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To cite this article: Olubukola A. Oni and Ahzegbobor P. Aizebeokhai 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **993** 012017

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# Aeromagnetic data processing using MATLAB

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**Abstract.** This study focuses on the evaluation of magnetic field variation in a two-dimensional plot in form of a contour map by carrying out interpolation on the magnetic field data and mapping regional structures to infer the direction of dykes. To pinpoint areas of magnetic highs and lows, MATLAB program was used to delineate magnetic field trends on the data. The program was also used to produce graphical, colourized and contoured plots of data from XYZ files (data with random locations) using interpolation functions. The program was used for both gridding and smoothening of the magnetic field data and also allow the setting of contour values and utilization of vivid colour scales. The aeromagnetic data vector may contain outliers which are due to instrumental error and data extraction during field data collection. These outliers were removed and replaced using three interpolation methods including linear, nearest-neighbour and cubic spline to have a non-distorted representation plot and they were also used to fit surfaces to the gridded data. The result shows that the piecewise cubic spline interpolant contour plot has finer precision with higher details at the output edges. From the piecewise linear surface  $B(X,Y)$ , where  $X$  is normalized by mean  $2.235e+05$  and standard deviation of  $3.202e+04$  and  $Y$  is normalized by mean  $7.809e+05$  and standard deviation of  $551$ . The residual magnetic intensity plot shows the magnetic field range between  $-200 nT$  for magnetic low and  $200 nT$  for magnetic high. However, the use of MATLAB is not to displace Oasis Montaj geosoftware but to give more scientific meaning to the automation of the filtering techniques used in Oasis.

**Keywords:** Aeromagnetic data, MATLAB, Interpolation, Oasis Montaj, Cubic, Piecewise.

## 1. Introduction

For more than three hundred years, it has been recognised that the Earth behaves like a strong magnet [1]. This makes the earth magnetic field method the oldest geophysical method among other geophysical methods. A wide range of applications is acquired from the measurement of the earth's field. The magnetic method is commonly used to detect and map subsurface



geological structures to give information on depth, magnetic susceptibility, lateral extension, size and thickness of the source body [2] and [3]. It is also used to detect magnetic anomalies due to variation in the subsurface magnetic field, as all earth materials possess magnetic properties. Measurement of the variation of the earth's magnetic field created by lateral and vertical variations in crust magnetization has been recorded after Earth's main core field has been subtracted from the total magnetic field [1]. Magnetic measurement can be acquired either through air, sea or spaceborne. Airborne magnetic method is referred to as the aeromagnetic method. The aeromagnetic method has been commonly used for various investigations such as geological analysis and mineral exploration [4].

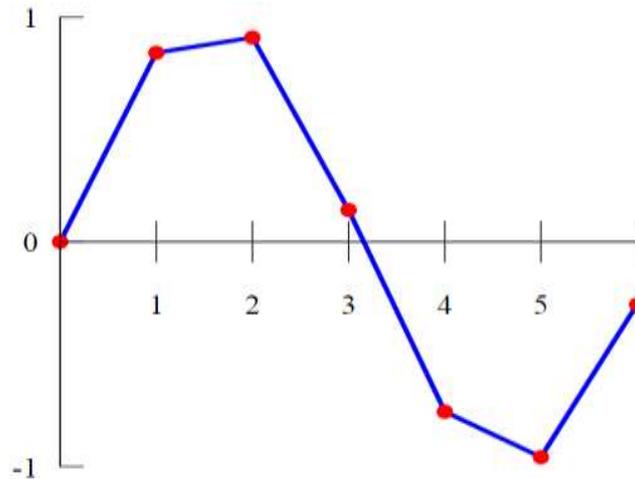
Magnetic processing/interpretation is a complex procedure due to the overlay of multiple magnetic anomalies during acquisition of data and error correction [3], as well as the dipolar nature of magnetic field [5]. Magnetic processing includes anything done to the magnetic data from collection of data to production of interpretable map, digital data set or profile [6]. Aeromagnetic data processing can be classified into two stages which are the pre-processing (verifying and editing the raw data and locating the data in X and Y plane), and the processing stage (parallax correction, removal of diurnal variation, removal of the component attributable to the Earth's regional field, data levelling, microlevelling- removal of any residual levelling errors and gridding/contouring) [6] and [7]. However, some of these processes can also be carried out using software such as MATLAB apart from the Oasis Montaj, to gain more understanding on the scientific concepts behind the automated processing especially during stages that involve filtering techniques. By analyzing magnetic field variation using MATLAB codes in a multi-dimensional plot in the form of a contour map using magnetic field data interpolation, this study covers the gap on raw data pre-processing, verification, and editing data. MATLAB is a high level programming language that serves as a platform for technical computing such as data analysis, algorithm development and simulation. Few authors such as [2-5] and [8] have used MATLAB for processing and analysing potential field data. Thus, the use of MATLAB contributed to many freeware and open-source codes, which are based on solution to a specific issue relating to potential field [2]. By considering these previous studies, it was assumed that it would be favourable to develop a programming code for the implementation of potential field data processing that would be beneficial to scientific studies and investigations. With the goal of

unravelling the understanding behind some of the filtering techniques used in Oasis Montaj, this study focuses on aeromagnetic data processing with MATLAB to interpret magnetic field for better insight into the mathematical and physics concepts behind the data manipulations, filtering and processing procedure. The specific objectives are evaluation of magnetic field variation of the data in a two-dimensional plot in form of a contour map by carrying out interpolation on the data; mapping magnetic perturbation of magnetic fields along the flight line using MATLAB code and delineation of magnetic field trends on the data to pin point areas of magnetic highs and lows.

