GEOLOGY 454
Environmental and Exploration Geophysics I
Lab Manual
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Geophysics software used in this class will be downloaded from my shared directory as described in the following section. The software you will be using is fully functional. Its use, however, is limited to specific models or data associated with individual labs. The lab data allows you to develop familiarity with the modeling process.

Feel free to work together in pairs during class. **However**, when working together in class, you need to make sure that each of you takes the time to become familiar with the operation of the computers in the lab. **Remember** that the lab reports you turn in must represent your effort and your ideas - not those of your partner(s). The nature of one’s individual effort should be reflected and evaluated in the lab write-up.

Geol 454 is generally held in rm 419.

*The PC’s in our 4th floor Computer labs generally have the following specs*: 160GB HDD, ATI Graphics Card, Intel Core 2 Duo processor at 2.6 Ghz, Standard keyboard, Basic optical mouse, 2Gb internal RAM and run Windows XP w/ service pack 3

**Following are PC start-up procedures needed to use geophysics software in this lab -**

1. Turn on the machine.
2. Once the Windows XP screen appears, use **Ctrl-Alt Del** to bring up the login screen. Supply your username and password. After a few seconds, the Windows Desktop opens up. Yours may look a little different from the one below. Go to the start button down in the lower left corner of the window to access software. We will be using IX1D v2. You’ll want to begin by creating an IX1D shortcut on your desktop.
Exploring IX1D
The Terrain Conductivity/Resistivity Modeling Software

From the Start Programs drop-down locate the IX1D v2 folder and create a shortcut to IX1D-v2 on your desktop. A copy of this icon (see right) will appear in your PC Window. Next copy the folder IX1D-TC from the Common H:\Drive to your G:\Drive. This folder contains model files we will be using in the terrain conductivity lab.

Now double click the IX1D icon and a window similar to that below should come up.

Opening IX1D window with sounding EM1.

Soundings EM1 or EM7 will be used in this terrain conductivity lab. These soundings were acquired at well locations and provide measurements of formation resistivity that serve as constraints on the modeling exercise. On the left of the display window is a graph of the horizontal dipole (□) and vertical dipole (+) terrain conductivity measurements. The symbols □ and + will be easier to see on your computer. The horizontal dipole observations are connected by a purple line that represents calculated conductivities for the model shown at right. The y-axis represents apparent conductivity in units of milli-Siemens /meter (same as milli-mhos per meter) measured by each of the 8 coil orientations. The x-axis is the effective exploration depth (recall lecture discussions about this general rule-of-thumb idea). The effective penetration depth should not be confused with actual penetration depth. The effective exploration depth provides a useful guide to the interpreter.

In the above example, a simple two-layer model (shown in the right plot panel) has already been defined. The model graph displays subsurface depth (y-axis) versus layer conductivity (x-axis). Depths are in meters, and conductivity is in m S/m or mmhos/m. The model graph depicts the conductivity layering that can be inferred from the measured terrain conductivities.
In today’s lab, we’ll actually build a model just to illustrate the operation of the program. Next time we’ll return and get you started on the terrain conductivity lab exercise. We will begin by keying in a different starting model. You can click on the edit model icon on the IX1D toolbar (circled in red below).

Also note that you can get to the current model through the Edit Model options on the IX1D menu bar or the short cut button. A window similar to the following window should appear.

Type the following three values in for \( \sigma \) (sigma - individual layer conductivities): 50, 10, and 15 (rows 1-3 in column 1), and type in values of 10 and 20 (rows 1-2) for the thickness in the adjacent column. Your window should look like that below.
Note that the model graph on the right of the IX1D screen will automatically be updated. Now **click the forward button** and note the fitting error in the upper right text box. That number in this case may be fairly small. Click OK at the bottom right of the model entry window to see the following.

This window illustrates the relationship between the subsurface distribution of conductivity variations and the individual measurements made with the EM31 and EM34 terrain conductivity meters. Next go to **Edit Data**. The following window will appear.
The frequency of operation is noted in the left-most column. Next to that you’ll find a column of intercoil spacings, and the height of the instrument when the measurement was made (we are assuming 0 in the lab exercise). The columns labeled HMD and VMD refer to the horizontal and the vertical dipole measurements obtained from the EM31 and EM34 conductivity meters.

Take a few moments to examine the relationship of the numbers listed in the table to the numbers appearing on the graph. Recall the □ marks the horizontal dipole data and the + sign marks the vertical dipole data. Try modifying conductivities to 50, 100 & 6 mmhos/m with thicknesses of 20 and 5 meters.

Data used in these labs are keyed in already so you don’t have to type in the data listed in the lab exercises. To examine the relationship between the model (set of conductive layers) and the observations (data recorded by the terrain conductivity meters), change one of the data values in your data set (go back to Edit Data) and click the forward button once again to the effect on the data graph. In the program display window shown below the last horizontal dipole measurement of 25.03 mmhos/m was replaced with the value 40 mmhos/m. The graph shown below is obtained.

Note that the calculated lines disappeared. To get these back, you’ll have to return to Edit Model and click the forward button once more. The blue and gold left arrow on the tool bar is also a shortcut Forward modeling button. Computing the Forward model simply calculates the apparent conductivities that would be observed for the model you have defined in your Edit Model table. Forward model calculation yields the following:
Note that the proposed model (graph at right) does not produce values that come close to the change we introduced. Thus the error is larger. In my case it rose to 33%.

Change that value back to its previous value and go to **Edit Model** (i.e. 13.5mmhos/m). Change the conductivity of the second layer to 100 mmhos/m and click **forward**. Comparison of the measured and calculated data values now look very different (see below).
As you would expect, assigning a higher conductivity to the 2nd layer causes the calculated conductivities (solid lines) to rise in value. The observations would not be consistent with your proposed model in this case, and you would know that your idea about the subsurface distributions of conductivity must be incorrect.

One way to find out what might be a better solution would be to use an **Inverse modeling** approach. Let’s say we’re sure about the conductivities of the upper and lower layers and we are also sure about the thicknesses of these layers, but we want to find the conductivity of the middle layer.

