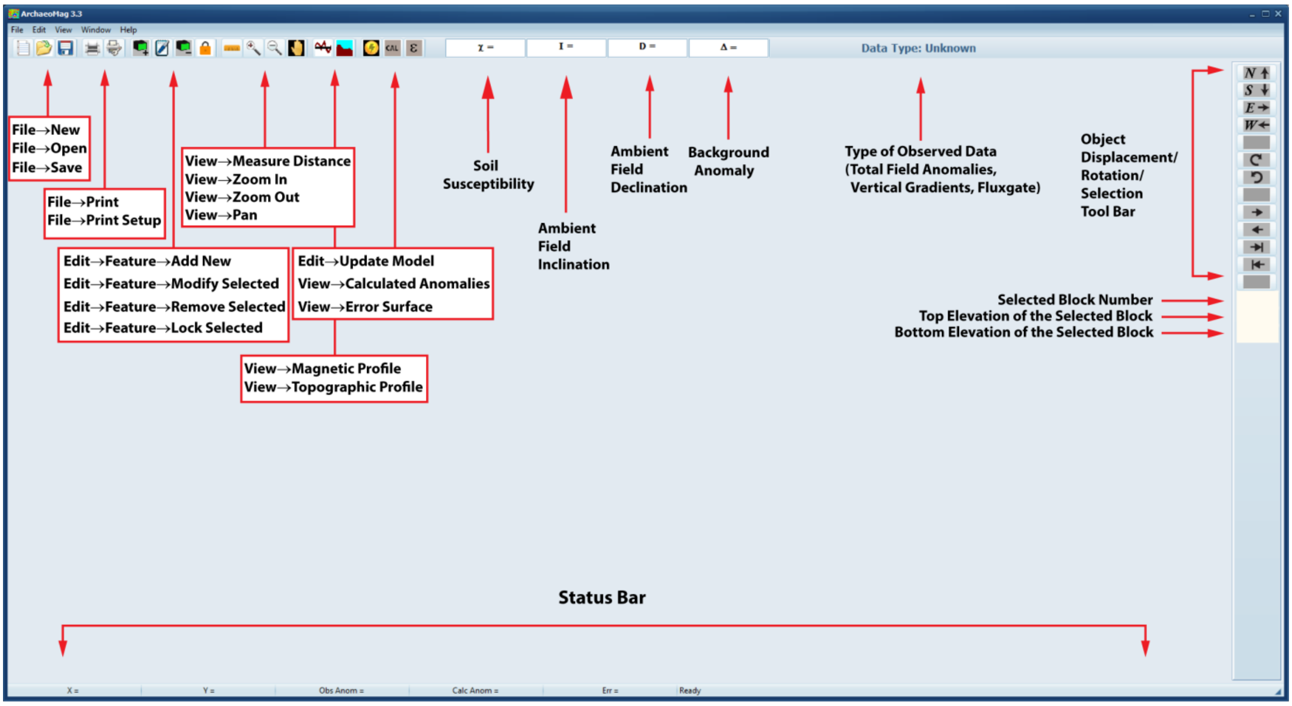

Figure 1. *Archaeomag* main window and user interface.

Specific features of the computer program include:

1. The possibility to load magnetic anomaly grids and visualize them at any scale through an advanced resampling algorithm;

2. Import and gridding of raw magnetic data in ASCII XYZ format;
3. Easy creation and editing of archaeological objects;
4. Interactive modelling by visual comparison of the observed data with the theoretical anomalies generated by the assumed set of buried features;
5. Possibility to model both induced and remnant magnetization;
6. Modelling of total field intensity anomalies, vertical gradients, and fluxgate data;
7. Automatic terrain correction;
8. Assessment of fitting error;
9. Import of features from GPR amplitude maps

The main menu includes the following commands:

File Menu:

- *New Project*: Creates a new project;
- *Open Project*: Opens an existing project;
- *Close*: Closes the open project;
- *Save*: Saves the content of the active window;
- *Save As*: Saves the content of the active window with a specified file name;
- *Import Uncertainty Grid*: Imports a grid of uncertainty for magnetic anomalies;
- *Import GPR Features*: Imports a set of rectangular prisms identified on a GPR amplitude map;
- **Export Submenu:**
    - *Model Blocks*: Exports the current magnetization model to a text file;
    - *Calculated Anomalies*: Exports the current grid of model anomalies;
    - *Gridded Data*: Export gridded observed anomalies to a binary *.flt file;

- *Print*: Prints the content of the active window;
- *Print Setup*: Selects the printer and allows to setup the printer page;
- *Exit*: This command terminates *ArchaeoMag*;

Edit Menu:

- **Feature Submenu:**
  - *Add New*: Creates a new object;
  - *Modify Selected*: Allows to modify the parameters of the selected feature;
  - *Remove Selected*: Allows to eliminate the selected feature;
  - *Lock Selected*: Allows to lock the selected feature;
  - *Unlock All*: Unlocks all the locked features at one time;
  - *Clear All*: Reset of the current magnetization model;
  - *Move North*: Moves the selected object northwards by one grid cell unit;
  - *Move South*: Moves the selected object southwards by one grid cell unit;
  - *Move East*: Moves the selected object eastwards by one grid cell unit;
  - *Move West*: Moves the selected object westwards by one grid cell unit;
  - *Rotate Clockwise*: Rotates the selected object clockwise by one degree;
  - *Rotate CounterClockwise*: Rotates the selected object anticlockwise by one degree;
  - *Select Next*: Selects the next block in a magnetization model;
  - *Select Previous*: Selects the previous block in a magnetization model;
  - *Select first*: Selects the first block in a magnetization model;
  - *Select first*: Selects the last block in a magnetization model;
- **Parameters Submenu:**
  - *Project Settings*: Allows to modify the parameters of the current project;
  - *Pen Styles*: Allows to modify the pen styles for any *ArchaeoMag* drawing;

- *Rotation Angle/Displacement*: Allows to change the angle of rotation associated with *Rotate Clockwise* and *CounterClockwise* commands, and the displacement associated with *Move East/West/North/South* commands;
- *Set Background Anomaly*: Allows to set the background (average) anomaly of the calculated anomalous field to a specific value (default is no correction);

- *Update model*: Re–calculates the model anomalies and updates all the open windows;

View Menu:

- *Measure Distance*: Allows to measure distances in the active window;
- *Zoom In*: Allows to select a rectangle and zoom the current view;
- *Zoom Out*: Returns to the previous zoom level;
- *Pan*: Activates the drag tool to change the current view;
- *Magnetic Profile*: Allows to select the trace of a new magnetic profile;
- *Topographic Profile*: Allows to select the trace of a new topographic profile;
- *Automatic Profile Update*: Flag indicating whether current magnetic profiles are automatically updated after the execution of a model update command;
- *Calculated Anomalies*: Opens the model anomalies window;
- *Error Grid*: Opens the error grid window;
- *Uncertainty Grid*: Opens the uncertainty grid window;
- *Show Features*: Flag indicating whether the current set of magnetized objects must be shown in the calculated anomalies window;
- *Show Background*: Flag indicating whether the background image of observed anomalies must be shown in the project window;

Window Menu:

- *Cascade*: Stacks all open windows and overlaps them so that part of each underlying window is visible;
- *Tile Horizontally*: Arranges the open windows from top to bottom without overlapping one another;
- *Tile Vertically*: Arranges the open windows from left to right so that they display next to each other;
- *Minimize All*: Minimizes all the open windows;
- *Close All*: Closes all open windows

Help Menu:

- *About ArchaeoMag*: Displays the *ArchaeoMag* version and contact information.

