

A GRAPHICAL USER INTERFACE (GUI) MATLAB PROGRAM *SYNTHETIC_VES* FOR COMPUTATION OF THEORETICAL SCHLUMBERGER VERTICAL ELECTRICAL SOUNDING (VES) CURVES FOR MULTILAYERED EARTH MODELS.

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ABSTRACT

An interactive and robust computer program for 1D forward modeling of Schlumberger Vertical Electrical Sounding (VES) curves for multilayered earth models is presented. The Graphical User Interface (GUI) enabled software, written in MATLAB v.7.12.0.635 (R2011a), accepts user-defined geologic model parameters (i.e. number of layers, their thicknesses and resistivity values as well as number of data points) and computes apparent resistivity dataset which is plotted as theoretical VES curve on a log-log graph paper by convolving linear filter coefficients with sampled resistivity transform function. For the purpose of reliability, the newly developed software was analyzed for accuracy using an empirical approach and the applicability of the software was tested on some multilayered earth models. In all cases, it was established that the computed apparent resistivity dataset is of high accuracy. The software is suitable for calculating the geo-electric response over any horizontally stratified multilayered earth models for known layer configurations.

Keywords: Graphical User Interface, Synthetic_VES, Schlumberger Curves, Earth Models

INTRODUCTION

One of the most popular methods for investigating the resistivity of the subsurface is direct current (DC) sounding. Schlumberger soundings have a very long tradition and are frequently used today in spite of the growing importance of two-dimensional measurements with multi-array arrangements. The reason is that the overall effort required to carry out multi-array measurements is much higher than that for Schlumberger measurements and in many cases the information obtained from Schlumberger measurements is sufficient to image the subsurface (Yunus and Alper, 2008).

The work of several researchers in the subject of geo-electric sounding have resulted in the development of programmable algorithm for generating theoretical VES curve for horizontally multi-layered earth models. This algorithm requires one to evaluate a convolution integral Sheriff (1992). This calculation, using linear filtering, is rapid and convenient with traditional programming languages. A great variety of computer programs for generating theoretical VES

curve for horizontally multi-layered earth models have been published and commercially available. Examples are the works of Leaman (1976), Haines and Campbell (1980), Kahwagy (1980), Sheriff (1992), Patra and Nath (1999) and Ademilua and Olorunfemi (2007). In most cases, the programs do not meet the requirements for easy usage for large modelling work mostly because of the limitation in the input and output functionality of the programming language used in developing them. Most of these existing software are console based DOS program with little flexibility and poor user interface in addition to limitations in the number of layers that can be modelled or the number of electrode spacing values that can be computed.

The computer program presented here took advantage of the high-level language, speed and robust computation ability in conjunction with the built-in graphical user interface (GUI) functionality provided by the MATLAB programming language to development a new software which provides a quick, convenient and graphical way of calculating the expected response from

Schlumberger geo-electric sounding over any user-defined horizontally layered model of the subsurface with no restrictions to the number of layers or electrode spacing values that could be computed for. The GUI approach employed in its development also facilitates easy usage and flexibility with advanced input and output functionalities which are needed for large modeling works. The computer program has been further developed into a standalone application which will run on all windows operating system where the WIN32 MCR installer, Version 7.15 has been installed.

The newly developed software is relevant in planning of field surveys or in designing geo-electric sounding experiments which allows one to exploit information of variable value from the local area and from one's experience. For example, one might use available well control to formulate a model, calculate the expected results, and subsequently design an efficient field program to test the hypothesis. Alternatively, one could iteratively adjust a geologic model until the theoretical results fit existing field measurements. Likewise, if an assumption on the expected resistivity conditions in the project area can be made, this forward calculation of sounding curves allow an assessment of the length of electrode spread required to get information about the target horizon, or show if the target horizon can be detected on the Schlumberger Vertical Electrical Sounding (VES) curve in connection with a resolution study.

The greatest advantage of the newly developed software is its marked increase in speed of computation, high accuracy and inherent operational simplicity.

THEORETICAL BACKGROUND

The method for solving the one-dimensional variation of resistivity with depth starts with the calculation of potential on the surface. Stefanescu *et al.* (1930) explained as stated in Ghosh (1971a) and O'Neil (1975) that the integral representation for the potential at a distance r from a point source of current I on the surface of a horizontally stratified earth is given as:

$$V(r) = \frac{I\rho_1}{2\pi} \left[\frac{1}{r} + 2 \int_0^\infty B(\lambda) J_0(\lambda r) d\lambda \right] \quad (1)$$

Where:

$V(r)$ – is the potential measured at a point on the earth surface at a distance r from the current source.