To do this **Edit Model** and change the parameters in your window to look like those below.

![Resistivity Model](image)

What we’ve done by checking off the check boxes next to the two conductivities and the layer thicknesses is to **Fix** these values, so that when we try and determine the conductivity of the middle layer, the program will not vary these other parameters – only the conductivity of the middle layer.

Now click the **One Iteration** button and note how that changes the left graph (next page).
The results of the inversion appear in the Model window, and are also graphed in the main display window. If you click on More Iterations the software will do the best it can to minimize the difference between the model and observed calculations.

Results of inverse modeling process. You may get something very different.

Note that the error will drop and the Inverse model (the model we have derived by trying to minimize the errors) changes to reflect changes in conductivity of the middle layer.
Deriving a model that makes geologic sense is a key objective of the modeling process. Gaining familiarity with the modeling process is an important objective or outcome for you to achieve in this course. Incorporating your geologic background into the interpretation and modeling effort is perhaps one of the most critical aspects of the modeling process. The reason for this is that if the models you derive have little to do with the geology (do not make geologic sense) then they are of little value to anyone interested in the practical application. Sometimes inverse modeling does not provide a 0% solution. Then you have to guess – use your geological insights into the problem. Even if you obtain a solution that gives you 0% error, if the model is not consistent with the local geology then it may be worthless.

A realistic limitation of geophysical modeling is that there are several possible subsurface models that could explain the results within a certain percent error. That possibility is illustrated by the analyze equivalence option provided by IX1D. Note that the analyze equivalence option can be accessed from the icons on the main display window (see below).

Note: If you download the demo version from the Interpex web site some of these buttons do not work especially if too many changes to the input model and data are made. You can, however, make use of this functionality using the same buttons in the model dialog window.
**Analyze Equivalence**

To illustrate how the **analyze equivalence** computations work, bring up another data set. **Go to File Open (remember you can save modified files under a different name)** and then bring up EM2.IXR. Follow along in class as we build a model. Run the forward computation and then, after inversion, click on the analyze equivalence button. Your window may look like the following display.

[Image of a computer interface with graphs and data]

Raw starting model for sounding EM2

[Table showing data]

Edit the model (use shortcut buttons) and enter two additional layers as shown below.
Do a forward computation and exit to get the following.

Go to Calculate >> Inverse >> Multiple Iterations to obtain

Next go to Calculate >> Analyze Equivalence. Click on the Analyze Equivalence option to obtain the following:
The dashed lines shown in the subsurface model at left (above) depict different subsurface models, each of which will yield similar apparent terrain conductivity observations at the surface. The above comparison of equivalent models illustrates the kind of ambiguity that can exist in an interpretation. These equivalent models *emphasize the importance of the role that the geologist plays* in determining which interpretation, of all the possible interpretations, is the one most consistent with the geology of that particular area.

Generally the evaluation of *equivalent solutions* is conducted in a more refined manner. You may wish to evaluate the possible range of thicknesses that might be associated with the aquifer. In this case you could fix certain parameters as shown below.

In the above model window, the conductivities of the upper and lower layers in the model have been fixed. We assume that these conductivities don’t change much from their values at the logged well. We also fix the thickness of the upper layer, again, assuming that this layer is relatively constant in thickness across the area.

Next> click the Forward button
Then > click the One Iteration button

This will yield the following display.
Now click on the **Analyze Equivalence** icon on the IX1D toolbar. This yields the following result.

You can see that the range of possible options has decreased. You can move your mouse tip to the various dashed lines in the model (plot on the right side of the display window) and read off the values of depth and conductivity (see below).
All of the geophysical modeling exercises we undertake will incorporate an analysis of equivalent solutions. This helps the geologist/geophysicist accurately convey the limitations of the model to the client. A sound geological interpretation is an essential component of the geophysical modeling process.

*And that is why good geologists make the best geophysicists!*

Name: ____________________  

Geol454: In-class exercise. Terrain Conductivity inversion

Pick one the soundings EM2 through EM6, Go through the modeling process and write down the conductivity and thickness of the contaminated zone after inversion. Explain your result within the context of the problem.

\[ \sigma_{\text{contaminated layer}} = \text{___________} ; \quad \text{Thickness of contaminated layer} = \text{_______________________} \]

Comment:
A copy of this practice sheet will be handed out in class.

Practice sheet for EM soundings 1 through 6

Spend some time exploring the capabilities of the program.

Depth to base of aquifer constrained by local geologic mapping and well control in the surrounding area?

The formal lab requires that you analyze soundings EM7 through 12. Develop models of these soundings for practice and discussion this Thursday.
Between now and Thursday:
Spend some more time familiarizing yourself with the IX1D modeling software. Try and complete the cross section on the preceding page.

On Thursday, we will introduce the terrain conductivity lab problem.

Review Terrain Conductivity Lab 2 (see class web page 6) and discussion slides. As we work through the analysis of data for the lab (soundings 7 through 12) consider bringing up word and making screen captures. There is a link on Thursday’s 6.0 topic on the class page titled “copying images into text.” Have a look at this procedure if you do not already know how to do this.

Refer back to report guidelines and remember to show and refer to key figures in the lab discussion. Be selective. This will help you prepare an effective lab report.
ELECTROMAGNETIC TERRAIN CONDUCTIVITY COMPUTER LAB
Electrical conductivity lab

Evaluating the extent of groundwater contamination from a leaky landfill

Electromagnetic methods are frequently used in the geophysical assessment of hazardous waste sites. Background on the most commonly used EM survey tools and methods is provided in Chapter 8 of our text (Berger, Sheehan and Jones) and in the article by McNeill titled *Electromagnetic Terrain Conductivity Measurement at Low Induction Number*. The main points from McNeill’s technical note have been covered in class lecture. The results of EM surveys conducted for various types of site investigations are presented in the articles on reserve in the 4th floor mail room.

This computer lab is designed to give you some brief but practical experience with the analysis of EM sounding and profiling data and development of a subsurface conductivity model. The exercise is designed specifically around the analysis of EM data collected by commonly employed EM-instruments in shallow geotechnical investigations (the Geonics EM31 and EM34).