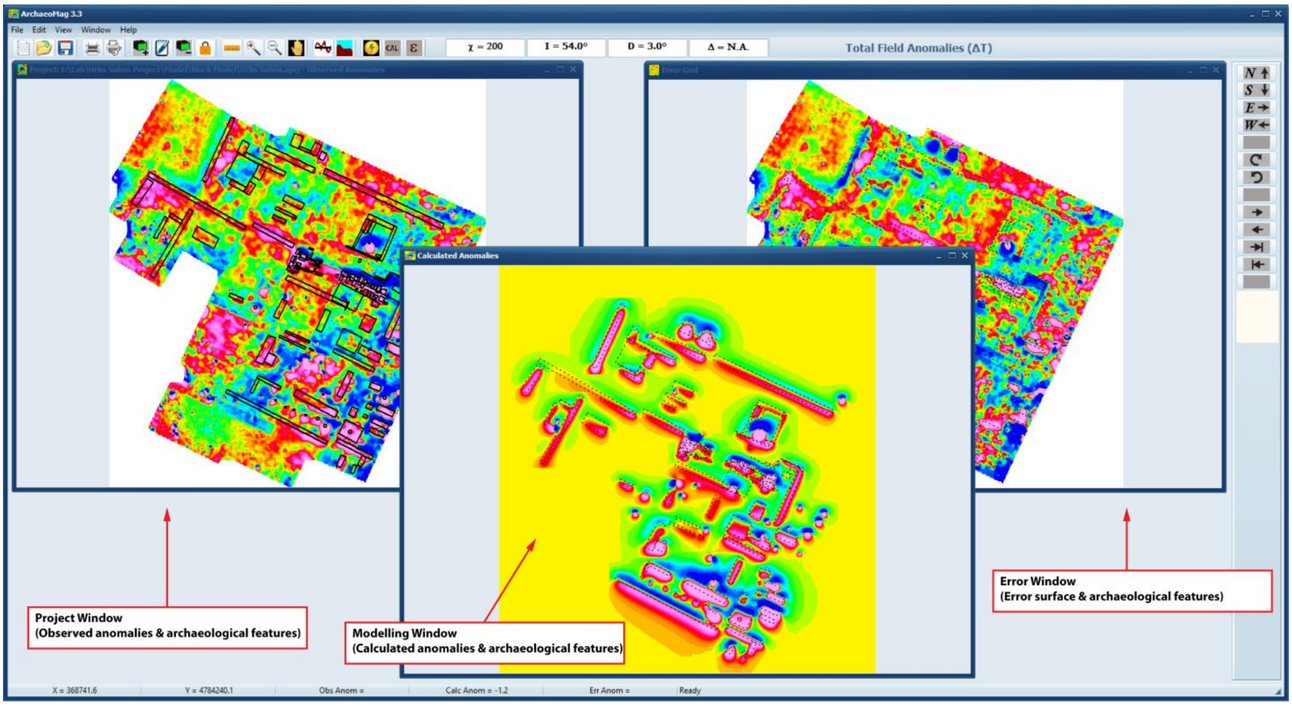

Figure 2. *ArchaeoMag* basic windows.

The modelling module allows to manage three basic kinds of windows: *observed anomaly* (*project*) *windows*, *forward modelling windows*, and *error windows*. An open project is associated with a unique observed anomaly window. Eventually, you can choose to have an open forward modelling and/or an error window. A project window displays observed anomalies, while a forward modelling window shows the anomalies calculated from the current magnetization model. Finally, the error window shows the difference between observed and calculated anomalies (Fig. 2). In addition to these three windows, you can choose to open one or more windows that display magnetic or topographic profiles (Fig. 3), or the uncertainty grid (if loaded). If you close the observed anomalies window, the project is automatically closed. However, you can choose to have no open forward modelling or error windows, because the definition of new blocks or changes to their current set of parameters is done exclusively in the main project window.

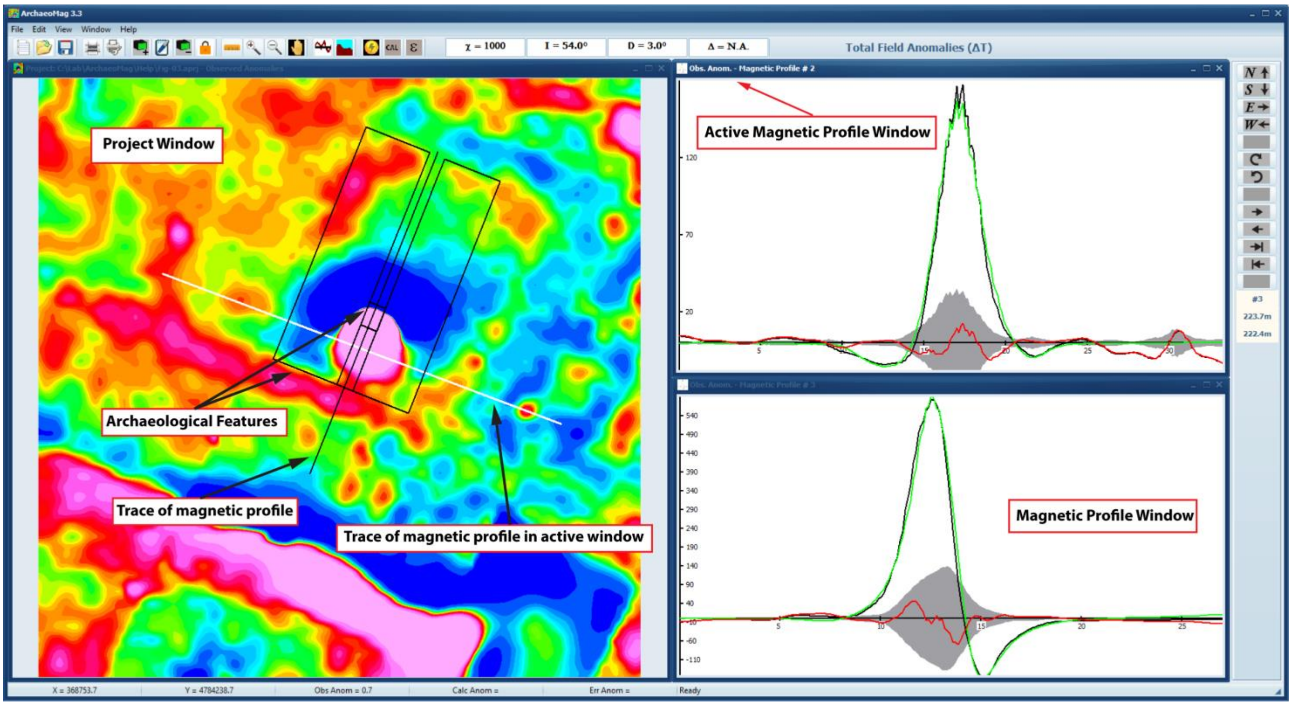

Figure 3. *Archaeomag* profile windows. Green line = Calculated anomaly; Black line = Observed anomaly; Red line = Misfit between observed and calculated anomalies. Gray band shows the local uncertainty.

In general, a modelling session could start with the identification of all dipolar anomalies and their modelling through magnetized spheres. In this instance, the user adds new features selecting Magnetic Dipole in the object property dialog (see below). For each new feature, it is useful to define one or more magnetic profiles across the corresponding anomaly and then run the *Update Model* command to check the misfit between observed and model anomalies in the profile windows (Fig. 3). In this way, the user can modify the object parameters (remnant magnetization, susceptibility, depth, size, etc.) to reduce the misfit.

This procedure is repeated for all the observed dipolar anomalies, until the error is reduced below an acceptable threshold. At the next step, it is possible to consider the anomalies generated by objects having the shape of horizontal prisms and repeat the procedure described above, taking into account that complex observed anomalies may result from the superposition of anomalies generated by nearby objects. Finally, *ArchaeoMag* allows to define composite objects for the modelling of complex structures. In this version (v. 3.0), the unique class of composite objects that can be created is represented by stairway–like structures. Starting from versions 2.x, *ArchaeoMag* also allows to load an uncertainty grid (Ghezzi et al., 2018 ; Schettino et al., 2018 ; Schettino & Ghezzi, 2020), which can be used to stop the forward modelling procedure of an anomaly when the fitting error falls below the local uncertainty. To start a modelling session of an existing project, the user should execute the *Update Model* command, which will calculate the anomaly field for all the existing objects. This initial step could take a considerable time lapse, depending from the performance of your computer, the total number of objects, and the quantity of general vertical prisms in the model. At any successive update, only the field of the modified objects will be recalculated. In addition, it is suggested to have an open window with the calculated anomalies, for comparison with the observed data.

Starting from version 3.0, *ArchaeoMag* allows to model gradiometer data in addition to the usual total field intensity anomalies. When a new project is being created, the user now specifies the kind of observed data, which can be total field anomalies (ΔT), total field vertical gradients ($\partial T/\partial z$) and pseudo−gradients, or fluxgate data ($\partial T_z/\partial z$) (either true gradients or pseudo−gradients). Clearly, in the case of gradiometric data, execution time of modelling routines will take twice as long as that required for total field intensities, because the field values must be calculated at two different locations for each grid location. In version 3.0, *ArchaeoMag* assumed that in the case of gradient data (either total field or fluxgate), the input dataset was formed by pseudo−gradients (differences between values observed at two heights). Starting from ver. 3.1, it is possible to load both pseudo−gradients and true vertical gradients of T and T_z.