$B(\lambda)$ is the resistivity kernel function for an n -layered earth.

ρ_1 is the resistivity of the upper layer.

I is the strength of electrical current emitted by the pole i.e. the current intensity.

r is the distance between the current source and the potential measuring station.

λ is the integration variable.

J_0 is the Bessel function of the first kind and zero order.

The resistivity transform function $T(\lambda)$ can be expressed in terms of the kernel function $B(\lambda)$ by

$$T(\lambda) = \rho_1 [1 + 2B(\lambda)] \quad (2)$$

Therefore,

$$V(r) = \frac{1}{2\pi} \int_0^\infty T(\lambda) J_0(\lambda r) d\lambda \quad (3)$$

For a Schlumberger electrode configuration, the apparent resistivity $\rho_a(s)$ is given as:

$$\rho_a(s) = -\frac{2\pi s^2}{I} \left[\frac{dV}{dr} \right]_{r=s} \quad (4)$$

Where

s –is half the current electrode spacing.

To express the apparent resistivity (ρ_a) in terms of the resistivity transform function $T(\lambda)$, we introduce a first order Bessel function given by Equation (5)

$$\int_0^\infty J_1(\lambda r) \lambda d\lambda = \frac{1}{r^2} \quad (5)$$

Likewise,

$$\frac{dJ_0(r)}{dr} = -J_1(r) \quad (6)$$

Putting Equation (3) into Equation (4) and using Equations (5) and (6) we have:

$$\rho_a(s) = s^2 \int_0^\infty T(\lambda) J_1(\lambda s) \lambda d\lambda \quad (7)$$

Equation (7) gives the apparent resistivity in terms of the resistivity transform function $T(\lambda)$ for different values of the electrode spacing (s).

Equation (2) can be substituted into Equation (7) to yield

$$\rho_a(s) = (1 + 2s^2 \int_0^\infty B(\lambda) J_1(\lambda s) \lambda d\lambda) \tag{8}$$

Equation (8) is fundamental to the interpretation of resistivity sounding data.

Furthermore, an expression for the resistivity transform function in terms of the Schlumberger apparent resistivity can be obtained by applying Hankel's inversion to Equation (7) to give:

$$T(\lambda) = \int_0^\infty \frac{\rho_a(s) J_1(\lambda s)}{s} ds \tag{9}$$

The integral Equation (7) is time consuming to evaluate because the Bessel function in the integrand oscillates and converges very slowly for many geologically reasonable models. The only method in use today involves the substitutions: $x = \ln(s)$ and $y = \ln(1/\lambda)$ to convert it to a convolution integral Equation which is the standard form for linear filtering.

$$\rho_a(x) = \int_{-\infty}^\infty T(y) J_1(e^{x-y}) e^{2(x-y)} dy \tag{10}$$

Equation (10) is a convolution integral where $\rho_a(x)$ is the output function, $T(y)$ from the model is the input function and $J_1(e^{x-y}) e^{2(x-y)} dy$ is the filter function.

Since convolution can more simply be handled in the frequency domain, Equation (10) is transformed to Equation (11) for a case where resistivity transform is the input and apparent resistivity is the output as

$$F(f) = G(f) \cdot H(f) \tag{11a}$$

We can rewrite to have

$$G(f) = F(f) \cdot Q(f) \tag{11b}$$

Where:

$$Q(f) = 1 / H(f).$$

$T(y)$ is a Fourier transform pair of $F(f)$ and $G(f)$ is a Fourier transform pair of $G(f)$ and $H(f)$ is the frequency characteristic of the resistivity filter. $Q(f)$ is the frequency characteristic of the inverse filter and can be determined from Equation (11b) by taking the Fourier transform of partial resistivity transforms (Koefoed, 1968; Ghosh, 1971).

In the time domain, the discrete equivalent of Equation (11) which gives the digital values of

the apparent resistivity and suitable for programming use is given by:

$$R_m = \sum_{j=\beta}^{\alpha} (b_i T_{m-i}) \tag{12}$$

Where:

$m = 0, 1, 2, \dots$

b_i is the inverse filter coefficients.

T_{m-i} is the sampled resistivity transform.

α is the subscript of the last leading inverse filter coefficients

β is the subscript of the first trailing inverse filter coefficients

For each calculated value of m , the resistivity transform T_m must be computed for enough samples to accommodate both the leading and the trailing filter coefficients. Therefore, the first step in the determination of apparent resistivity is the computations of the resistivity transform values to be used.