**Background scenario for the exercise:** A small community is located down the hydraulic gradient from an industrial waste site. Local inhabitants are concerned about the possibility that leaky sludge ponds and wastewater lagoons at the site may contaminate residential aquifers. The possible presence and extent of contamination was evaluated through terrain conductivity soundings collected along a transect across the area. Terrain conductivity data was collected using the Geonics EM 31 and EM 34 conductivity meters; the full range of intercoil spacings (3.66, 10, 20, and 40 meters) for both horizontal and vertical dipole orientations were employed.

In this lab, we examine the results obtained from six electromagnetic conductivity soundings collected at 25 m intervals along one profile down gradient from the site. The sounding profile crosses the area at right angles to the hydraulic gradient. Water wells in the area along with limited borehole data reveal little variability in the depth to, and thickness of, the aquifer in the survey area.

Subsurface geology in the area is known based on the interpretation of data from several boreholes in the area. Two of these boreholes were logged to provide information about the resistivities of stratigraphic intervals encountered in the area. These resistivity logs (along with the other boreholes in the area) reveal that the aquifer (an unconsolidated sand) lies at a relatively constant depth of 10 meters beneath a near-surface clay layer. The borehole resistivity logs indicate that the near-surface clays have resistivities of 20 ohm-m on average, while the uncontaminated aquifer has an average resistivity of about 100 ohm-m. In the vicinity of the survey, the aquifer is approximately 20 meters thick across the area and is underlain by a thick silt zone that has a resistivity of approximately 66.7 ohm-m.

You can bring a shortcut to the modeling program IX1D onto your desktop by right-clicking the program in your start > all programs > IX1Dv2 folder, dragging it on the desktop and selecting the...
*create shortcut* option. Copy the IX1D-TC folder from the common drive to your personal N:Drive. Save all results to your N:Drive.

**Remember – Soundings EM1-6 are just for practice. Hand in cross section before leaving today.**

The borehole data referred to in the above background discussion were collected at sounding 7 (EM7). A listing of the individual sounding data is presented below. Ask questions if you aren’t sure what the data below represent. These data are already entered as sounding data for EM7 through EM12. At this point, you should have an understanding of how these data are obtained.

Table 1: Each row in the table lists measured conductivities for the two instruments we’ve been studying (the EM31 and EM34) for each dipole configuration (vertical or horizontal).

<table>
<thead>
<tr>
<th>INSTR.</th>
<th>DIPOLE ORIEN.</th>
<th>COIL SPAC. (m)</th>
<th>CONDUCTIVITIES (mmhos/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7   8 9 10 11 12</td>
<td></td>
</tr>
<tr>
<td>31 V</td>
<td>3.66</td>
<td>40.11 42.48 42.6 42.71 42.63 42.8</td>
<td></td>
</tr>
<tr>
<td>31 H</td>
<td>3.66</td>
<td>45.02 46.25 46.41 46.36 46.32 46.4</td>
<td></td>
</tr>
<tr>
<td>34 V</td>
<td>10</td>
<td>27.40 35.2 34.0 35.53 35.46 35.2</td>
<td></td>
</tr>
<tr>
<td>34 H</td>
<td>10</td>
<td>35.16 42.89 42.2 43.05 43.00 42.9</td>
<td></td>
</tr>
<tr>
<td>34 V</td>
<td>20</td>
<td>19.25 41.9 30.6 38.9 40.19 35.0</td>
<td></td>
</tr>
<tr>
<td>34 H</td>
<td>20</td>
<td>32.2 48.33 40.99 46.48 47.29 44.0</td>
<td></td>
</tr>
<tr>
<td>34 V</td>
<td>40</td>
<td>13.50 37.0 21.04 30.68 33.00 25.4</td>
<td></td>
</tr>
<tr>
<td>34 H</td>
<td>40</td>
<td>25.03 49.37 35.16 44.41 46.31 39.7</td>
<td></td>
</tr>
</tbody>
</table>

The following models should not require much time to develop. The process should be familiar to you by now. **Station 7 is located near the borehole mentioned above.** Geographically you can think of station 7 as being on the left (let’s call it west) end of an east-west oriented transect. The three conductivity layers revealed in the borehole log tell you what your starting model should be for sounding EM7.IXR, at station 7.

Enter the model. Remember how to convert from Ω-m to mmhos/m? You have three layers that from top to bottom have resistivities of 20, 100, and 66.7 Ω-m. The thicknesses of the upper two layers are 10 and 20 meters respectively. The third layer, within the context of our near-surface focus of investigation can be considered bottom-less. The last layer in these models never has a thickness specified.

Conductivity (σ) is just the reciprocal of resistivity (ρ). So your model values for σ will be ____, ____ , and ____ , for the upper clay, potable aquifer, and underlying silt, respectively.
After you enter the data, click the FORWARD button and note your error. Your error should be very small since your model was derived from subsurface measurements of resistivity (conductivity).

Remember, based on the borehole data and interpretations, the geologist tells us we can assume: 1) that the surface clay layer is everywhere 10 m thick and has a constant conductivity, 2) that the aquifer interval, if uncontaminated, has constant conductivity of 10 mmhos/m, and 3) that the underlying silt layer also has a constant conductivity (15 mmhos/m) across the profile. Within the context of the model defined by the geologist, then, we assume that the aquifer, if contaminated, will consist of a contaminated layer and a freshwater layer. Although the contaminants are denser than water and the transects are close enough to the source so that contaminants are still migrating down through the aquifer.

Given these assumptions, stations 8 through 12 will be modeled using a 4 layer conductivity model (see figure below): that is, by three finite-thickness layers corresponding to 1) the upper clay layer (10 meters thick), 2) an upper contaminated zone in the aquifer (of unknown thickness), and 3) a lower fresh water zone (also of unknown thickness). The deepest layer is a semi-infinite half-space representing the lower silt interval. While we do not know what the thicknesses of the contaminated and uncontaminated portions of the aquifer are, we do know that their combined thickness will be approximately 20 meters. We are simplifying things by assuming that the contaminated water occupies the upper part of the aquifer and that fresh water occupies the lower part of the aquifer. The conductivity of the contaminated water leg is, therefore, the only unknown conductivity. Hence, it will only be necessary to free the conductivity of the contaminated interval (leave the fix box unchecked for that conductivity).