Oasis Montaj geosoftwares play an important role in the interpretation (either qualitative or quantitative interpretation) and analysis of aeromagnetic data [8]. The incorporation of various filtering techniques such as reduction-to-pole (RTP), vertical and horizontal derivatives, tilt derivatives, analytic signal and Euler deconvolution among others during analysis is necessary for both data enhancement and noise suppression [2] and [8]. One of the most paramount issues with the use of Oasis Montaj is to understand the basic principles behind each automated ready-made filtering techniques available on the software before analysis, to have some hands-on experience and in-depth knowledge on how the filtering process takes place. To prevent poor analysis with minimal noise ratio that can lead to misleading results, another sophisticated tool that has the capacity to unravel the scientific concept behind the step-by-step filtering techniques is required. Thus, analysing these data on MATLAB with the goal to understand the basic mathematical/physics concepts behind these filtering techniques is desirable. However, previous aeromagnetic interpretation without proper knowledge on proper data treatment might lead to wrong data interpretation and might even lead to interpretation of noise signal as geological features. Thus, analysing aeromagnetic data using MATLAB will increase the physical understanding behind the automated filtering analysis in the Oasis Montaj geosoftwares. This research aims at filtering processing of aeromagnetic data using MATLAB.

## 2. Method

Interpolation was used as a technique to estimate the value of a query point within the domain of a set of sample data points [6]. A sample data set was interpolated to generate a function as in Equation (1) specified by point X and corresponding values of V.



**Figure 1:** Schematic diagram of linear interpolation on a data set.

$$V = F(X) \quad (1)$$

This function can then be used to evaluate a query point  $X_q$ , to give

$$V_q = F(X_q) \quad (2)$$

A unique value of  $V_q$  was generated for every query  $X_q$  within the domain of  $X$ . The interesting aspect of using interpolation function is that it cut across all the data points. This is a significant difference between interpolation method and curve or surface fitting. In surface fitting, the function does not necessarily pass through the sample data points. After the coordinates points  $(x_0, y_0)$  and  $(x_1, y_1)$  are determined then the straight line between these points was refer to as linear interpolation (Figure 1). The linear interpolation involves the use of linear polynomials to generate new data points within a discrete range of existing data points. Solving the equation for  $y$  from the equation of slope of a straight line to give:

$$y = y_0 + (x - x_0) \frac{y_1 - y_0}{x_1 - x_0} = \frac{y_0(x_1 - x) + y_1(x - x_0)}{x_1 - x_0} \quad (3)$$

Equation (3) is referred to as linear interpolation of  $(x_0 - x_1)$  interval. The nearest neighbour algorithm chooses the nearest point value and does not make use of the neighbouring point values, resulting into a piecewise interpolant. For the cubic interpolation, polynomial interpolation of third degree was used. If the values of a function  $f(x)$  and its derivatives are

known at  $x = 0$  and  $x = 1$ , then the function can be interpolated on the interval  $[0, 1]$  using a third degree polynomial.

### 2.1 Piecewise Function

The piecewise function is a functional notation that helps to choose the interval between the subdomains of a function to represent the whole domain of the data set. Some of the interval may include degenerated intervals, in other words single data points or unbounded interval. Application of this mathematical analysis is used in image modelling consisting smooth regions separated by edges. Common example of this function include piecewise linear function.

### 2.2 Fast Fourier Transform

Fourier transform can simply be referred to as the transformation from a real space domain to a spectral domain[6]. Assuming the function  $f(x)$  represent the magnetic anomalies in a finite length segment of  $x$  axis, to give:

$$\int_{-\infty}^{\infty} |f(x)| dx < \infty \quad (4)$$

$$F(k) = \int_{-\infty}^{\infty} f(x) e^{-ikx} dx \quad (5)$$

Equation (5) is the Fourier transform of equation (4), where  $i = \sqrt{-1}$  and  $k$  is wave number which is inversely proportional to wavelength  $\lambda$  from the equation  $k = \frac{2\pi}{\lambda}$ . Equation (6) gives the inverse operator of the Fourier transform:

$$f(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(k) e^{ikx} dk \quad (6)$$

The two-dimensional (2D) Fourier transform of a function gives:

$$F(k_x, k_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) e^{-i(xk_x + yk_y)} dx dy \quad (7)$$

While the equation for the inverse 2D Fourier transform is written as

$$f(k_x, k_y) = \left(\frac{1}{2\pi}\right)^2 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(k_x, k_y) e^{i(xk_x + yk_y)} dk_x dk_y \quad (8)$$

where  $k_x$  is the wave number in  $x$  and  $k_y$  is also wave number but in  $y$  direction.

Aeromagnetic data at sub-nanotesla resolution scale was collected from the Nigeria Geological Survey Agency (NGSA). The high resolution aeromagnetic data were acquired by Patterson Grant and Watson (PGW) and Fugro Airborne Survey Services, Canada, between the year 2003 and 2009 under the supervision of the Nigerian Geological Survey Agency (NGSA).

### 2.3 Data Processing and Analysis

The gridded data as obtained from NGSA was converted into a database using Oasis Montaj 7.0 after the regional effect have been eliminated from the total magnetic intensity. This database was later exported to Microsoft excel 2007 in form of a dot csv file. The database appears in X, Y and Z channels. The database shows the Cartesian coordinate X, Y in meters representing the UTM Easting and UTM Northing while Z represents the residual magnetic intensity in nano Tesla (nT) which was derived after removing the regional effect from the total field. MATLAB R2017b, was the major software used from this phase of analysis down to completion. The programming tool was used to create the RMI plots afterwards. The aeromagnetic data vector may contain outlier, which are defined as point outside three standard deviation from the mean. The outliers were replaced with the nearest element that is not an outlier using this command:

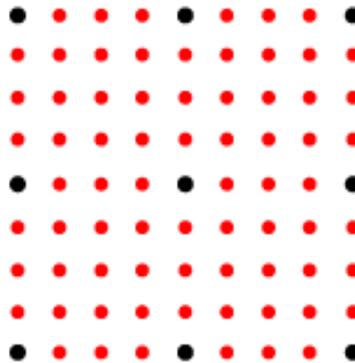
```
B=filloutliers(Aeromag,'nearest','mean'); %remove outliers, replace with nearest as mean.
```