II Menu Command Dialogs

2.1 File Menu

File → New Project

This command creates an empty project. A new project parameters dialog window is open, ready to receive information about the ambient field, the soil, and the observation area (Fig. 4).

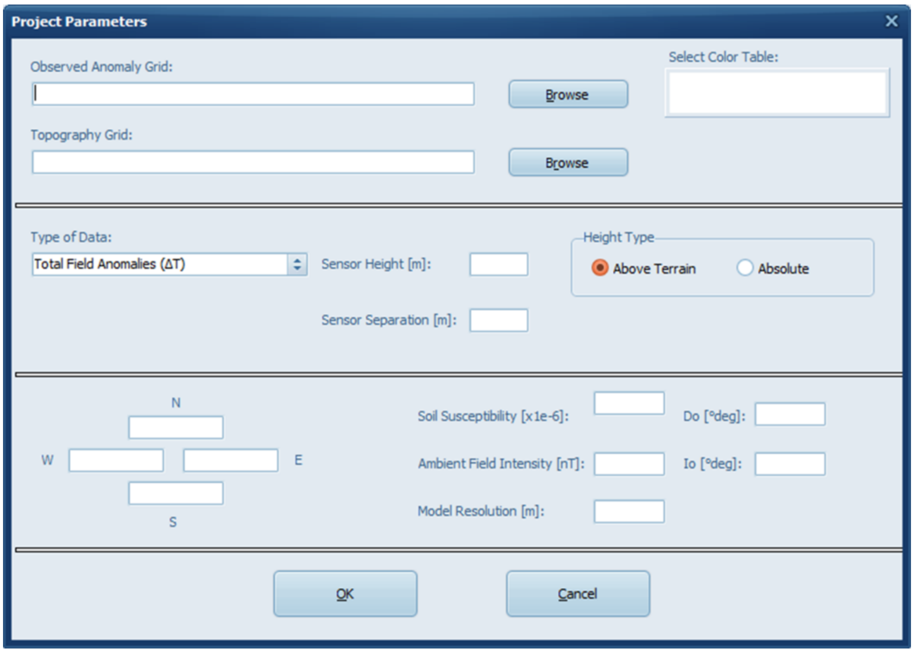

Figure 4. *ArchaeoMag* project parameters dialog.

In the *Observed Anomaly Grid* field the user can specify the path to a (*.flt) grid containing the observed anomalies (directly or selecting the file through the *Browse* button). In the current version, the grid must have *squared* cells with 32–bits floating point values containing magnetic anomaly or gradient data. The file can be easily generated using any GIS software (e.g., GlobalMapper^{TM}) or potential field data processing software (e.g., Surfer™, Oasis Montaj™). It must be accompanied by an ASCII header file (*.hdr), having the same file name but different extension, with the following mandatory rows (and corresponding keywords):

ncols	*number of columns*
nrows	*number of rows*
xllcorner	*X–coordinate of lower-left corner*
yllcorner	*Y–coordinate of lower-left corner*
cellsize	*grid resolution (meters per pixel)*
nodata_value	*numerical value representing absence of datum in a grid cell*

Starting from version 3.3, *ArchaeoMag* allows to import raw magnetic data in ASCII format and perform an automatic gridding. In this case, the user specifies the path of a file having *.xyz extension. The program assumes that this is an ASCII file with rows in the format:

Lon,Lat,Anomaly

where the three fields are separated by commas, tabs, spaces, or semicolons. The raw data are automatically gridded using an Inverse Weigthed Distance algorithm, with parameters *power* = 2 and *slope* = 1. The resulting grid has boundary coordinates based on the minimum and maximum longitude and on the minimum and maximum latitude. The grid resolution is calculated according to the following expression: *res* = sqrt(*Lon range* * *Lat range* / *number of points*) / 4.

ArchaeoMag does not assume a specific map projection for the input grid. You can use either UTM coordinates or a simple local reference frame. However, the program assumes that any location parameter, distance, or size is expressed in meters. The parameters included in the grid header file are used not only for the appropriate display of the background image, but also in a number of other computations. Therefore, it is strongly suggested that the input grid and its header file are generated by standard computer programmes. Once you have selected the correct grid, the program automatically fills the *N–S–E–W* and *Model Resolution* input boxes, which specify survey area limits and grid cell spacing. In this instance, these input fields are disabled and cannot be changed by the user. Alternatively, if you do not provide an input grid of observed anomalies, it is necessary to manually fill these boxes to define the survey area limits and the horizontal resolution of the model.

In the *Topography Grid* field the user can specify the path to a grid containing the relief surface (directly or selecting the file through the *Browse* button), a DTM that must encompass the survey area. This file and its header must have the same format of the anomaly grid but may have different resolution. If you don't specify an input grid of topography, the program assumes that the observed anomalies have been acquired along a flat horizontal surface at some orthometric height.

In order to allow the conversion of anomaly grid values to specific colours, the user must also choose a colour table clicking on the *Select Color Table* box. This opens a dialog box for the selection of a colour table file. This is an ASCII file containing an ordered list of *n* RGB triples that will be used by an histogram equalization procedure to dynamically build colour classes. R, G, and B values should be separated by spaces, tabs, or commas and must be in the 0–255 range. For a better visualization, we strongly suggest to use tables whose colours are compatible with the colour palettes defined in standard geophysical data visualization programmes (e.g., Oasis Montaj™).

The *Type of Data* selector allows to specify what kind of data are stored in the *Observed Anomaly Grid* file. As mentioned above, these data can be total field anomalies (ΔT), total field vertical gradients ($\partial T/\partial z$), or fluxgate data ($\partial T_z/\partial z$), as well as the corresponding pseudo−gradients.

In the *Sensor Height* box the user must specify the elevation (in meters) of the magnetic readings relative to either the terrain or the sea level depending from the selected *Height Type* selector. In the case of gradient data, this value represents the height of the *lower* sensor and the user must also specify the *Sensor Separation* (in m). Even when the input data are real gradients, it is necessary to input a value in this box.

The *Ambient Field Intensity* allows to define the average ambient geomagnetic field intensity F (in nT), which should be representative of both core and crustal fields in the survey area. This value is used by *ArchaeoMag* to calculate an induced magnetization intensity M_I given a magnetic susceptibility contrast $\Delta\chi$ of an archaeological feature: $M_I = \Delta\chi F/\mu_0$, μ_0 being the magnetic permeability of the vacuum: $\mu_0 = 4\pi\times10^{-7}$ H/m. The *Soil Susceptibility* field allows to input a background volume susceptibility, χ_0 (in SI non–dimensional units $\times10^{-6}$) for the soil that surrounds the archaeological features. This quantity is used by *ArchaeoMag* to calculate the magnetic susceptibility contrast $\Delta\chi$ given the susceptibility χ of a buried object: $\Delta\chi = \chi - \chi_0$. Finally, the user must provide a value for the inclination, I_0, and declination, D_0, of the ambient field, which will be used to determine the field axis versor, $\hat{\boldsymbol{F}}$. This vector is used both in the calculation of theoretical total field anomalies and vertical gradients of the total field intensity. It is not effectively necessary in the modelling of fluxgate data. In fact, if $\Delta\boldsymbol{F}$ is the anomalous field generated by a buried object, then the total field anomalies, ΔT_{mod}, and vertical gradients of the total field intensity, $\partial T/\partial z$, are calculated by the following expressions:

$$\Delta T_{\mathrm{mod}} \cong \hat{\boldsymbol{F}} \cdot \Delta\boldsymbol{F} \tag{1}$$

$$\frac{\partial T}{\partial z} \cong \frac{\partial \Delta T_{\mathrm{mod}}}{\partial z} \cong \frac{\partial}{\partial z} \hat{\boldsymbol{F}} \cdot \Delta\boldsymbol{F} \tag{2}$$

Conversely, theoretical fluxgate data are modelled as follows:

$$\frac{\partial T_z}{\partial z} \cong \frac{\partial}{\partial z} \Delta \boldsymbol{F} \cdot \boldsymbol{k} \quad (3)$$

where $\boldsymbol{k}$ is a base versor in the z direction. Once all the necessary information has been input to the program, the user clicks the OK button to close the dialog and start a modelling session.

File $\rightarrow$ *Open Project*

This command allows to open an existing project. A project parameters dialog window is open, which displays the current parameters of the project (Fig. 5). The user can accept the current configuration or modify some parameters before closing the dialog.