During the inverse calculations, use the FIX option and FREE (i.e. leave unchecked) only the conductivity of the contaminated aquifer interval, and the thickness of the upper contaminated and lower uncontaminated parts of the reservoir. The remaining parameters will be fixed.

Now, develop models for soundings EM8 through EM12. Remember, the starting model has 4 layers and 4 conductivities (50, 10, 10, and 15 mmhos/m, top to bottom). All but the contaminated aquifer conductivity will have the Fix box checked. You can start with thicknesses of 10, 10, and 10 meters for the clay, contaminated and uncontaminated aquifer respectively. Only the thickness of the upper clay layer will be fixed. Typical starting model shown at right.

Exit the model window and use the Forward button on the menu bar at top. Note the result. Next click the One Iteration icon. Note how the free parameters begin to adjust.
Calculating equivalent solutions
Within a certain range of error there are several equally valid results regarding the thickness of the contaminated zone estimated at each sounding. One reason for this is that real data are often noisy. Noise can arise in terms of variation in surface conditions, environmental noise (metal objects you don’t know about, underground irregularities associated with non-geologic debris and so on. To make an estimate of the range of possible answers to the question “How thick is the contaminated zone?” you have to leave some error (i.e., some differences between the observed and calculated values) in the results. The data we are working with is model data, so the error can be reduced almost to zero, but again, in practice, with real data, you will almost always have some remaining error that you cannot eliminate.

For this exercise, you need to leave at least about 5% error in the results for the soundings you use to estimate equivalent solutions. To do this, you can click and drag the conductivity of the contaminated layer as well as the depth to the base of this zone to increase the error between observed and calculated values. Alternatively, you can do this directly in the model window by simply by changing thickness/depth and conductivity. Throw the result off to about 30% or so, because you will have to rerun one iteration in order to compute equivalent solutions and this will reduce the error once again. You may have to go back and forth with these adjustments a few times to get enough error in the calculations to work with. But it all happens quickly. When you get a model with significant error, save it, so you can come back to it for reference.

Click the run equivalence icon and note the various equivalent solutions (see Figure 2). Equivalent solutions tell you about the possible variations in the thickness of the contaminated zone in the aquifer. How did it work out for the two examples you chose. Note maximum and minimum thickness and conductivity and jot down your results.

After answering that question run more iterations to minimize the error. These models are so easy to run and rerun it only takes a few minutes to explore numerous possibilities. So experiment.

Save your final model as Em8_your initials or your name.IXR. For example, EM8TW.IXR or EM8_wilson.IXR. Keep track of your results. On table provided, write down the resultant conductivity for the contaminated zone, as well as the thicknesses of the upper contaminated and lower uncontaminated portions of the aquifer. Locate these boundaries on the cross section provided in class. Repeat the process for soundings EM9 through EM12. At each point transfer your results to the cross section. Print off the results for two of your equivalent models (e.g. see below) and include them in response to questions.

What do the equivalent models tell you?
Do the equivalence models suggest that the contaminated interval is well defined by your original inversions? For example, do you feel that you know the thickness to within a couple meters – within 10 meters? Note that the way we’ve set up our model, only the conductivity of the contaminated portion of the aquifer along with its thickness and the thickness of the fresh water intervals in the aquifer are free to vary. Hence the equivalent solutions are obtained by varying only
these three parameters. The main reason for doing this is to gain some understanding of how reliable your results are. Also, if you are working for a client, you want to let them know your answers aren’t exact, but that you know that the contaminated zone is within a certain range of thickness with error you note. So, again, what do you think, do the equivalent solutions suggest variability is possible within the error you left in the solution? How would you express it?

Also note that while the combined thickness of the fresh and contaminated water intervals in the model you obtain may exceed 20 meters, don’t forget that the geologist tells us that the thickness of the aquifer doesn’t vary much and is on average about 20 m thick. Hence, you should adjust the thickness of the freshwater zone so that its base lies at 20 meters. Note that the error will still be quite small after you readjust the thickness.

Figure 2: Illustration of an intermediate step in the modeling process set up for estimation of equivalent solutions. 14% error was left between the observed and calculated conductivities. The different, equivalent, solutions—all showing a similar level of error—are plotted as dashed lines in the conductivity model at right.

**Read over this guide carefully.** Ask questions if you are unsure about what to do.

**Assignment:**
Things to do for next time: go through the modeling of each sounding and bring your results to class in table form as shown below. I will make a brief in-class check of your results. Remember that the thicknesses of the contaminated and uncontaminated portions of the aquifer add to 20 meters.
1) Fill out the following table. \( T \) represents thickness and \( \sigma \), conductivity.

<table>
<thead>
<tr>
<th>Sounding</th>
<th>EM7</th>
<th>EM8</th>
<th>EM9</th>
<th>EM10</th>
<th>EM11</th>
<th>EM12</th>
</tr>
</thead>
<tbody>
<tr>
<td>T=thickness</td>
<td>T</td>
<td>( \sigma )</td>
<td>T</td>
<td>( \sigma )</td>
<td>T</td>
<td>( \sigma )</td>
</tr>
<tr>
<td>Clay</td>
<td>10</td>
<td>50</td>
<td>10</td>
<td>50</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Contaminated Zone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fresh Water Zone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower Silt</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Answer the following questions and hand in with the table above and your labeled cross section.

You estimate that the conductivity of the contaminated zone is 90mmhos/m.
2) The resistivity of the contaminated zone is a) \( \frac{1}{2} \) that of the fresh water zone; b) Eight times the resistivity of the fresh water zone; c) one-ninth the resistivity of the fresh water zone; d) one-eighth the resistivity of the contaminated zone.

3) The depth of penetration of the EM31 vertical dipole configuration is a) 12 feet, b) 18 feet, c) depends on layer conductivities, d) all of the above.