Several formulation and computation methods are available for the calculation of the resistivity transform values for use in Equation (12), a convenient form for automatic processing is given by Das and Ghosh (1974) and stated below:

$$T_{i-1} = \frac{T_i + \rho_{i-1} \tanh(\lambda d_{i-1})}{1 + \frac{T_i \tanh(\lambda d_{i-1})}{\rho_{i-1}}} \tag{13}$$

Where:

T_{i-1} is the resistivity transform value for a particular layer i

ρ_i is the resistivity value for the layer i

d_i is the thickness for the layer,

λ is inverse distance

Equation (13) symbolizes a process of stacking layer upon layer starting from the bottom layer designated symbol 'i' till one reaches the layer closest to the surface.

The resistivity transform function T , only depends on the thicknesses and resistivities of the enclosing layers in a geo-electric section and can be computed fairly simply.

For this development, the O'Neil (1975) twenty point filter coefficients for Schlumberger array which allow sampling at the rate of six points per

decade as presented in Table 1 was adopted for the development of this software. The electrode spacing ($AB/2$) values are automatically determined starting from a fixed initial value of 1 m and increasing at a constant interval of six points per decade until the user-defined number of data point is reached.

Table 1: O'Neil (1975) 20-Point Inverse Filter Coefficients

b_{-5}	0.003042	b_5	2.7044
b_{-4}	-0.001198	b_6	-1.1324
b_{-3}	0.01284	b_7	0.3930
b_{-2}	0.02350	b_8	-0.1436
b_{-1}	0.08688	b_9	0.05812
b_0	0.2374	b_{10}	-0.02521
b_1	0.6194	b_{11}	0.01125
b_2	1.1817	b_{12}	0.004978
b_3	0.4248	b_{13}	0.002072
b_4	-3.4507	b_{14}	0.000318

PROGRAM DESCRIPTION

The Forward Modeling Software (*Synthetic_VES*)

Basically, the computation process carried out by the software is in three steps outlined below:

- (i) The use of Equation (13) provided by Das and Ghosh (1974) to recursively calculate the resistivity transform function $T(\lambda)$ for the user defined geologic model. The basic inputs for this computation are the model parameters which include the number of layers, their thicknesses and resistivity values and the number of data points ($AB/2$ values) which is computed automatically at a sampling interval of six points per decade starting from 1 m. All these parameters are supplied to the software through the input graphical user interface (GUI) segment of the software (Figure 1c) either manually or through a Microsoft Excel files.
- (ii) A click on the Compute and Plot button on the input GUI screen (Figure 1c) starts up a convolution process involving the use of the sampled resistivity transform function $T(\lambda)$ computed in step (i) above

and the O'Neil (1975) 20-point filter coefficients developed for the Schlumberger array as provided in Table 1 is carried out as mathematically expressed by Equation (12) to obtain digitized values of the apparent resistivity dataset for the specified number of electrode spacing ($AB/2$) values.

The computation process mentioned in step (i) and (ii) above is handled in the MATLAB program by a function called `forwardsim`. The source code is presented below in Appendix A.

- (iii) The computed apparent resistivity values is then plotted against the electrode spacing ($AB/2$) values on a log-log graph paper to obtain a theoretical Vertical Electrical Sounding (VES) curve for the user defined geologic model as shown in Figure 1d. This is handled in the MATLAB program by a function called `ForwardPlot1`. The source code is presented below in Appendix B.

For ease of usage, the software has been further developed into a stand-alone application which can run on any Windows-based operating system where the MATLAB Runtime Compiler (MCR) Version 7.15 has been installed. A copy of the MATLAB Runtime Compiler (MCR) Version 7.15 can be downloaded freely at the following web address: <http://aritter.webs.ull.es/Software/MCRInstaller.zip>

A copy of the stand-alone application of the newly developed software (*Synthetic_VES*) is also provided freely for reader's use and can be downloaded at the following web address: http://www.4shared.com/file/a6_Zvpxg/SyntheticVES.html

After installing the MATLAB Compiler Runtime (MCR) Version 7.15, the starting point of using the software is to make a double click on the standalone application icon (Figure 1a). This will pop-up a welcome screen (Figure 1b) which informs the user about the functionality of the software. A subsequent click on the start button

on Figure 1b then pop-up the inputs GUI screen (Figure 1c).

The software works using two modes of operations. The parameters fixed option allows for one computation at a time and the parameters varying option allows automatic generation of geologic models by varying user defined initial geo-electric parameters. Likewise, there are two methods of supplying user defined inputs to the software. One is by manual typing and the other is by uploading a Microsoft Excel file containing the inputs in a specified format. A comprehensive flowchart containing detailed instruction on how to use the software utilizing both modes of operation and input methods is provided in Figure 2.