Next was to use MATLAB to mesh the data on a gridded mesh whose limits and intervals depends on  $t_i$  in 'meshgrid' format;

```
ti = -100000:100:100000; % grid intervals in (m)
[XI,YI] = meshgrid(ti,ti);
%Matlab cubic interpolation mesh grid 'XI,YI' on data 'x,y,z'
ZI = griddata(x,y,z,XI,YI,'cubic');
```

Interpolation can be divided into two categories, which could either be interpolation of ordered gridded data or scattered data. These categories depend on the structure of the sampled data. The sample data may either be dispersed or arranged in an axis-aligned grid. If the sample points are of gridded distribution, one can effectively locate the sample points in the neighbourhood of the query by using the ordered gridded structure. On the other hand, the interpolation of scattered

data involves a triangulation of data points, which requires higher level of computation. Figure 2 illustrates the interpolated values (in red) placement between nine sample values in black. The black data spot represents observed data spaced 400 m apart whereas the interpolated values are represented in red having intra spacing of 100 m apart.



**Figure 2:** Schematic representation of the field sample data (black) having interpolated values (red).

The final grid data is now simply denoted as Aeromag (X,Y,Z) formally computed as (XI,YI,ZI). The data type, description, units, and other descriptive statistics for each variable is summarize in Table 1 using the MATLAB summaryfunction.

```
summary (Aeromag); % command to produce Table 1
```

**Table 1:** Descriptive statistics for aeromagnetic grid data used for analysis

Variables Type	X (m)	Y (m)	Z (nT)
<b>Data Type</b>	611306×1 double	611306×1 double	611306×1 double
<b>Maximum UTM(m)</b>	2.792e+05	8.301e+05	400.79
<b>Minimum UTM(m)</b>	1.685e+05	7.743e+05	-428.08
<b>Difference UTM(m)</b>	1.107e+05	0.558e+05	828.87
<b>Median UTM(m)</b>	2.239e+05	8.021e+05	4.1133

#### *2.4 Regional and Residual Separation*

In geophysical studies, the observed magnetic data are the sum of magnetic fields generated from all underground sources. The right estimates involve the removal of regional field from the original observed field measurements (total magnetic intensity) which in turn gives the residual field created by the target sources[9]. Regional anomalies are known as high wavelength component of magnetic anomaly. This deep feature emerges as a regional pattern and tends in a smooth manner to a more aerial coverage. The residual anomaly can be described as a shorter wavelength which is seen to be small (local pattern) but of considerable significance. In line with the I.G.R.F reduction technique, a low pass filter which is the Butterworth filter was applied to the data in order to remove the effect of regional from the aeromagnetic data of the study area. The interpretation was carried out by inspecting the Total Magnetic Intensity (TMI) map. Butterworth low-pass filter had been used to eliminate regional effects from total magnetic intensity data. This optimal low-pass filter excludes all frequencies higher than the cut off frequency and passes the low signal. Using the Butterworth low pass filtering method, the residual magnetic intensity (RMI) data was processed to improve signal to noise ratio and eliminate any high frequency event which may reflect cultural, or other noise types or error in data and are then subjected to further processing. The RMI plot was derived using MATLAB software afterwards.

#### *2.5 Interpolation*

Interpolation technique serves as edge detection and can be used as a smoothing tool on existing data. There are different alternative interpolation methods such as linear, nearest, bilinear, next, previous, p-chip, cubic, bicubic, v5cubic, maxima or spline[4]. The MATLAB algorithm was used with linear, nearest neighbour and piecewise cubic interpolant to determine the interpolation RMI field distribution from the measured magnetic data.

This interpolation method was used to examine the closest two pixels by drawing a line between them and then designating a value as the output pixel value along that line. The nearest pixel value was used to assign the output pixel visualization in nearest-neighbor interpolation. This is the fastest form for interpolation but the output image contains jagged borders/edges. The cubic interpolation approximates a sine interpolation, which was approached with the use of cubic

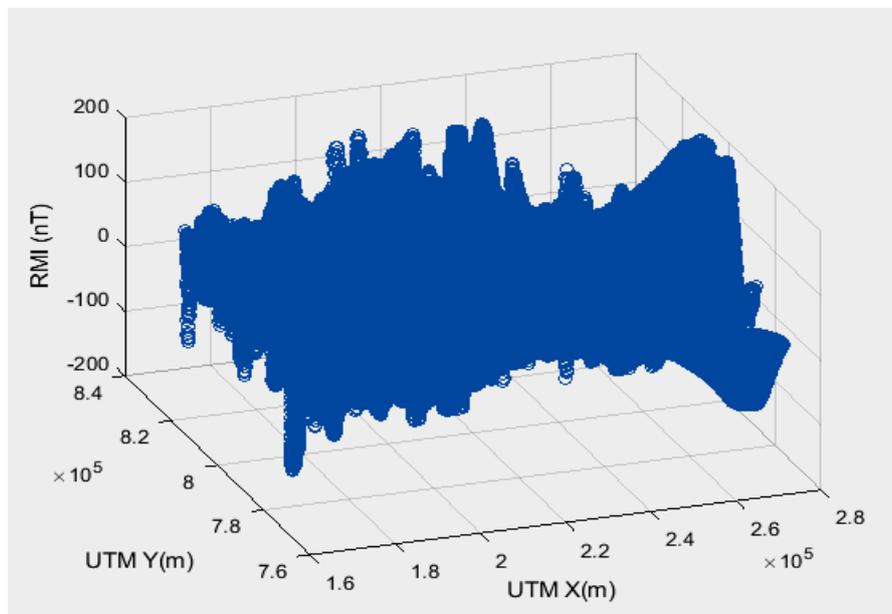
polynomial waveforms rather than linear waveforms while resampling a pixel. This method examines four neighboring pixels using a one-dimensional (1D) source. The method surveys 16 pixels with a three-dimension (3D). Cubic spline interpolation gives minimal error, thus preserving the highest amount of fine detail in the resulting image. However, it should be noted that this interpolation method involves more processing time.