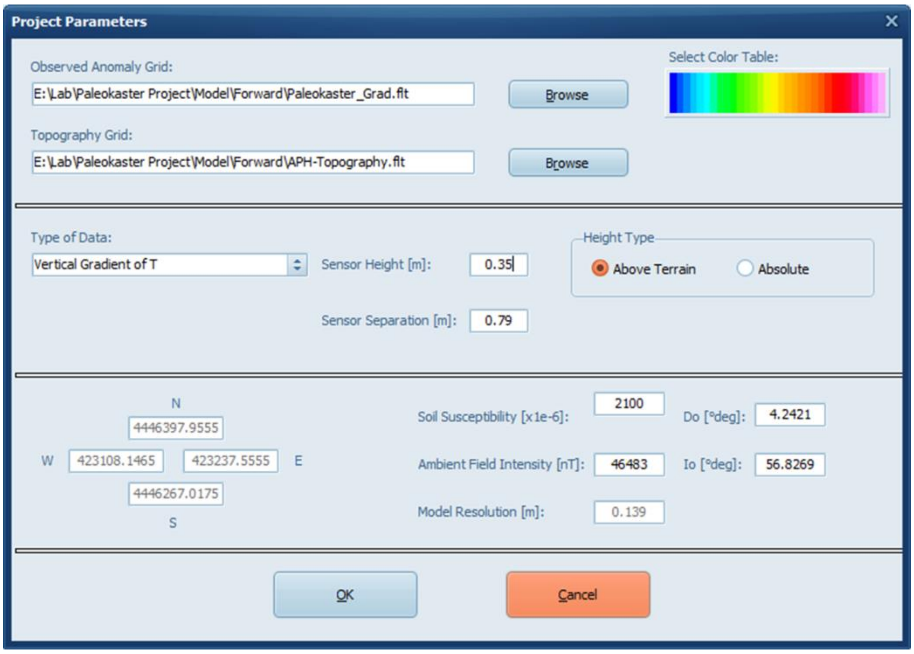

Figure 5. *ArchaeoMag* project parameters dialog for an existing project.

File $\rightarrow$ Import Uncertainty Grid

This command allows to select the path to a grid containing the uncertainty of the observed anomalies or pseudogradients (directly or selecting the file through the *Browse* button). The grid must be a 32–bits floating point file (*.flt) containing uncertainty values. In the case of total field anomalies, these values are obtained multiplying the analytic signal by the half–magnitude of the positioning error and adding a constant uncertainty associated with other errors (Ghezzi et al, 2018 ; Schettino et al., 2018). The file can be easily generated using potential field data processing software (e.g., Oasis Montaj™). It must be accompanied by an ASCII header file (*.hdr), having the same file name but different extension, according to the rules mentioned above.

File $\rightarrow$ Import GPR Features

This command can be used to integrate GPR and magnetic data using the method described in Ghezzi et al (2019). The user must select the path to an ASCII file (*.xyz) containing the UTM coordinates of a set of rectangular prisms. Four vertex coordinates in the format (Lon,Lat) must be provided for each feature. The separator can be a TAB, a comma, a semicolon, or a space. The records can be separated by a blank line or any sequence of lines not starting with a digit. The following default parameters are assigned to each features:

Type = Rectangular Prism;

Units = 1;

Magnetic Susceptibility (χ) = 0.0 SI;

Top burial depth (Z_{top}) = 0.5 m;

Bottom burial depth (Z_{bottom}) = 1.0 m;

Cutoff Distance = 5.0 m;

Induced Magnetization (I_I) = $-\chi_0 F/\mu_0$;

Remnant Declination (D_R) = 0.0°;

Remnant Inclination (I_R) = 0.0°;

Remnant Magnetization (M_R) = 0.0 A/m;

Total Declination (D) = D_0;

Total Inclination (I) = I_0;

Total Magnetization = M_I;

Of course, the user can change these values at any time after the execution of the import procedure.

File $\rightarrow$ Export Model Blocks

This command creates a simple text file (*.xyz) containing the (X,Y,Z) coordinates of all the features included in the model, Z being the orthometric height of the upper block surface. A single row is generated for dipolar sources, while in the case of prisms a point is generated for each vertex in the polygon that represents the upper surface. In this instance, the list of vertices is preceded by a heading row that includes the string: “CLOSED=TRUE”. This is useful if the file must be imported in programs such as GlobalMapper™ to generate closed polygons.

File $\rightarrow$ Export Model Anomalies

This command creates a grid file (*.flt) in binary single precision floating point format with all the calculated anomalies. It works when a *Calculated Anomalies* window is open. This kind of grids can be read by any GIS or potential fields software.

File $\rightarrow$ *Export Gridded Data*

This command only works when you have performed an import of raw magnetic data in the *xyz* format. The command creates a grid file (*.flt and *.hdr) in binary single precision floating point format with the gridded observed data, which can be loaded in subsequent sessions.

2.2 Edit Menu

Edit $\rightarrow$ *Feature* $\rightarrow$ *Add New*

This command creates a new archaeological feature. An object parameters dialog window is then open (Fig. 6), where the user can specify the object geometry, its depth, height and magnetization, and the maximum E–W and N–S distance from the centroid (*Cutoff Distance*) at which the program calculates model anomalies. The latter parameter is necessary to improve the program performance, because it avoids that the anomalies of each object in the model are calculated over the entire survey area, even at distances where their amplitude is negligible. It is strongly suggested to start with a cutoff distance of 5–10 m, depending from the feature size, and adjust this parameter for all the features to a higher value (e.g., 20 m) only when the model is complete for the whole area. Of course, this adjustment will require a final check of the goodness of fit.

The object geometry can be chosen among three basic classes of shapes, corresponding to common archaeological features: 1. Spheres (magnetic dipoles), 2. Rectangular prisms, 3. Generic vertical prisms, and 4. Cylinders (Fig. 7). In the present version, it is also possible to select a composite stairway–like object formed by *n* rectangular prisms. Future versions will allow selection of a larger number of basic or composite shapes.

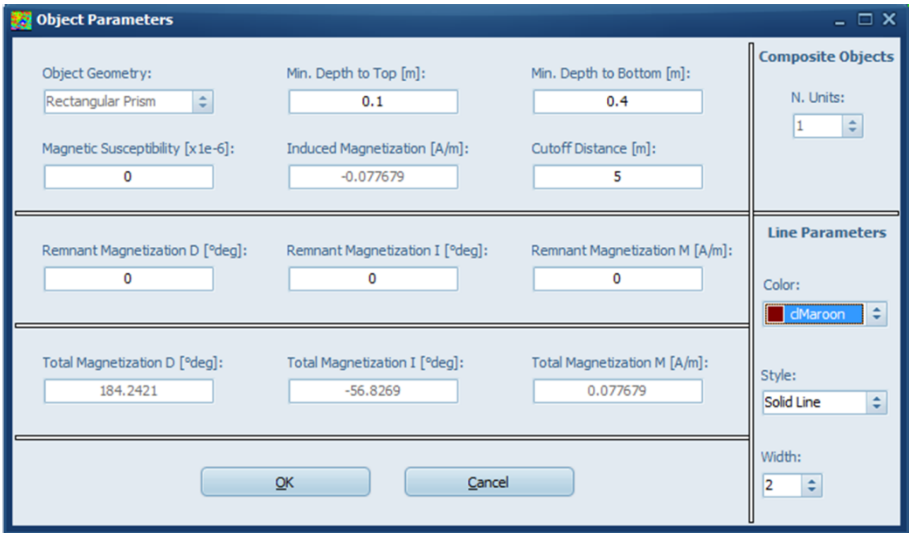

Figure 6. *ArchaeoMag* object parameters dialog.

For any object, the object parameters dialog allows to specify the minimum and maximum burial depths, the magnetic susceptibility, χ, and a remnant magnetization vector (M_R,D_R,I_R).