For each computation, the apparent resistivity dataset, the user defined geo-electric parameters for the earth model and the plotted theoretical vertical electrical sounding (VES) curve is automatically saved in a folder located in the computer directory where the software is installed for future use.

LIMITATION OF THE SOFTWARE

The major limitation of the algorithm used in developing the software is that it does not allow computation for arbitrary values of electrode spacing ($AB/2$) because the O'Neil 20-point filter coefficients used are optimized for sampling at six points per decades. This inherently places a restriction on the values of electrode spacing that can be accepted and computed for. Likewise the minimum electrode spacing ($AB/2$) value cannot be less than 1 m.

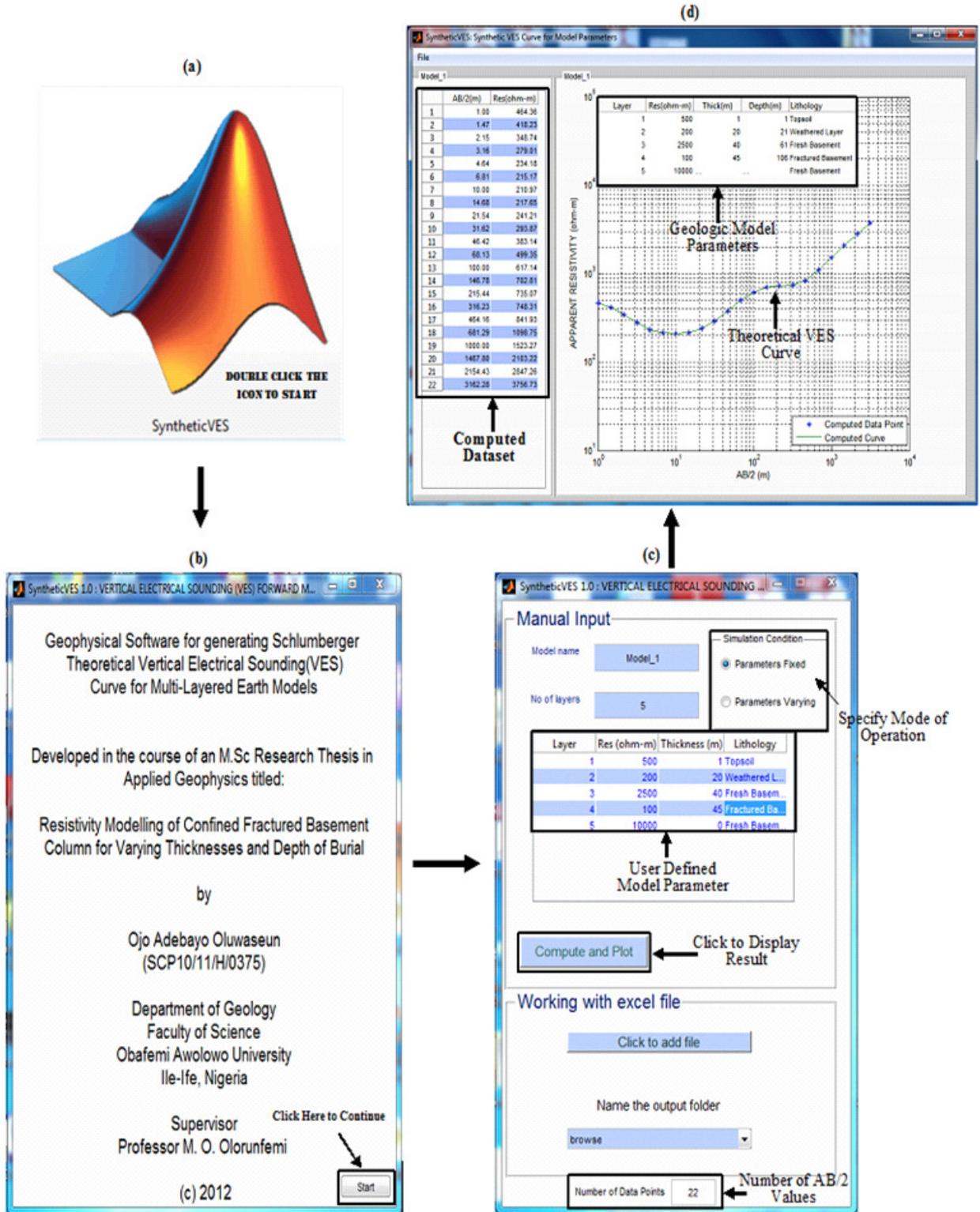


Figure 1: (a) *Synthetic_VES* Software Icon (b) Welcome Screen (c) Input GUI (d) Output GUI