4) In Figure 2, the base of the contaminated zone a) lies between 12 meters to 14 meters beneath the surface, b) 15 meters to 20 meters, c) is 4 meters thick, d) none of the above.

5) choose 2 soundings (other than sounding 7), illustrate the thickness range of the contaminated zone. Show your findings in a labeled figure and state them in the figure caption. Make sure you work independently and that you choose different soundings than those you are working with.

**Assignment is DUE ___ Thursday, Sept. ____**
Start by copying the folder IX1D-Res from the common drive to your G:\drive.

From your start programs list go to IX1D v2 and bring up the program. If you haven’t done so already create a shortcut to IX1D v2 on your desktop.

Open up sounding SS1 in the folder IX1D-Res. The layout should appear as below and be updated to show labels of apparent resistivity and resistivity on the data and model plots.

Next, click on File > New > Sounding > DC Resistivity Sounding and select Wenner as the Array Type (see below).
In the data Entry/Edit window (below) enter the spacings listed in the in-class problem and the Apparent resistivities you computed from the voltages and current given in that problem.
Your data plot should look something like that shown below.

Do you think all the data are good? Is there a bad data point in the observations?

Local pockets of high or low resistivity materials often contribute “noise” to the data. These lateral near-surface inhomogeneities often lead to scattering of apparent resistivity in the resistivity sounding.

Note that back in the entry/edit window you can mask bad data points. This will leave them in, but prevent them from influencing the computations.

Consider the following questions. Based on the apparent resistivities measured in this survey, how many layers would you guess are responsible for the observed apparent resistivity variations?

What would you guess are the resistivities of these layers?
What would you guess is the depth to the boundary between the near surface layer and the one below?

Next create a model that incorporates your guess. Put in the two resistivities and depth. Your model entry
My guess wasn’t too good. How did you do? Now go through the inversion process. What is the likely depth to the boundary? What are the likely resistivities of these two layers?

You may have some trouble converging on a solution. If you do, then manually adjust the layer depth so that you get you in the ballpark and then continue with your inversions. The manual adjustment can be done because you know there are two layers and it looks like the lower layer is at a greater depth.

In this example, you’ll be left with more error than you’ve encountered previously working with the terrain conductivity lab data. Run equivalence and report your results below. Tear off and hand in before leaving class today.

Inversion of this Wenner resistivity data yields a _____ layer model. The layers in the model have resistivities of ________, ________ & ________. The depths to the top of each layer are ________, ________, & ________. What is your RMS error? ________

Name:__________________
Part 1

Exploring for Fresh Water Aquifers in Glacial Deposits

This problem is based on the data sets presented in Frohlich’s paper. As you work through the analysis of the data given here, familiarize yourself with the discussions and conclusions presented by Frohlich.

PROBLEM: The basis for this lab is centered on the analysis of five Schlumberger soundings collected over glacial drift for the purpose of locating a fresh water aquifer. In this exercise you can assume that the center-points of each sounding are located equal distances from each other. However, refer to class slides for more detailed view of survey locations. The soundings (referred to herein as S1 Through S5) correspond to D.S. (depth soundings) 7, 24, 25, 26 and 27 located west and north of Tindall on Figures 1 and 7 of Frohlich’s paper (also see class slides). Fresh water aquifers are present in gravel bodies in these glacial deposits. The gravels are confined to preglacial stream channels. The soundings you will analyze in this lab were collected in approximately the same locations but using a newer model resistivity meter. The data you will be working with is less noisy than Frohlich’s.

Drill hole investigations reveal a section consisting generally of near-surface clays. These clays are often differentiated into shallower less conductive yellow clays with resistivities of between 15 and 25 ohm-m that overlie more conductive gray clays that have resistivities of between 5 and 15 ohm-m. Clay with sand is sometimes encountered in the area. The resistivities of the sandy clay generally lie between 30 and 35 ohm-m. Gravels at the base of the drift may form fresh water aquifers and have resistivities between 40 and 50 ohm-m. These gravels lie above a limestone bedrock that has resistivity between 45 to 55 ohm-m. Near surface gravels are also common in the area. These gravels contain potable water and have resistivities that range from 60 to 110 ohm-m. The main reasons for conducting these surveys is to locate aquifers suitable for farmland irrigation and domestic waters supply. Read through Frohlich for more details.
A comprehensive analysis and interpretation of these soundings is quite difficult: the geology is much more complex than we worked with in the terrain conductivity lab and the equivalent solutions give rise to many possible solutions. You will undertake limited analysis of the data to gain insights into some of the modeling and interpretation challenges one encounters in complex geologic environments.

**PART 1 - RESISTIVITY MODEL DEVELOPMENT**

Undertake the following tasks.

1) The soundings used for this lab effort are stored in the **IX1D** directory S1.IXR through S5.IXR. These data sets are slightly different from those illustrated in the following pages. The illustrations in the following pages use data from Frohlich’s paper. They are very similar to the data you will analyze and are reviewed here to illustrate general modeling approaches.

2) Enter the resistivity-modeling program IX1D modeling program.

3) Resistivity-modeling is very similar to terrain conductivity modeling and uses the same program. Once in IX1D, go to **Open File** and open the first sounding – S1.IXR.

4) The view shown in the figure below will appear. At this point we will consider the qualitative approach to model development referred to as the *inflection point* technique discussed in class. We will use this procedure to develop a rough estimate of the depth to different resistivity boundaries associated with the sounding response. This estimate will serve as a preliminary model. Refer to class discussion and slides.

![Image of resistivity data](image)

**Figure 1: SS1 data.**

5) Based on class discussion input the starting model S1. S1 is similar to SS1, but a little less noisy.
6) Run the forward model computation just as you did in the preceding terrain conductivity lab. Spend some time modifying your starting model with the mouse to obtain better accuracy. This will give you some appreciation of the sensitivity of the apparent resistivity measurements at different spacings to changes of depth and actual resistivity in the subsurface.

It’s interesting to try and guess what the distribution of layers is along with their resistivities, however, as you probably found, your guess may not have been very close. The most useful information you can take advantage of from the shape of the resistivity sounding curve is the minimum number of layers needed to produce the low and high apparent resistivity changes observed in the sounding. Add enough layers to account for these apparent resistivity variations.
7) Now run the inverse computations a few times. Your fit should be a little better (see below).