### 3. Presentation of Results

In this investigation, the distribution interpretation of aeromagnetic survey analysis was critically presented with the appropriate graphical plots produced from each mathematical filter. This section showed all results generated during the research analysis, which were represented in graphical, colored and contoured plots.

#### 3.1 Residual Magnetic Intensity (RMI)

After the removal of the regional anomaly from the data, a two-dimensional graphical plot of the residual magnetic field was generated using MATLAB algorithm. A 3D view of the residual magnetic intensity was produced for a small section of the field. Figure 3 represents the 3D RMI plot against distance X and Y.

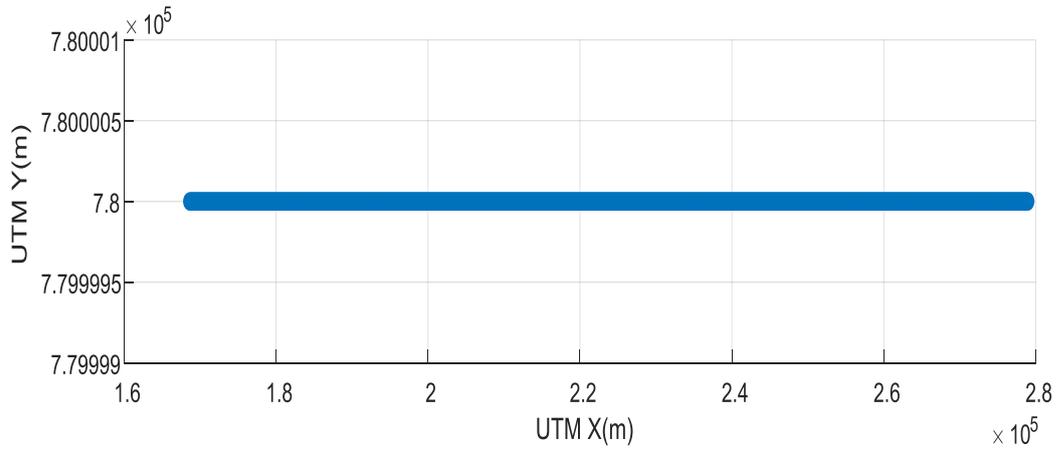


**Figure 3:** 3D residual magnetic intensity RMI plot against distance X and Y.

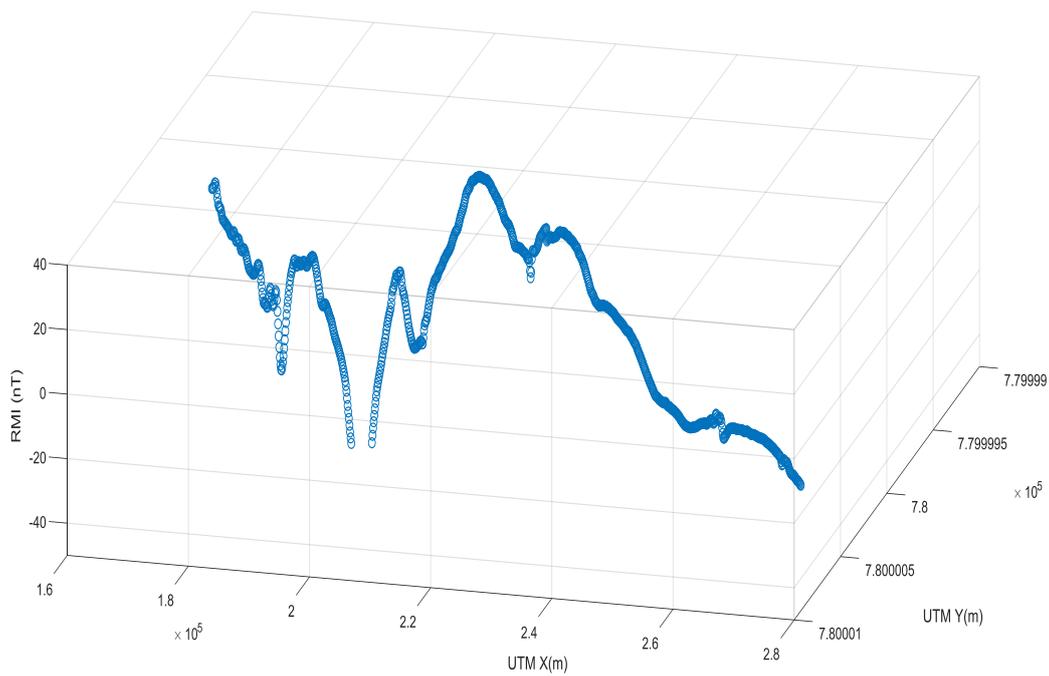
### 3.2 Presentation of Interpolation Results

Figure 4 shows the interpolated aeromagnetic data without outliers for a single line plot of  $B=(B.X(60304:61408),B.Y(60304:61408))$ . The interpolated plot was produced and shows clearly that the lines of flight are parallel to the x axis. Figure 5 represents the single line plot appearance of a the 3D residual magnetic intensity plot against distance X and Y showing  $B=(B.X(60304:61408),B.Y(60304:61408))$  for the benefit of clarity. It clearly displays the sectional perturbations in the magnetic potentials along the flight line. The interpolated aeromagnetic RMI without outliers for multiple lines plot of a section of  $B=(B.X(60304:81408),B.Y(60304:81408))$  was shown in Figure 6 is a plan view of the field lines revealing consistency in lines spacing and data point coverage along all lines.