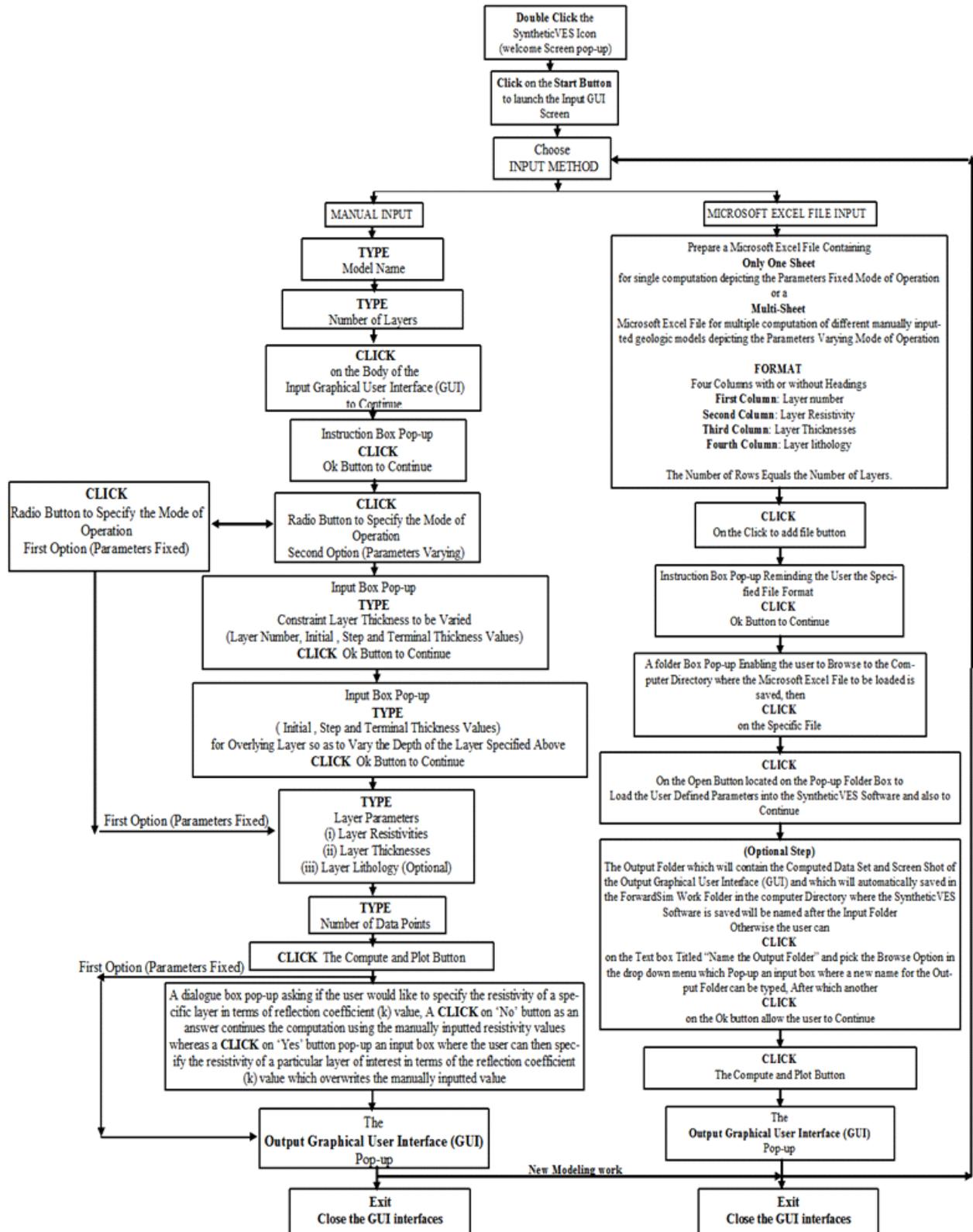


Figure 2: Comprehensive Flowchart for *Synthetic_VES* Forward Modelling Software.

ACCURACY TEST

For the purpose of reliability, any newly developed software needs to be tested for accuracy, consistency and dependability. Hence, the newly developed software (*Synthetic_VES*) was checked and analyzed for accuracy using an empirical approach proposed by Ademilua (2007). The approach involves using the newly developed software to generate theoretical apparent resistivity dataset for different geologic models. The computed apparent resistivity dataset is then inputted as field data into pre-existing renowned geo-electric sounding inversion software (WinResist v1.0) in order to recover a geologic model. The Root Mean Square (RMS) error or fitness level is then used in determining the accuracy level of the newly developed software.