![Figure 4: Model obtained after multiple inversions.](image)

8) Notice that we have a bad data point that will increase error and reduce accuracy of you derived model. Mask that point in Edit Data. In sounding SS1 the bad data point corresponds to data point 5 (see below). Return to edit model and run additional inversions.

![Figure 5: Mask or turn off the bad data value for point number 5.](image)
9) At this point save the results you obtained for S1 as S1-Initial_Your Initials. Then, calculate equivalent solutions as we did in the conductivity lab. You’ve recognized that it is important to **have some hypothesis in mind when you run equivalence**. You want to have a specific problem in hand to evaluate. For example, let’s evaluate the significance of the resistivity and thickness of the high resistivity interval located at a depth of about 5 meters. **Fix parameters** as shown in the figure below, close the window, and do **one forward and one inverse computation**.

![Resistivity Model](image)

Figure 6: Re-enter the inverse model derived earlier, and fix layer parameters as shown above.

Now **run equivalence**: your result should look somewhat like that shown below.
Figure 7: Equivalent solutions shown in dashed lines for resistivities and thicknesses fixed as shown in Figure 6

In the example (Figure 7), the equivalent solutions indicate the presence of a very high resistivity (~1000 $\Omega$-m) layer that is very thin. We know this is unlikely based on the background information we have regarding the resistivities of the fresh water aquifers in the area. Near surface fresh water gravels have resistivities that tend to vary between 60 to 110 $\Omega$-m. Could the resistivity be much actually be higher? Of course, but it seems unlikely that it would be that much higher based on available background information. Results that are most consistent with the background information on the area correspond to equivalent solutions that have resistivities of about 100 $\Omega$-m. The equivalent solutions indicate that this lower resistivity zone can also be modeled by a much thicker fresh water zone that extends from about 2 meters to 10 meters subsurface using a resistivity similar to those reported in the area.

9) Now begin modeling the remainder of your soundings (S2-S5). For the remainder of the soundings, start by making sure that there are enough layers in your starting model to account for the changes of apparent resistivity observed in the sounding data. This can be done quickly by examining the data in your main display window (for example, see data display for sounding SS2 below). Data for sounding S2 is similar to SS2 observations.
Figure 8: Data from Sounding 2. To get started, estimate the number of layers and their resistivities. While this involves a good bit of guess work, remember getting the right number of layers in the starting model is the key issue.

Set up each model with the appropriate number of layers and then run the inversion a few times to reduce the error. Assuming that you have included enough layers in your model, IX1D will usually develop a model that has less than 5% error.
Bringing it all together

a) For the remainder of today, concentrate on deriving models for each of the 5 soundings. Bring your results to class this Thursday for discussion. How could your derived models be translated into the geology of the area? In other words, what lithology would you associate with each layer in the models you developed?

b) Next time we will talk about the need to refine your models. You know a lot about the area and interpretations of these soundings are presented in Frohlich’s paper. By Thursday compare your models to those obtained by Frohlich and consider if it might be necessary to make some modifications to your initial models. Did you get enough layers in your starting model? Does the range of depths you obtained look similar to that obtained by Frohlich?

Following additional discussion this Thursday begin preparing the following materials for submission as part of this lab assignment.
1) Make copies of the models you obtained for each sounding. Bring them into a word document and label the layers in each sounding.
2) In your figure captions note thickness of any aquifers you believe are present in your results.

The resistivity lab will be due __________. There will be some additional discussion of the lab and opportunity to ask questions. Part 2 concerning the equivalence solutions will be introduced ________
Discussion

We have mentioned several times in class that subsurface distributions of conductivity and resistivity derived by the computer to explain anomalous variations of observed apparent terrain conductivity and resistivity are non-unique. There are a large number of different geometrical distributions of physical properties that will yield similar or equivalent results. Several of these may be geologically plausible.

Inverse models are inherently non-unique. In the terrain conductivity model studies we had fairly rigid constraints. For instance, we had significant information about the subsurface environment. We knew that the upper clay layer had a relatively constant thickness and conductivity. We were also fairly confident that the aquifer had a relatively constant thickness, and that the underlying clay had constant conductivity. This helped to significantly constrain the numbers of variables that could affect observed terrain conductivity across the area.

The geologist uses all available data to help constrain their modeling efforts. We also make practical compromises in the lab so that we can get through the course in one semester. This also happens in the workplace: you have a deadline you must meet – no matter what. Nature is never quite as simple as inverse models portray it. In this resistivity lab, you are faced with the challenge of analyzing real data from a very complex depositional environment. Glacial channel deposits consist of extremely heterogeneous distributions of various sediment types. In addition, one of the key distinctions sought in Frohlich’s survey effort is not clearly defined by a significant difference in resistivity. The intrusion of brackish formation water through fractures in the limestone bedrock reduces bedrock resistivity so that basal gravel aquifer and limestone bedrock may have little if any difference in resistivity. The uncertainties in subsurface interpretation are inherent to any situation where subsurface control is incomplete. We always end up making some kinds of assumptions and we need to evaluate those assumptions carefully and keep them in the forefront of the interpretation. Depending on the time and financial constraints under which you are operating and the requirements of the project for precision, you may be satisfied with a rough idea of what’s going on. On the other hand if greater precision is needed, you may want to consider alternative geophysical methods such as refraction seismic or gravity surveys. The resistivity data in this case may provide a rough glimpse that can be further refined using additional geophysical techniques or selective drilling of additional exploratory wells. What one does and how well one can tightly constrain their interpretations usually boils down to $$. The resistivity analysis you are currently undertaking will illustrate the variability of possible solutions that are obtainable from the same data. We have some subsurface descriptions from wells in the area that reveal the glacial drift to be a complex mixture of sands, clays and gravel
with different resistivities. The bedrock itself is also not homogeneous. The number of possible variables increases, and with it, so does the number of equally probable or *equivalent* interpretations.