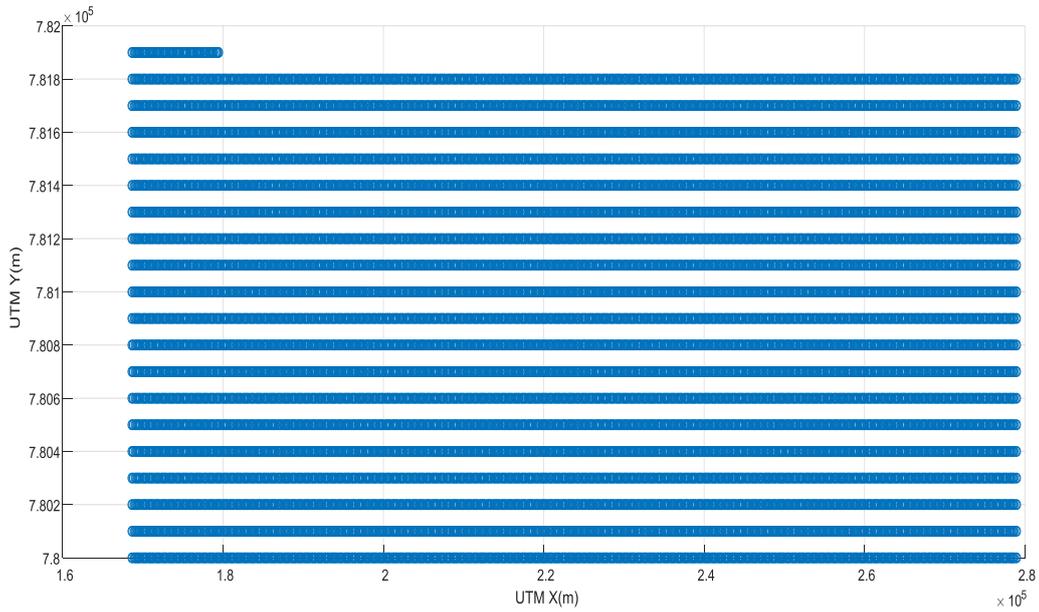
On the other hand, Figure 7 shows interpolated aeromagnetic data without outliers. Figure 7 was produced using multiple lines plot of a section of  $B=(B.X(60304:81408),B.Y(60304:81408),B.Z(60304:81408))$ . Figure 8 shows interpolated aeromagnetic data without outliers with RMI greater than 0. Multiple lines plot of a horizontal section of  $B=(B.X(60304:81408),B.Y(60304:81408))$  was used for the plot. Figure 9 shows the piecewise linear interpolate surface from the grid data. A surface was fitted to the data lines set using linear interpolant as shown in Figure 9 using MATLAB command: `cftool(B.X(60304:81408),B.Y(60304:81408),B.Z(60304:81408))`. The linear interpolation RMI field distribution can be better appreciated with a surface contour map as shown Figures 10, 11 and 12. Figure 10 shows linear interpolant of the RMI with surface contour while Figure 11 shows plot of nearest neighbour interpolant and lastly Figure 12 reveals Piecewise cubic interpolant contour plot.



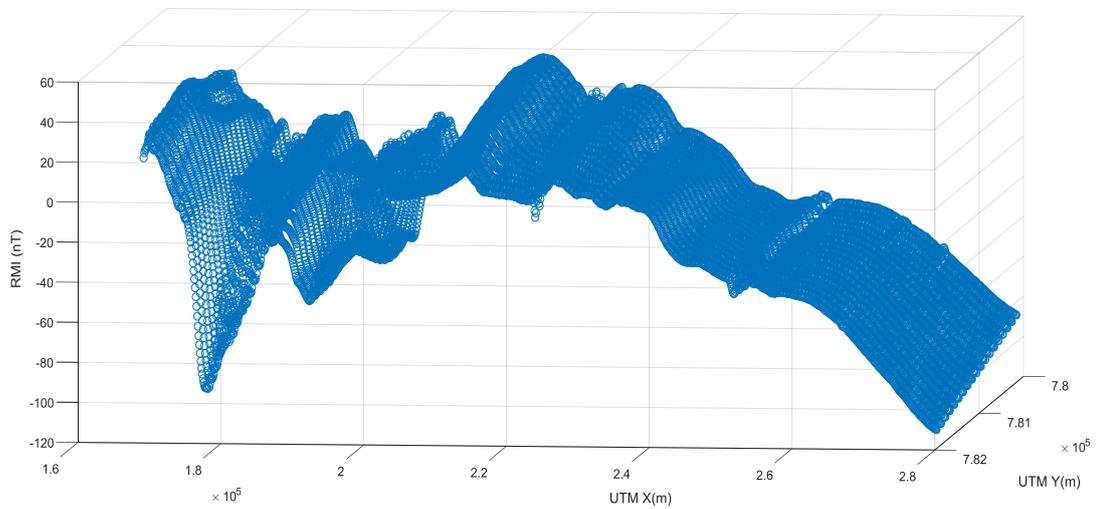
**Figure 4:** Interpolated aeromagnetic data for a single line plot of  $B=(B.X(60304:61408),B.Y(60304:61408))$ .