Figure 3 and Figure 4 presents graphically, sample result of the accuracy test for a 3, 4, 5 and 7-layer earth model. The result showed that the geoelectric parameters of the actual geologic model used in the forward modeling step were recovered back accurately from the iterative inversion process using the WinResist v1.0 software within Root Mean Square error of 0.0 to 0.2. It was noted that none of the inversion stage allowed for any form of iteration i.e. the number of iteration was zero. This obviously showed that the computed apparent resistivity dataset is of high accuracy and that it has comparable accuracy to the forward modeling module of the iterative inversion software. Hence, it can be concluded that the newly developed software (*Synthetic_VES*) is reliable and dependable.

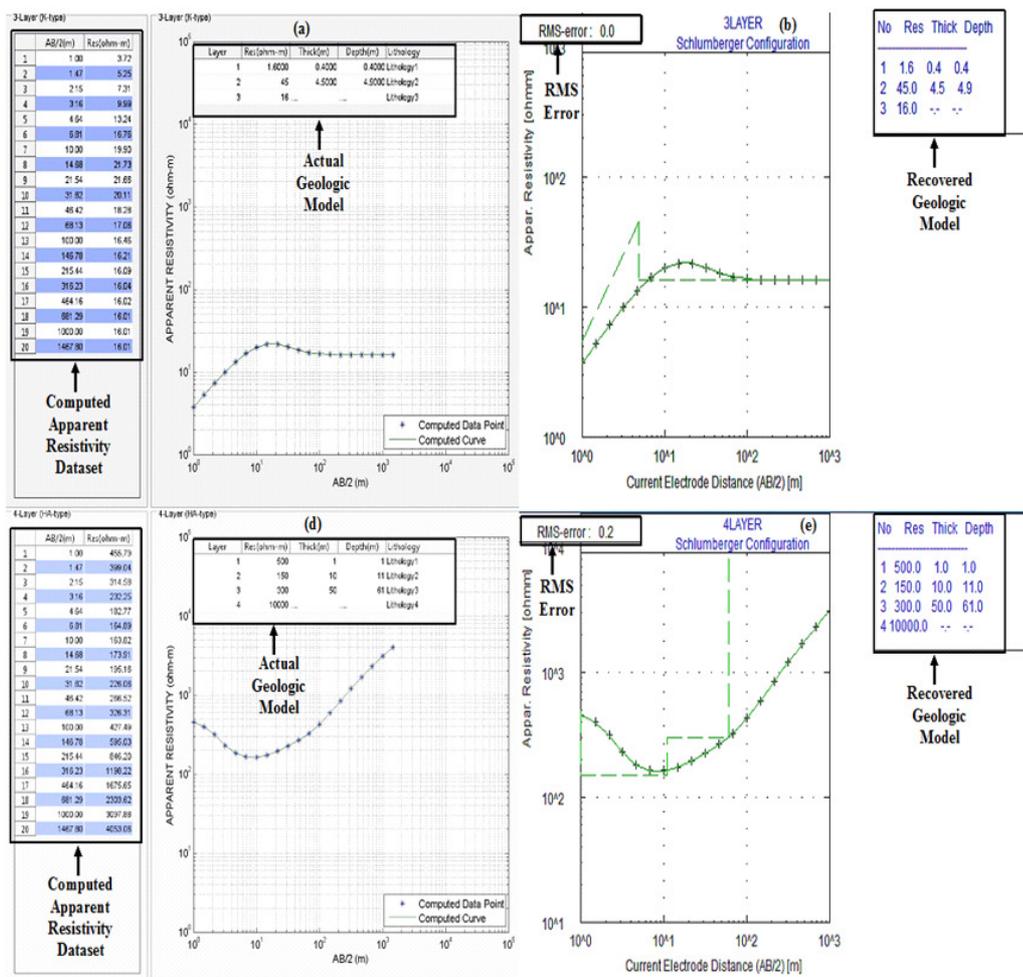


Figure 3: (a) Forward Modelling of 3-Layer Model
 (b) Inversion of 3-Layer Model
 (c) Forward Modelling of 4-Layer Model
 (d) Inversion of 4-Layer Model