The program IX1D that you used to analyze the resistivity soundings in **part 1** of this lab provides a useful option for us to evaluate the range of possible or equivalent solutions. This **part** of the **Resistivity Computer Lab** is designed to give you the opportunity to examine the range of equivalent solutions and to consider their possible geological merits.

**Additional Lab Activities**

a) **Analyze Equivalence:** After you have completed the inversion and achieved a relatively good fit between the calculated and observed apparent-resistivities, run the **ANALYZE EQUIVALENCE** operation on at least two soundings.

As you know from the terrain conductivity lab, the **ANALYZE EQUIVALENCE** option will calculate a series of models, all of which, yield calculated apparent values (conductivity/resistivity) that are within a certain error threshold of the **observed** apparent resistivity values. This threshold is determined by the remaining error you leave between the model calculations and the actual observations of resistivity.

b) **FIX** certain resistivities and thicknesses or depths in your model to test your idea. Consider the following examples:

1) Since you are trying to evaluate the reliability of fresh-water aquifer identification, choose a suspected aquifer interval and evaluate the range of possible thicknesses, depths and resistivities for that interval that could give you similar answers. Ask yourself: Do the range of equivalent answers all support the presence of a fresh-water aquifer? What is the range of possible depths to the top of the aquifer? What is the range of possible thicknesses?

2) If you think you have identified the contact between a basal gravel aquifer and the limestone bedrock, try using the equivalence options to evaluate your conclusion. There are several possibilities here, one of which may be that the increase in resistivity deep within the subsurface may not actually be there. In other words if you were to remove the interface or eliminate the resistivity contrast across it you would get nearly the same answer within an allowable percentage of error. Your equivalent solutions should indicate that as a possibility, if so.

**What idea would you like to test?** Pick a problem to explore and explain. Remember to leave about 5 % error or so in your inversions so that you can get a realistic assessment of the potential variability present in an interpretation. Calculations are made twice for each of the model parameters: once to find the upper bound (defined by the error threshold) by increasing the model parameter, and once to find the lower bound by decreasing the model parameter.

Not required, but if you wish to explore, note that from your print window you can check only the **print layered equivalence information** box to obtain more detailed information about equivalent solutions (see below).
As we did in lab the other day, we derived a model for sounding SS1 from the example data set (see below). Note this sounding is similar to your sounding S1 and is located close to well control to help constrain your model result.

Figure 2: This model is set up to test the range of possible solutions associated with the freshwater aquifer located 8 meters beneath the surface with resistivity 135Ω-m. The result is shown on the next page.
In the model shown below the RMS error after inversion is 4.5%. Some of the model parameters were fixed to test the range of possible thicknesses, depths and resistivities that could exist for the 6-meter thick high resistivity interval (possible shallow fresh water aquifer) encountered at a depth of 2.1 meters (below).

The graph above reveals that this high resistivity interval **could have lower resistivity and be much thicker**, or it **could have higher resistivity and be much thinner**. Frohlich has told us that the shallow fresh water gravels have resistivity of approximately 100 Ω-m, and so, on that basis, we would go back to our model and use that information to make the “appropriate” changes to the resistivity and thickness of this interval. These changes would make the model consistent with what is known about the resistivity of subsurface intervals or believed to be known. There may be some validity to various alternatives; however, we generally constrain models to be consistent with the background geology unless we personally have additional data that suggests otherwise.

For practice undertake a similar evaluation of Sounding S1. But, for this exercise, focus on the possible range of depths to bedrock. Note equivalent solutions. Is a bedrock depth of about 32 meters an equivalent solution? Also remember (although not required for this lab) that you can use the print layered equivalence information option to view tabulated listings of the minimum, maximum and best fit values for each of the parameters in your model.

Figure 3: Remember we know the answer should be similar to the result Frohlich obtains for this sounding since borehole data are available near this sounding.
Bringing it all together

1) Make copies of the models you obtained for each sounding. Bring them into a word document and label the layers in each sounding.
2) In your figure captions note thickness of any aquifers you believe are present in your results.
3) Illustrate your analysis of Sounding 1 (see page 35, Figure 3 above and lecture slides) in the same document file. Does placing bedrock at 32 meters give you an equivalent result with low error? Comment in your figure caption.
4) Pick one additional sounding (different from those working next to you) and evaluate the possibility of an alternative result or interpretation. Include a figure showing the equivalent solutions. Label, and in your caption, explain what idea you tested and what the equivalent solutions suggest about the possible range of results and interpretations.

The resistivity lab will be due on Thursday October 15th. There will be some additional discussion of the lab and opportunity to ask questions next Tuesday and the Thursday following the midterm exam.
INTRODUCTION

Modeling the Earth’s gravitational field

An Introduction to the Gravity Modeling Software GM-SYS
Introductory Lab - GM-Sys

Start Programs

The gravity and magnetics modeling software we'll be using is accessed through the Start Programs program-list. Click on the Start button (above), and then go up to Programs and open up the program list, and there you should see the program GM-SYS 4.7.

You can right-click and drag a shortcut onto the desktop. Double click to start the program.
Today in this brief introduction, we will open a simple subsurface model that consists of a small cave buried beneath the floor of a narrow valley. Before we can go any further, copy the file `cave.sur` from the `Common:Drive` to your network `N:\drive`.

From the **File** button on the main menu bar at top, **Open cave.sur** from the `G:\Drive` or other directory. In the window that opens you will see two sub-windows. Changes in the gravitational field across the valley and underlying cave are shown in the upper pane. The subsurface model is shown in the lower pane.

You may have a lot of extra lines or curves in the upper data display. To simplify this view go to **Gradients** and **uncheck** the Enable Grav. and Mag. Gradients options. Then under **Display >>** uncheck the Grav Err. Option.

### Notes
In this demonstration, we’re just going to illustrate some basic operations that will allow you to modify display parameters, change the cave geometry around, and evaluate the effect of changing density contrasts.

To begin with, right click in the gray axis area to the left of the gravity observations and calculations window (as shown at below).

Select **Change Range** and the window (right) will appear. **Change the min to –4 and the max to 1.** Note change in the appearance of the calculation window.