The program calculates automatically the induced magnetization vector, $\boldsymbol{M}_I$, and the total magnetization vector, $\boldsymbol{M}$, by the following equations:

$$\boldsymbol{M}_I = \frac{\chi - \chi_0}{\mu_0}\boldsymbol{F} \equiv \frac{\Delta\chi}{\mu_0}\boldsymbol{F} \tag{4}$$

$$\boldsymbol{M} = \boldsymbol{M}_I + \boldsymbol{M}_R \tag{5}$$

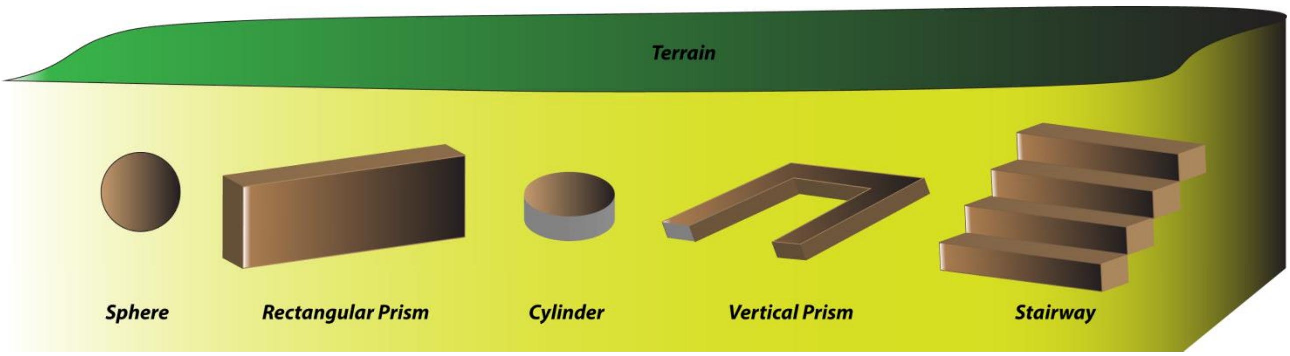

Figure 7. Basic shapes allowed in *ArchaeoMag* for the definition of magnetized bodies.

For each feature, you can select the drawing style through the three selection boxes in the *Line Parameters* pane (Fig. 6). Please note that in Microsoft Windows non–solid lines can have only unitary thickness. The *N. Units* selection box is enabled only in the case of composite objects. In the present version, it allows to specify the number of steps in the stairway. Once the user confirms the parameters pressing the *OK* button, the program enters the *Create/Modify* mode and waits for the mouse input of a number of vertices depending from the object geometry. In the case of a dipolar source, a single mouse click is sufficent to define the centre of a magnetized sphere. Rectangular prisms require the input of only three vertices, because the location of the fourth one is calculated automatically by the program, in order to guarantee that the object has a perfectly rectangular shape. To create a generic vertical prism having *n* vertical rectangular facets, the user inputs *n* vertices and then exits the *Create/Modify* mode by a mouse right–click. Creation of a stairway is as simple as the creation of a rectangular prism, because the user simply specifies the vertices of its horizontal projection by clicking three points on the screen. Then, the program automatically calculates the thickness and size of each step. Finally, to create a cylindrical object (column, skylight, etc.) the user clicks a starting location and then drags the mouse to a new location. When the mouse is released, the program will create a cylinder passing through these two points.

If, at a later time, the user wants to modify parameters, shape, position, or orientation of an existing feature, it is sufficient to click within the area occupied by the object to enter the *Modify mode* (Fig. 8). This operation allows to delete the feature by the command *Edit→ Feature → Remove Selected* or simply pressing the *Del* key. It is also possible to change the object parameters through the *Edit→ Feature → Modify Selected* menu command. Finally, it is also possible to move or rotate the object using the right tool bar or corresponding menu commands (Fig. 1). In the *Modify mode*, it is also allowed to change the shape of a prism dragging, removing, or inserting a vertex. To this end, the user must click on the vertex that needs to be moved, deleted, or followed by a new vertex (Fig.

8). This vertex is then highlighted in red. To remove the selected vertex, the user presses the *Del* key, while to insert a new vertex it is sufficient to press the *Ins* key. Finally, a selected vertex can be dragged by the mouse and moved to a new location. To modify the diameter of a cylinder, it is sufficient to select a boundary vertex (which will be displayed in red) and drag it outwards or inwards to increase or reduce the diameter, respectively. You can also use the ruler to measure the exact diameter of a cylinder and eventually proceed to modify it.

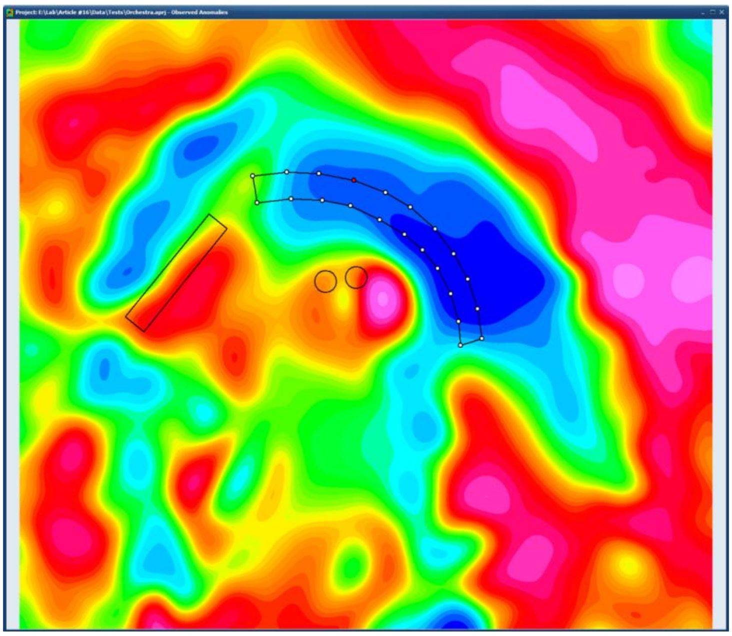

Figure 8. A selected vertical prism, whose vertices are highlighted by white dots. The red dot indicates a vertex that has been selected to be moved, deleted, or followed by a new additional vertex.

Edit → Feature→Lock Selected

This command allows to freeze a block, in such a way that it cannot be modified anymore. This is useful when you have overlapped blocks and cannot select a feature clicking inside the representative polygon, because it is enterely encapsulated in another larger polygon.

Edit → Feature→Unlock All

This command allows to unlock all the locked blocks at one time.

Edit → Feature→Clear All

This command deletes all the blocks in a magnetization model

Edit → Feature→Move North/South/East/West

This set of four commands allows to translate rigidly a block in N−S or E−W direction.

Edit → Feature→Rotate Clockwise/Counterclockwise

These commands allows to rotate a block

Edit → Feature→ Select First/Last/Next/Previous

This set of commands allows to browse through the list of blocks that compose a magnetization model. The number of the currently selected block is displayed just below these buttons, together with its maximum and minimum elevation.

Edit → Parameters → Project Settings

This command allows to modify some parameters of the current project. A project parameters dialog window is created (Fig. 9), which allows to change the data acquisition parameters and the anomaly rendering colour table, but not the survey area and topography grids. Once the user has confirmed the new values pressing the *OK* button, the program automatically launches an update of the anomalies and the basic windows are redrawn.

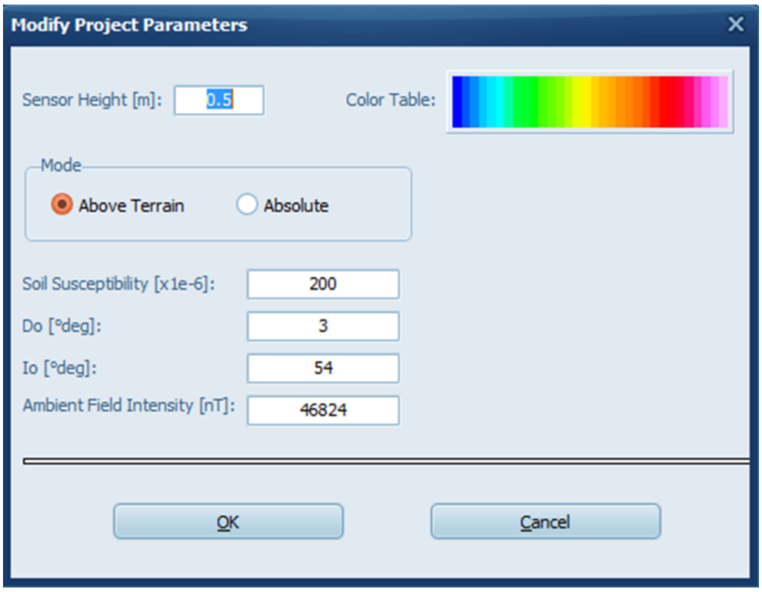

Figure 9. Dialog for modifying the open project parameters.

Edit $\rightarrow$ *Parameters* $\rightarrow$ *Pen Styles*

This command allows to modify the style of all the pens used in the current project. The pen style parameters include a *Style* (solid, dashed, etc.), an RGB colour, and a thickness. The dialog illustrated in Fig. 10 shows the user interface to change these values. It should be noted the unique allowed *Style* for pens having thickness greater than one is *Solid Line*, independently from the user selection.