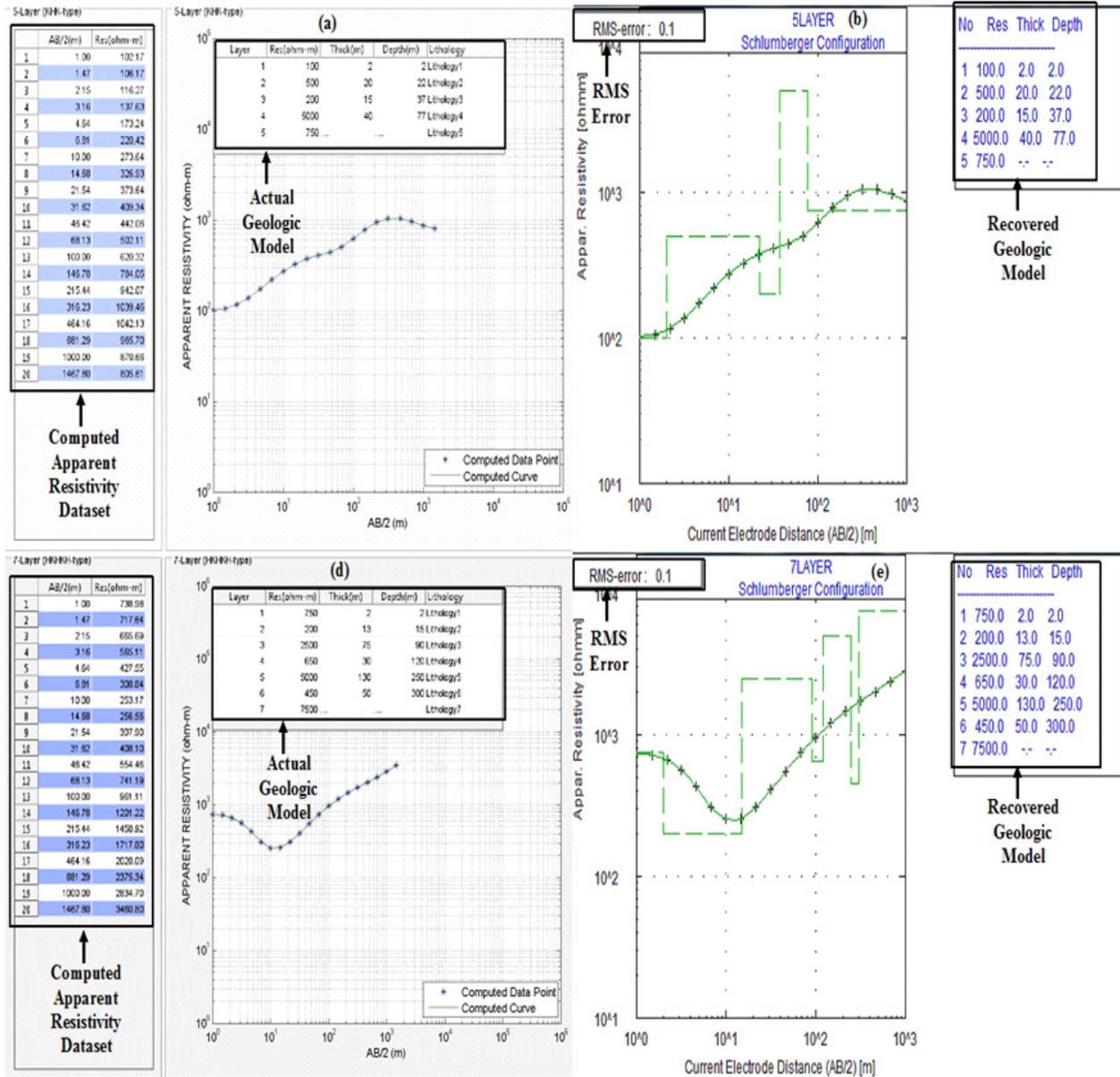


Figure 4: (a) Forward Modelling of 5-Layer Model
 (b) Inversion of 5-Layer Model
 (c) Forward Modelling of 7-Layer Model
 (d) Inversion of 7-Layer Model

CONCLUSIONS

A MATLAB-programmed 1-D forward modeling software developed for Schlumberger electrode configuration for computing the theoretical geoelectric signature over a horizontally stratified multi-layered earth model is developed and tested for accuracy using synthetic geologic models consisting of different number of layers resulting into different VES type curve is presented in this

paper. The presented forward modeling scheme is computationally simple, fast efficient and easy to use. The program simply convolves sampled resistivity transform function with linear filter coefficient to obtain digitized values of apparent resistivity which is plotted against electrode spacing as theoretical VES curve. The results obtained from the accuracy test ascertain the reliability of the newly developed software. The

program is suitable for large modeling work requiring any number of layers and electrode spacing values in addition to advance input and output functionality with ease.