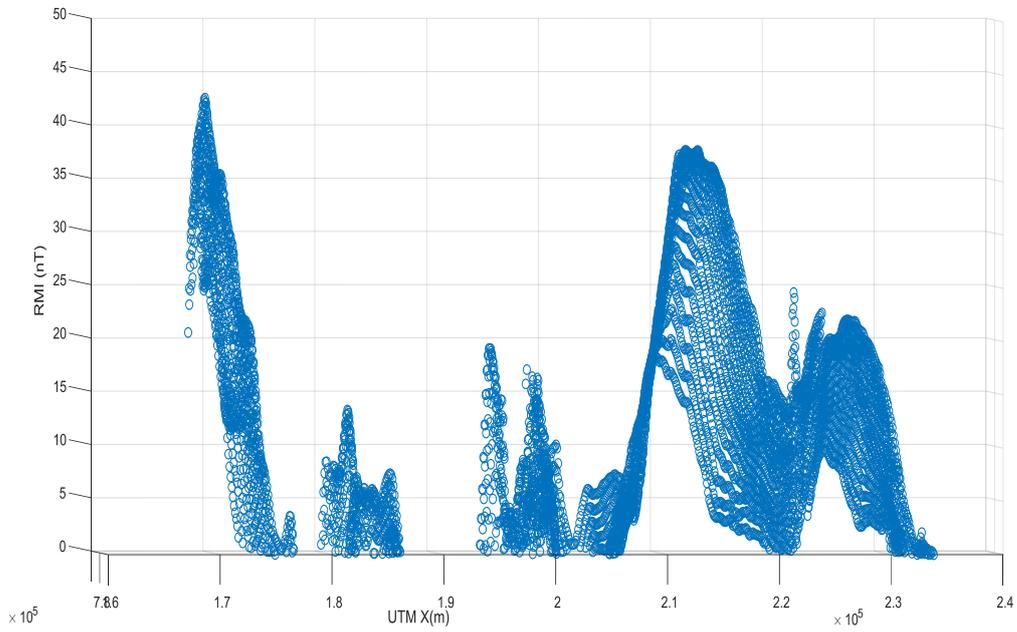
**Figure 5:** A single line 2D RMI plot against distance X and Y interpolated aeromagnetic showing of  $B=(B.X(60304:61408),B.Y(60304:61408))$



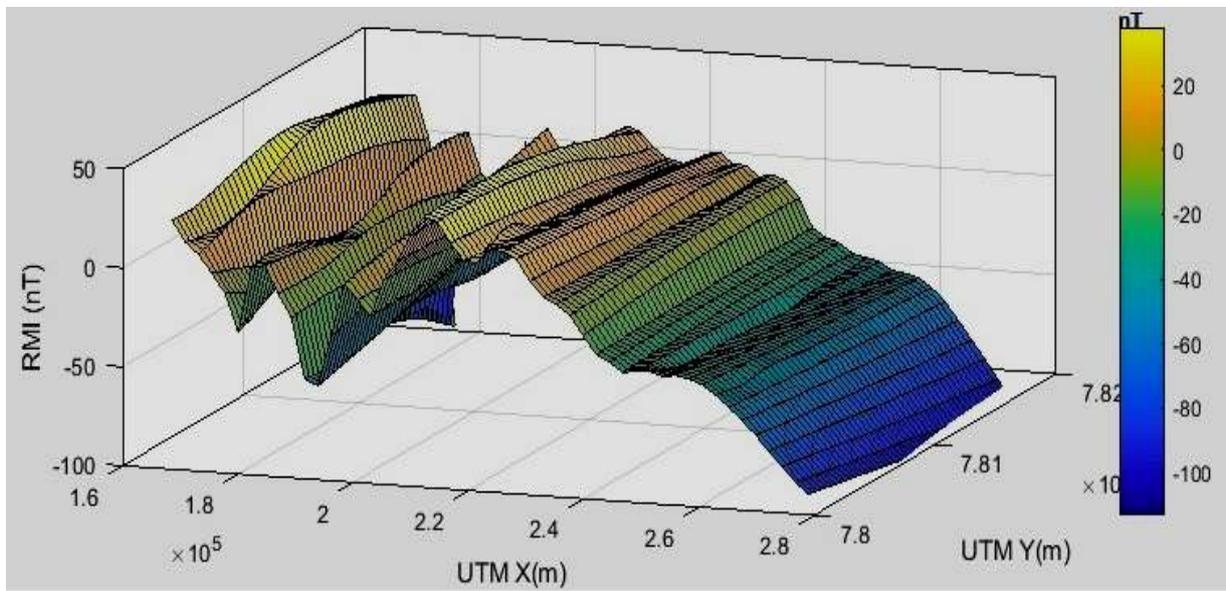
**Figure 6:** Interpolated aeromagnetic RMI for multiple lines plot of a section of  $B=(B.X(60304:81408),B.Y(60304:81408))$ .



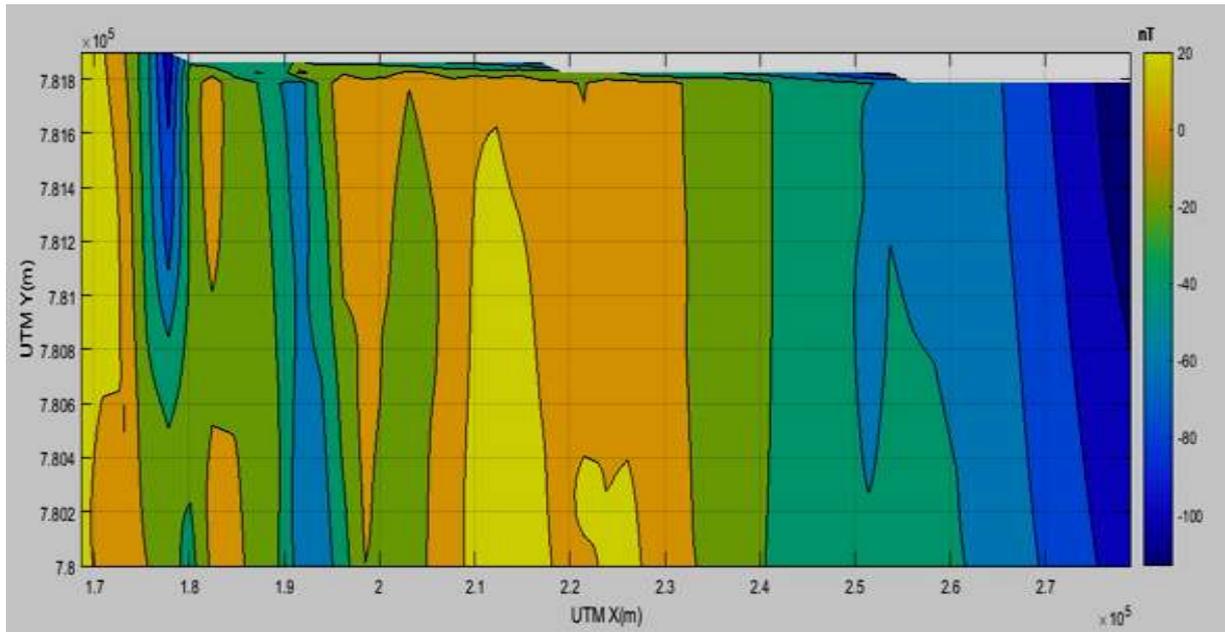
**Figure 7:** Interpolated aeromagnetic data showing multiple lines plot of a section of  $B=(B.X(60304:81408),B.Y(60304:81408),B.Z(60304:81408))$ .