Edit $\rightarrow$ *Parameters* $\rightarrow$ *Rotation Angle/Displacement*

This command allows to modify the angle of rotation associated with commands that rotate features about their centroid. It also allows to change the amount of displacement associated with *Move* commands. The dialog illustrated in Fig. 11 shows the user interface to change the value of these parameters.

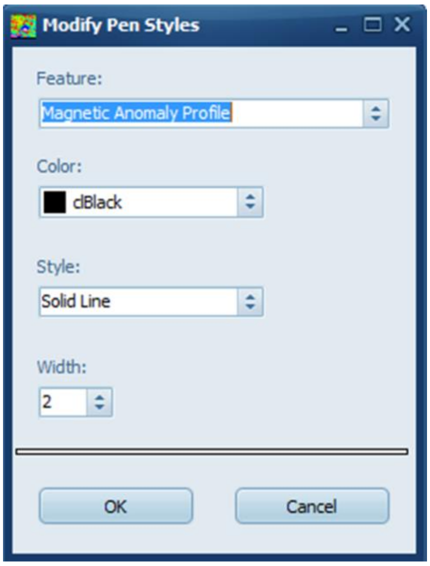

Figure 10. Dialog for modifying the pen style parameters.

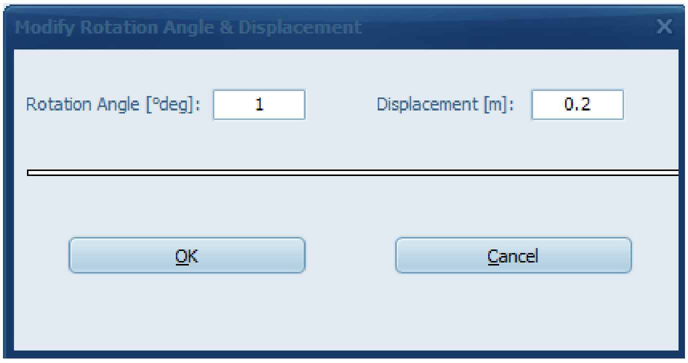

Figure 11. Dialog for modifying the rotation angle and displacement.

Edit $\rightarrow$ *Parameters* $\rightarrow$ *Set Background Anomaly*

This command allows to constrain the spatial average of the theoretical anomaly field to a specific value, the default being no correction. The dialog illustrated in Fig. 12 shows the user interface to change the value of this parameter. You should leave this field empty in order to disable any reduction of the calculated anomaly field average to a specific value. This command should be used carefully, because when a background anomaly is assigned, any addition of new blocks forces a reduction of the average to the assigned background anomaly. Consequently, any previous fit of theoretical anomalies to observed values is changed by a constant offset.

Edit → Update Model

This command allows to calculate the model anomalies and update all the open windows.

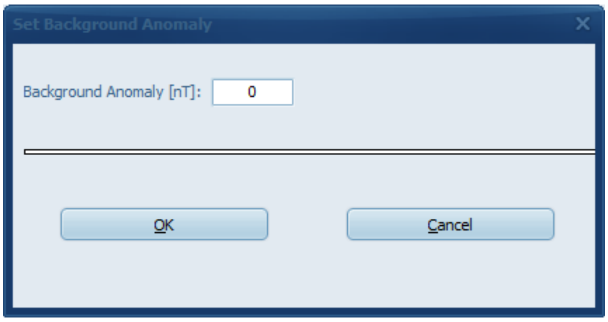

Figure 12. Dialog for assigning a value for the spatial average over the calculated anomalies.

2.3 View Menu

View → Measure Distance

This command allows multiple measurements of distances through the three basic windows. Once activated, the program waits for an user *click–drag–release* operation, which creates a trace through the active window. A dialog window is open (Fig. 13), which shows at any time the starting and ending point coordinates and the distance between these two points. The user can repeat the operation to take other distance measurements. To terminate the command, it is necessary to press again the *Measure Distance* button on the main control bar (Fig. 1).

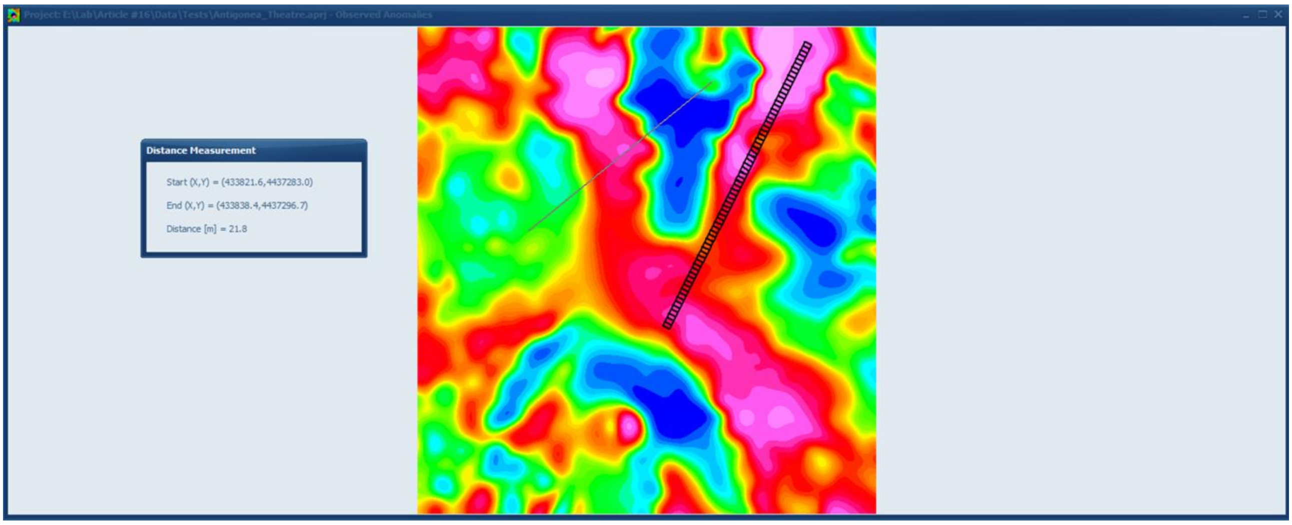

Figure 13. Dialog for the visualization of the current distance measurement.

III Forward Modelling Tips

Modelling of an archaeological feature by one of the basic *ArchaeoMag* shapes should start with a guess about the burial depth and with a characterization of the remnant magnetization component, which is predominant in most of the situations that can be studied by magnetic methods. The burial depth influences the lateral width of an anomaly, which increases with the top depth z_1, while the presence of a remnant magnetization component can be easily established by the detection of one or more among the following features: 1. A magnetic anomaly amplitude exceeding a few nT; 2. A deviation of the strike of the simmetry axis of a dipolar anomaly from the present day reference field declination, D_0; 3. A deviation of the anomaly shape from the expected shape for the given reference field inclination, I_0. Fig. 14 shows an example of observed total field anomalies that can be modelled by objects having a remnant magnetization component.

In general, the observation of anomalies associated with induced magnetization requires one or more among the following conditions: 1. A strong susceptibility contrast with the surrounding soil; 2. A random arrangement of natural remnant magnetization (NRM) components (e.g., a random orientation of magnetite grain spins in a paramagnetic matrix, a random build–up of bricks, etc.); 3. A low Koenigsberger ratio $Q = M_R/M_I$, and 4. The absence of nearby objects with a significant NRM component. Examples of archaeological features whose anomalies are dominated by induced magnetization contrasts are: graves, historical iron artifacts (Bevan, 2002), ditches and limestone walls. In contrast, remnant magnetization generally produces much stronger anomalies in materials with high Koenigsberger ratio or, more often, when the archaeological structures are fired materials (e.g., bricks) or materials that have been fired at a later time during historical or natural events.