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APPENDIX A

(MATLAB Source Code for the Computation Process)

```
function out_data=forwardsim(a1,a2,a3,a4,a5)
%Layer Resistivity Values=a1;
%Layer thicknesses=a2;
%No. of data_point=a3;
%No. of layers=a4;
%sampling_interval=a5;
b=[0.003042 -0.001198 0.01284 0.0235
0.08688 0.2374 0.6194...
1.1817 0.4248 -3.4507 2.7044 -1.1324 0.3930 -
0.1436 ...
0.05812 -0.02521 0.01125 -0.004978 0.002072
0.000318];
b=b(end:-1:1);
m1=2.5*a5; % first sampled data point
m2=m1+a3-1;
aaa=logspace(0,ceil((a3-1)/a5),ceil((a3-1)/
a5)*a5+1);
XVAL=aaa(1:a3); % AB/2 terms
n=1:m2+5;
L=10.^(2.556757-(n/a5));
T=zeros(1,n(end));
for ii=1:n(end)
for jj=a4:-1:1
if jj==a4
temp=a1(a4);
```

```

else
temp=(temp+a1(jj)*tanh(L(ii)*a2(jj)))/
(1+(temp*tanh(L(ii)*a2(jj))/a1(jj));
end
end
T(ii)=temp;
end
out_data{1,1}='AB/2 (m)';
out_data{1,2}='COMPUTED RESISTIVITY
(Ohm-m)';
for ik=m1:m2
TT=T(ik-14:ik+5);
out_data{ik-m1+2,1}=XVAL(ik-m1+1);
out_data{ik-m1+2,2}=dot(b,TT);
end

```

APPENDIX B

(MATLAB Source Code for Theoretical VES Plotting)

```
function hlabel = ForwardPlot1(handles)
```

```
format bank
```

```
hMainFigure = figure(...
```

```
'Units','pixels',...
```

```
'Menubar','figure',...
```

```
'Toolbar','none',...
```

```
'Name','SyntheticVES: Synthetic VES Curve
```

```
for Model Parameters',...
```

```
'NumberTitle', 'off', ...
```

```
'Position',[470 100 886 601],...
```

```
'PaperPositionMode','manual',...
```

```
'PaperUnits','inches',...
```

```
'PaperOrientation','landscape',...
```

```
'PaperType','A4',...
```

```
'PaperPositionMode','auto',...
```

```
'WindowStyle', 'normal');
```

```
hDataPanel = uipanel(...
```

```
'Parent',hMainFigure,...
```

```
'Units','pixels',...
```

```
'Title',handles.plotname,...
```

```
'Position',[0 7 222 590]);
```

```
hPlotPanel = uipanel(...
```

```
'Parent',hMainFigure,...
```

```
'Title',handles.plotname,...
```

```
'Units','pixels',...
```

```
'Position',[226 7 648 590]);
```

```
hPlotAxes = axes(...
```

```
'Parent',hPlotPanel,...
```

```
'Units','pixels',...
```

```
'YLimMode','manual',...
```

```
'HandleVisibility','callback',...
```

```
'YScale','log',...
```

```
'Position',[66 63 490 490]);
```

```
hDataTable = uitable(...
```

```
'Parent',hDataPanel,...
```

```
'Units','pixels',...s
```

```
'Position',[14 11 196 552],...
```

```
'BackgroundColor',[1 1 1;0.702 0.780 1.00],...
```

```
'ColumnFormat',{'bank','bank'},...
```

```
'RowStriping','on',...
```

```
'RowName',{'numbered'},...
```

```
'ColumnName',{'AB/2(m)','Res(ohm-m)'},...
```

```
'Data',handles.plotdata1);
```

```
hPlotTable = uitable(...
```

```
'Parent',hPlotPanel,...
```

```
'Units','pixels',...
```

```
'Position',[66 535-18*(handles.layerNo+1) 410
```

```
18*(handles.
```

```
layerNo+2)],...
```

```
'BackgroundColor',[1 1 1],...
```

```
'Data',handles.plot_table,...
```

```
'RowStriping','off',...
```

```
'RowName',{'},...
```

```
'ColumnName',{'Layer','Res(ohm-
```

```
m)','Thick(m)','Depth(m)','Lithology
```

```
{});
```

```
axes(hPlotAxes);
```

```
loglog(handles.plotdata1(:,1),handles.plotdata1
```

```
(:,2),'*',handles.plotdata1(:,1),handles.
```

```
plotdata1(:,2),'-');legend('Computed Data
```

```
Point','Computed
```

```
Curve','Location','SouthEast');
```

```
axis([1 100000 1 100000]);
```

```
xlabel('AB/2 (m)');
```

```
ylabel('APPARENT RESISTIVITY (ohm-m)');
```

```
grid;
```

```
hlabel=hMainFigure;
```

```
saveas(hMainFigure,[handles.folder '\'
```

```
handles.plotname '.jpg']);
```