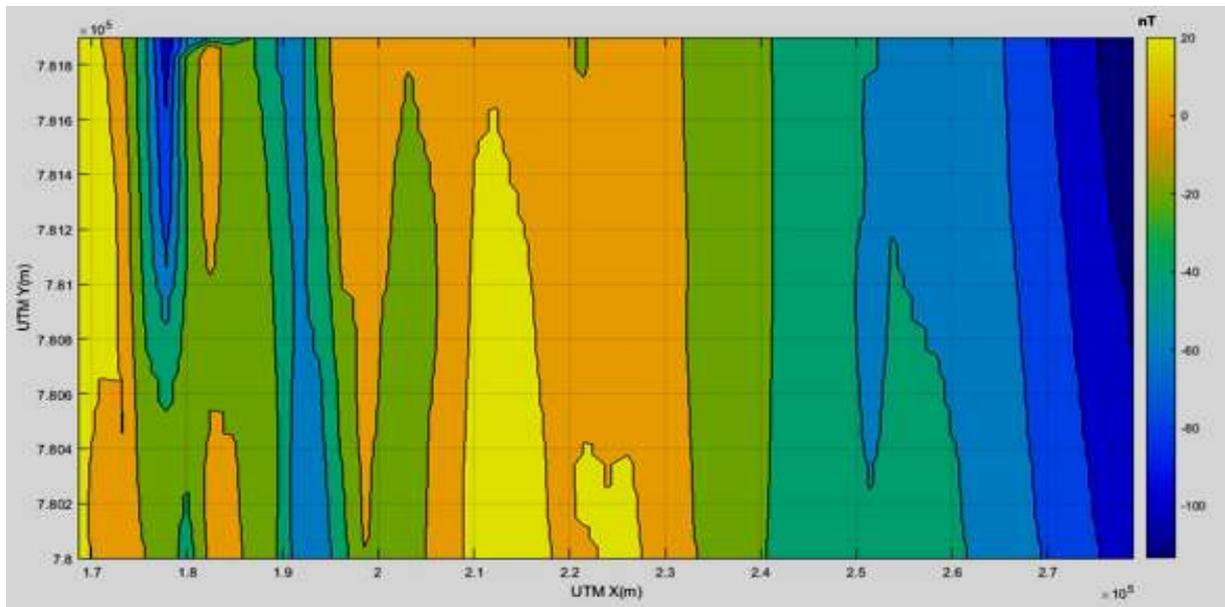
**Figure 8:** Interpolated aeromagnetic data plot with RMI greater than 0.



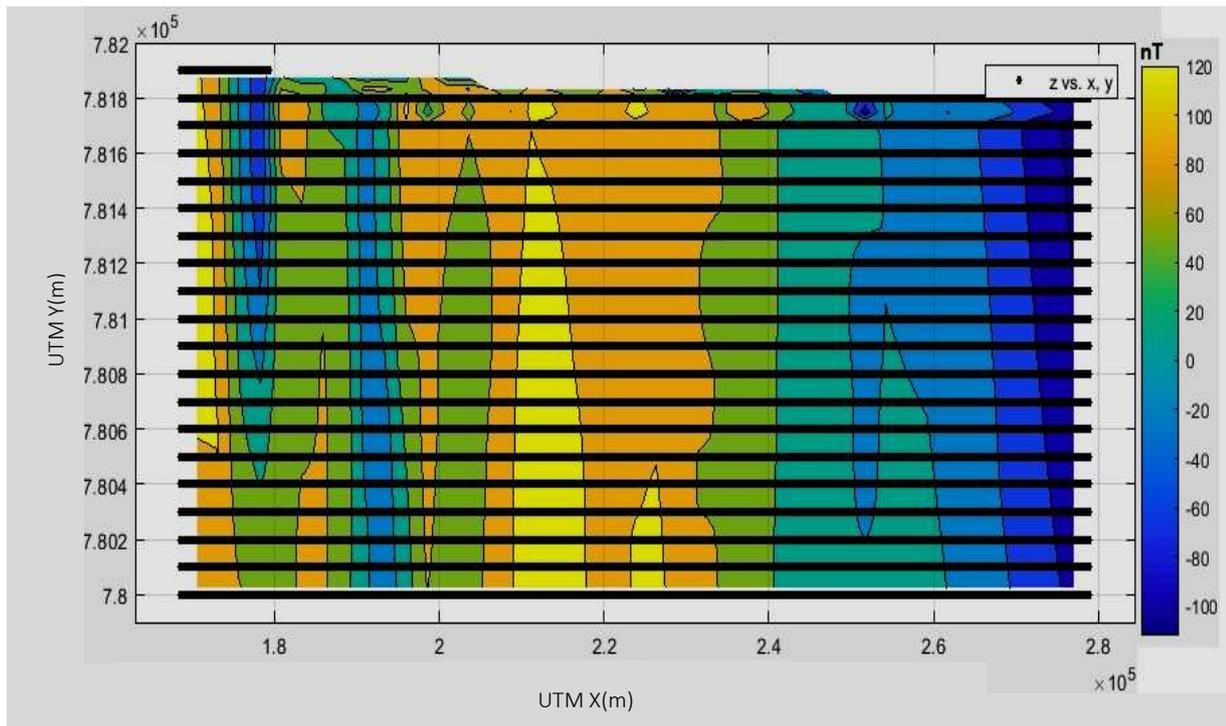
**Figure 9:** Surface Piecewise linear interpolation plot showing gridded mesh data.