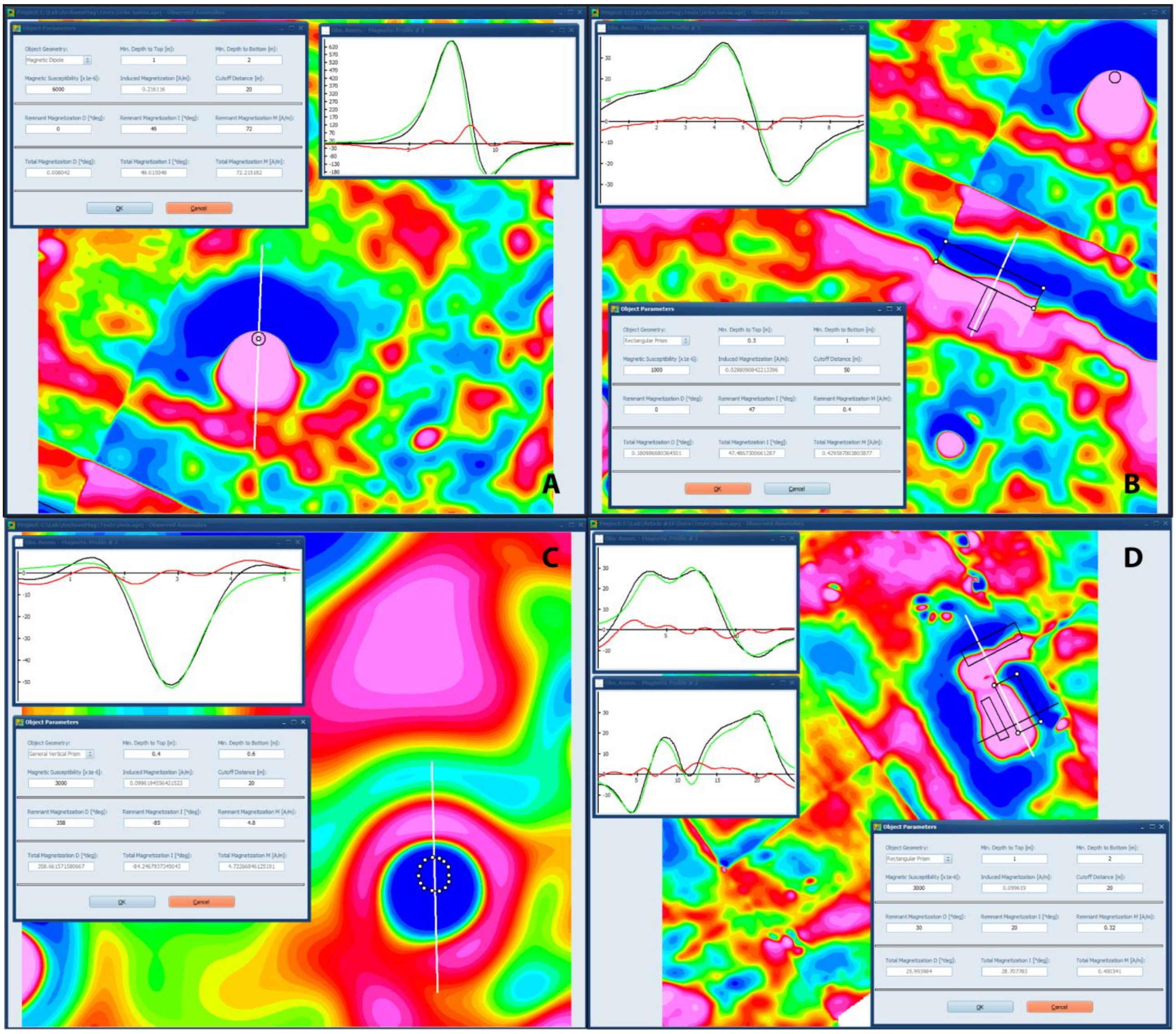

Figure 14. Four examples of archaeological total field anomalies that can only be modelled by sources with a significant component of remnant magnetization. The magnetic profiles show observed and model anomalies (black and green lines, respectively), and the error curve (observed – calculated, in red) along selected traces (white lines). The buried objects are indicated by black lines and white dots. Model parameters are listed in the object properties dialog boxes. A: A strong dipole anomaly whose peak exceeds 620 nT, most probably a furnace (Powell et al., 2002). B: A T–structure, probably representing a combination of a segment of a long and 2m large WNW–ESE oriented wall and a transversal smaller wall. C: A small cylindrical structure, 70 cm diameter by 20 cm height, characterized by a very anomalous inclination (I = –85°) of remnant magnetization. D: A composite anomaly, resulting from the superposition and coalescence of the anomalies associated with three distinct buildings. The upper profile refers to the black trace oriented WSW–ENE. The parameters of the selected object (delimited by white dots) are listed in the dialog window. The northernmost feature has D = 30° , I = 5°, M = 1.8 A/m, while the western prism has D = 30° , I = 60°, M = 0.3 A/m.

A forward modelling session of any observed anomaly should start with the selection of an object type (dipole, rectangular prism, etc.) and the creation of 1–2 magnetic profiles, as illustrated in Fig. 14. At this stage, it is possible to choose an arbitrary but reasonable burial depth or a depth suggested by the available archaeological information. Even the magnetic susceptibility must be chosen by a guess about the material, as suggested by the local archaeology. Finally, the user should decide if a NRM component is necessary, based on an accurate inspection of the anomaly amplitudes along the selected profiles, the relative amplitudes of the positive and negative peaks, and the 2–D shape of the anomaly field.

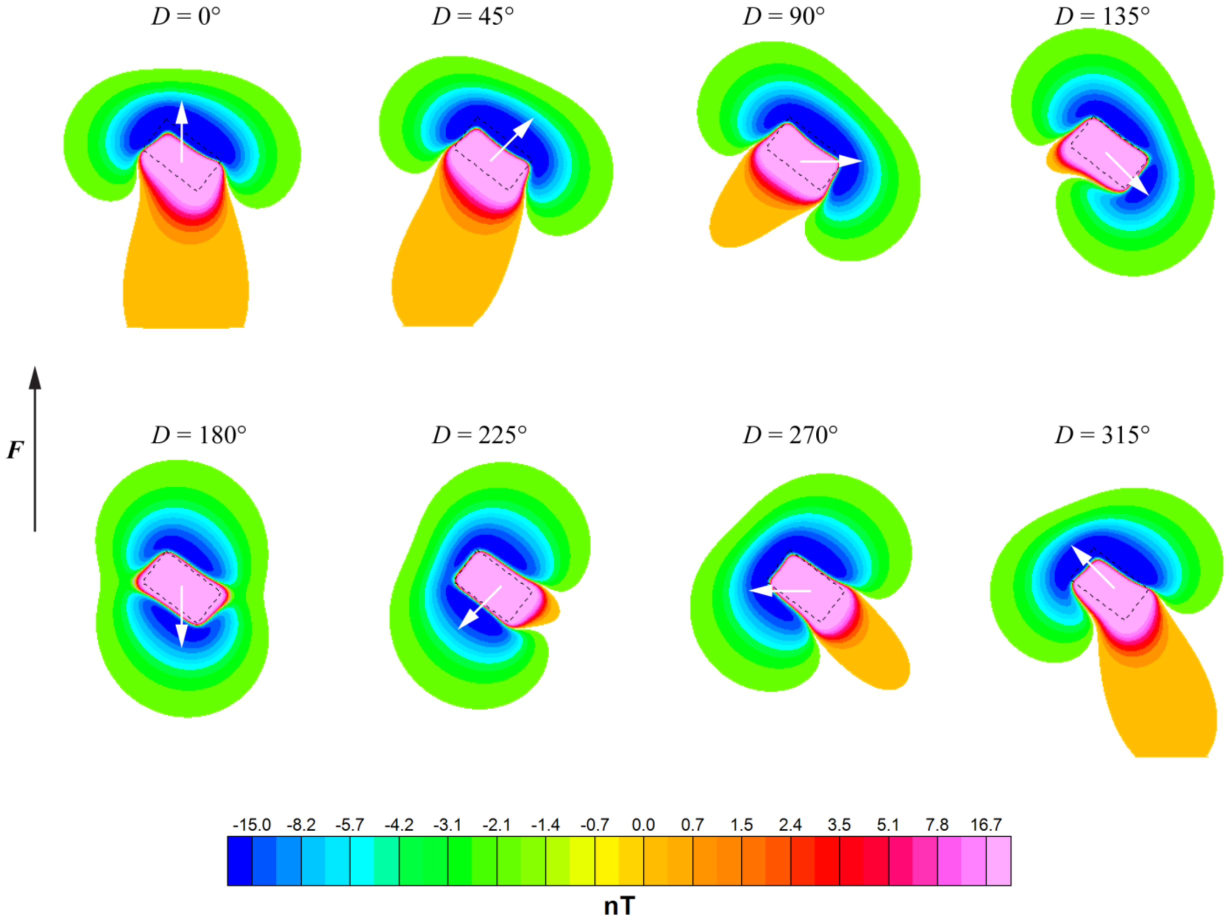

Figure 15. Effect of NRM declination on total field anomalies. A NW–SE wall (dashed rectangle) has NRM inclination I = 54° and M_R = 1 A/m. It is assumed that the ambient field has intensity F = 46824 nT, declination D_0 = 0°, inclination I_0 = 54° and that the sensor height is 0.5 m above a flat terrain. It is also assumed that the susceptibility contrast is zero. The white arrow shows the the horizontal projection of the RNM vector.