**Figure 10:** Linear interpolation of the RMI with surface contour.



**Figure 11:** Nearest neighbor interpolation plot.



**Figure 12:** Piecewise cubic interpolation contour plot.

#### 4. Discussion of Results

##### 4.1 Residual Magnetic Intensity RMI

The graphical plot in Figure 3 shows the residual magnetic intensity plot against distance. A plot of the entire two aeromagnetic data sheets is graphically represented in Figure 3. The plot is clustered with 611,306 data points. The plot appears like a continuous function within a small area. All data look bunched up like a continuous surface (plain view). It should be noted that the visual judgment form looking at the orientation of the graph might be tricky. What is seen from the 3D view is as a result of the perceptive in which the image is viewed. That is the reason why the strike lines are made adjacent to the dip lines, knowing that the orientation of the lines will determine the features seen in an anomaly. The magnetic intensity range between  $-200\text{ nT}$  for magnetic low and  $200\text{ nT}$  for magnetic high. The aeromagnetic data vector may contain outlier; therefore removal of outliers is required and is replaced using interpolation to have a non-distorted representation plot.

#### 4.2 Interpolation

The interpolating function estimates actually passes through observed data points. The interpolated aeromagnetic data for a single line plot was generated without an outlier (as shown in Figure 4) in the (X,Y) horizontal plane. The same data was reproduced in Figure 5, which shows the magnetic perturbations of the RMI along the flight line  $B = (B.X(60304:61408), B.Y(60304:61408))$ . It can be used to establish a prima facie that magnetic anomaly may exist prior to more detailed survey. Figure 6 indicates interpolated aeromagnetic RMI without outliers for multiple lines plot of a section of  $B=(B.X(60304:81408),B.Y(60304:81408))$ . The alignment of the field lines in a plan view as represented in Figure 6 revealed consistency in lines spacing and data point coverage along all surveyed lines. It also shows the orientation of flight lines. This serves as guide for interpolation method either to use gridded or scattered data technique which involves triangulation.

Figure 7 shows multiple lines plot of a section of the aeromagnetic data interpolated. The plot shows that visual clarity depends on viewing orientation as the features become clustered up when rotated. One needs to be careful as the orientation of the plots could give a wrong visual perception in form of clustered images. Figure 8 indicate the interpolated aeromagnetic without outliers with RMI greater than 0. Figure 9 shows the Piecewise linear interpolate surface from the grid data. It would be noted that an interpolated surface is superposed on the data lines as shown in colors.  $B(X,Y)$  is the piecewise linear surface computed from  $p$ , (where  $p$  is the coefficient structure),  $X$  is normalized by mean  $2.235e+05$  and standard deviation of  $3.202e+04$  and where  $Y$  is normalized by mean  $7.809e+05$  and standard deviation of  $551$ . The linear interpolant map was compared with two other methods of interpolation namely; nearest neighbour and piecewise cubic interpolant. Linear interpolation map (Figure 10) utilizes the nearest two observed data points to form a line between them and assigning a value along that line as the output data value. Its result was very identical to that of (Figure 11). The nearest neighbour interpolation (Figure 11) assigns the value of the nearest data to the data in the output visualization which is usually fastest interpolation method among the three methods employed except that the resulting image may contain jagged edges. The cubic convolution interpolation contour plot (Figure 12), as with the 3D source uses 16 neighbouring data set for interpolation which results in the least amount of error, thereby preserving the highest amount of fine detail in

the output map (Figure 12). Figure 12 shows finer precision with higher details usually at the edges when compared to Figure 11. The differences observed can be explained using the yellow colour band in the three respective (Figures 10; 11 and 12) maps. However, cubic interpolation required more processing time.

## 5. Conclusion

The graphics of the entire data plots using MATLAB tends to cluster with large data and for that reason, we have only considered about 10% of the entire data. This limitation makes MATLAB a lesser tool for professional aeromagnetic processing. Results show that the survey lines are parallel to the x-axis and adjacent to the undulating RMI field pattern which helps to see clearly if there are structures. The aeromagnetic survey data line spacing of 400 m was interpolated using a grid spacing of 100 m creating a surface map passing through the points. The magnetic intensity of the RMI plot range between  $-200\text{ nT}$  for magnetic low and  $200\text{ nT}$  for magnetic high. From the piecewise linear surface  $B(X,Y)$ , where X is normalized by mean  $2.235\text{e}+05$  and standard deviation of  $3.202\text{e}+04$  and where Y is normalized by mean  $7.809\text{e}+05$  and standard deviation of 551. A comparison of the surface maps was made using three interpolation methods. From the results, it was shown that the piecewise cubic interpolant contour plot shows finer precision with higher details usually at the edges.

The interpretation of the magnetic anomalies is complicated and heavily depends on the mathematical processes used. For example, the dipolar nature of magnetic field, the superposition of multiple magnetic sources and the presence of geological and culturally induced noise signals from pipe lines, power lines or railroads, can complicate the preprocessed data. This research successfully describes the use of MATLAB program for interpretation of aeromagnetic data. The major phase of the program used is filtering by interpolation. However, the use of MATLAB is not to displace Oasis geosoftware but to give more scientific meaning to the automation of the filtering techniques used in Oasis. The use of handy mathematical software tools such as MATLAB to perform the data processing task would help armature geophysicist and geologist to appreciate the signatures of processing methods on the geophysical interpretation of subsurface features.

## Acknowledgment

This is to appreciate Covenant University Centre for Research Innovation and Discovery (CUCRID) and Covenant University as a whole for their financial support towards this study.

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