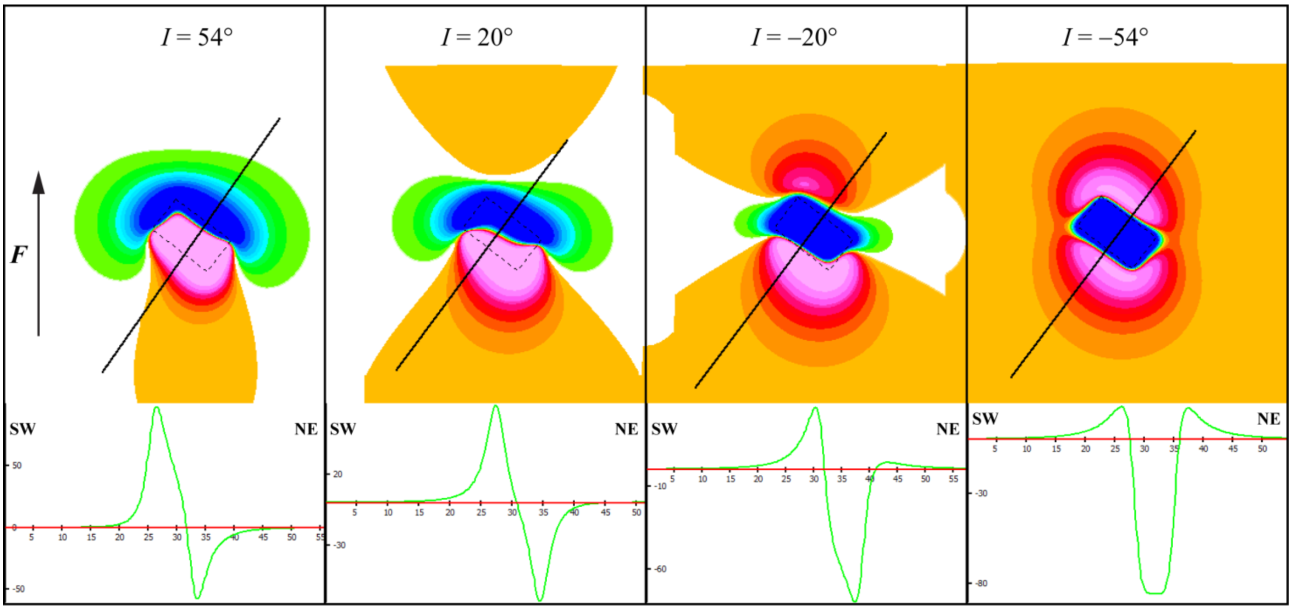

Figure 16. Effect of NRM inclination on total field anomalies. A NW–SE wall (dashed rectangle) has declination D = 0° and M_R = 1 A/m. It is assumed that the ambient field has intensity F = 46824 nT, declination D_0 = 0°, inclination I_0 = 54° and that the sensor height is 0.5 m above a flat terrain. It is also assumed that the susceptibility contrast is zero. The profiles show model anomalies along the traces indicated in the upper panel (black lines). Vertical units are nT, horizontal units are meters.

For example, Fig. 15 and 16 illustrate the effect of the NRM declination and inclination, respectively, on the total field anomalies generated by a NW–SE directed wall. Once all the necessary quantities have been specified in the object parameters dialog, the user runs the *update model* procedure, which recalculates the theoretical anomalies for all the objects in the project window and updates the existing profiles. At the next step, the user should inspect the magnetic profiles, in particular the error curve, in order to start an interactive trial–and–error procedure and determine a magnetization model that can explain the observed magnetic signal. At each iteration, the NRM parameters and eventually the depth and size of the object are adjusted to progressively minimize the mismatch between the model and observed anomalies along the profiles. The final result is not necessarily what we could find by direct excavation, because of the intrinsic ambiguity of potential field data. However, the availability of archaeological information can help to constrain materials and depths of the model objects, thereby allowing a realistic reconstruction of a buried settlement.

IV Calculation of Model Anomalies

The calculation of the anomalous field vector, $\Delta\boldsymbol{F}(\boldsymbol{r})$, produced at position $\boldsymbol{r}$ by an object with total magnetization $\boldsymbol{M}$ is performed through optimized versions of classical forward modelling algorithms (Blakely, 1995; Schettino et al., 2019). The anomalous field $\Delta\boldsymbol{F}(\boldsymbol{r})$ generated at location $\boldsymbol{r}$ by a uniformly magnetized sphere having radius a and total magnetization $\boldsymbol{M}$ can be obtained by the following expression:

$$\Delta\boldsymbol{F}(\boldsymbol{r}) \cong \frac{\mu_0 a^3 M}{3r^3}\left[3\left(\hat{\boldsymbol{M}}\cdot\hat{\boldsymbol{r}}\right)\hat{\boldsymbol{r}} - \hat{\boldsymbol{M}}\right] \tag{6}$$

In the case of a rectangular prism, total field anomalies and vertical gradients of T are not obtained projecting the anomalous field $\Delta\boldsymbol{F}(\boldsymbol{r})$ onto the reference field direction $\hat{\boldsymbol{F}}$. In this instance, *ArchaeoMag* calculates the anomalies directly, using a routine by Blakely's (1995). This algorithm is based on a solution proposed by Bhattacharyya (1964) for a rectangular prism oriented parallel to the coordinate axes and that extends from some depth z_1 to the infinity. To calculate the anomaly of a prism having finite thickness and arbitrary orientation, a coordinate transformation is performed from UTM coordinates to a reference frame where the prism has the required parallel orientation. Then, the routine is called twice, once with z_1 equal to the top of the prism and once with z_1 equal to the bottom depth but opposite magnetization, and subtracting the second result from the first one. Bhattacharyya's (1964) formula is simply an application of the following general volume integral over a region **R** filled by infinitesimal dipolar sources with magnetic moment $d\boldsymbol{m} = \boldsymbol{M}(\boldsymbol{r}')dV$ to the specific case of a rectangular prism.

We have:

$$\Delta T(\boldsymbol{r}) = -\frac{\mu_0}{4\pi}\hat{F}_i \frac{\partial}{\partial x_i}\int_{\mathbf{R}} M_j(\boldsymbol{r}')\frac{\partial}{\partial x'_j}\frac{1}{\|\boldsymbol{r}-\boldsymbol{r}'\|}dV \tag{7}$$

where we have used an index notation with summation convention. In this expression, the observation point is at $\boldsymbol{r} = (x_1,x_2,x_3)$ and the integral extends over an arbitrarily magnetized region **R**, whose points $\boldsymbol{r}'$ have coordinates (x'_1,x'_2,x'_3).

The third class of objects that can be modelled using *ArchaeoMag* is represented by general vertical prisms (which includes cylinders). A vertical prism is a kind of polyhedron having identical upper and lower polygonal faces and *n* vertical rectangular faces. If magnetization is uniform, the magnetic anomaly of a general polyhedron can be calculated converting the volume integral (7) into a surface integral, so that the anomalous field generated by the object is equivalent to the field associated with a distribution of magnetic "charge" on the body surface:

$$\Delta\boldsymbol{F}(\boldsymbol{r}) = \frac{\mu_0}{4\pi}\oint_{S(\mathbf{R})}\hat{\boldsymbol{r}}\frac{\boldsymbol{M}\cdot d\boldsymbol{S}}{r^2} \tag{8}$$

where $S(\mathbf{R})$ is the boundary of **R** and the origin is assumed to coincide with the observation point. The integration surface $S(\mathbf{R})$ at the right hand side of (8) can be approximated by an appropriate *N*–facets polyhedron, so that this expression can be evaluated summing the contribution of *N* polygonal facets. *ArchaeoMag* uses the method proposed by Bott (1963) to calculate the contribution of any polyhedron facet. If the upper surface of a vertical prism is a polygon with *n* vertices, the program calls the routine once for this top surface, once for the bottom surface, and *n* times for the lateral vertical facets. This algorithm fails when an edge of any facet is orthogonal to the reference field direction $\hat{\boldsymbol{F}}$. In this specific case, the algorithm will return a zero anomaly. To overcome this problem, the user can either rotate the prism by a very small angle (e.g., 0.1°) or change the reference declination D_0 by the same small angle. This trick is especially useful in the case of fluxgate surveys, as for this kind of data *ArchaeoMag* uses Bott's (1963) routine even in the case of rectangular prisms.

Acknowledgments

We thank Bruce Bevan for his extensive testing of the program and helpful suggestions.

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