Next, right click on the calculation window to bring up the following selection boxes.
You can choose to display observed and calculated gravity, and you can also select to show gridlines (as shown). A show gravity gradients option will also show up if you have the Gradients >> Enable Grav. Gradients option turned on.

The lower pane shows the “model” window. This window contains our subsurface interpretation. In this case it is a relatively simple one. The model consists of only three horizontal layers with a cave in the middle layer (below).
Right click on the gray x-axis across the top of the model, and note that you can change the axis range, units, font, etc. When you right click on the background of the model itself, you get another selection window with various display selections that include – points, wells, stations … **NoCtrst** refers to the display of boundaries across which there is no density contrast. If you check this option, you’ll see that the center layer in which the cave placed actually contains another boundary. Inputting the cave into the middle layer actually requires that we insert and then split this “no-contrast” (i.e. no density contrast) boundary. This is something that you don’t have to worry about for now. So, turn off this display.

Let’s turn our attention to the **Action ToolBar** (right).

On the Action Toolbar - **Click on** the magnifying glass with the square inside. This button will allow you to zoom in on a specific area of your model. Zoom in for a detailed look at the cave (i.e. right click and drag out the small view window shown below.)
The zoom view will look like that at right. Turn on the grid lines if you wish.

Click on the eyeball in the action toolbar, and then click on one of the points outlining the cave. The eyeball is used to examine the values associated with individual points in your model.

The point you are examining is displayed in a cyan color.

Note the vertical (Z) and lateralex (X) dimensions of this small cave.
Cave height: _______ meters
Cave width: _______ meters

The easiest way to get back to the full view is to use the View >> Startup option from the main menu bar.

Right click on the gravity profile window (upper pane) and select edit anomaly.

The edit anomaly option brings up a table. Inspect the values in the table and write down the minimum calculated (Calc +DC) gravity value occurring over the valley.

The negative gravity anomaly associated with this cave is _______ milligals observed at X = _______m along the profile.

Close the table (File >> Cancel Table).
Now return to the close-up view of the cave (zoom in).

From the **Action ToolBar** select the **Move Point** option. Then bring the mouse to points defining the cave and readjust their location until the cave is about 1 meter high by 1 meter wide (see below).

![Move Point](image)

Now return to the start-up view. Did the calculated gravitational acceleration over the cave change? Right click in the data window and go to Edit Data Anomaly to check the value of the gravitational acceleration. Gravity anomaly associated with the small cave is _______ milligals.

As it turns out, the anomaly you see across the valley is not associated with the cave, it is associated with the valley. The reason for this is that as the observer goes down into the valley, the mass of the surrounding topography above the observer exerts an upward pull that increases as one descends farther and farther down into the valley.

In order to see the effect of the cave by itself let’s explore more of this model. Go back to the eyeball. And click to activate the examine process; bring the mouse over to the model and click on the interior of the uppermost layer beneath the surface.

![Eyeball](image)

Note that this layer is referred to as the **weathered Bedrock** and it has a density of 2.55 gm/cm³. The block window (nest page) contains a list of information specified for the layer being examined.
While this window is up click on the **color pattern** window and select a foreground and background colors for your weathered zone.

The **Foreground** color specifies the color of the lithology pattern and the **Background** color to specifies the fill color.
Alternatively, you could select black as your Foreground color and select a pattern that might be suggestive of the lithology as shown below. Your background color in this case would be white.

Do this for all the layers in your model (you’ll have to do it twice for the cave zone), and write down the densities you observed associated with each layer.

Density of weathered layer is __________ gm/cm³.
Density of cave zone is ___________ gm/cm³.
Density of the basal Strata is ___________ gm/cm³.

Model with colored strata shown below.
Also check the density of the air. It should be no surprise that for all practical purposes the density of the atmosphere is 0 gm/cm³. Your model window may look something like the one above.

However, if somehow we could eliminate the effect of the topography, then, effectively the contrast between the topography and surrounding void would be eliminated along with the influence of topography on the local acceleration. In our introductory discussions we talked about the influence of topography and the corrections needed to remove it (Bouguer plate correction and terrain correction). In GMSYS we can easily eliminate the influence of topographic features on the acceleration due to gravity by making the density of the weathered zone (or zones containing surface topography) equal to 0 gm/cm³. Alternatively, we could also set the density of the air equal to the density of the weathered zone (see figure below).

Try both ways to see what happens: 1) click on the air-layer and change its density to 2.55gm/cm³; 2) click on the topographic layer and change its density to 0.0 gm/cm³. Note how the calculated gravity values change across the profile (see below). The pronounced 3.6mGal anomaly across the area has been eliminated!

![Image of GMSYS model window showing density changes and gravity profile](image)

You’ll have to right click the gravity axis and select auto scale to be able to see the very small variations in gravity associated with the cave. The anomaly that remains now has nothing to do with the topography. It is due solely with the density contrasts between the cave and surrounding cave zone.
(-2.62gm/cm³).
What is the magnitude of the gravity anomaly associated with the cave?
1-meter cave has gravity anomaly of _________ milligals.

Change the gravity scale to μ gals and read the value of the anomaly.
The cave produces a _________μ gals anomaly in the Earth’s gravitational field.

Now zoom in on the cave and change its size to – let’s say 8 meters high by 1 meter wide. This might occur if solution was occurring along a large vertical fracture zone.
The eight-meter high cave has an anomaly of __________ milligals.

Click on View 1 >> Startup, and use auto-scale on the gravity axis to observe the anomaly.
Introductory Gravity Lab Observations: Inspect the model and anomalies, then fill in the blanks below.

The density of the air is _____________ gm/cm³
The density of the weathered layer is _____________ gm/cm³
The density of the cave zone is _____________ gm/cm³
The density of the basal strata is _____________ gm/cm³
The anomaly associated with the topographic effect is _____________ milligals
The gravity anomaly associated with the 1-meter diameter cave is _____________ milligals
The gravity anomaly associated with the 8-meter high cave is _____________ milligals

Think about what you observed in the modifications you made above and answer the following question
The -3.6 mGal anomaly observed in the initial model is a) associated with a much larger and deeper cave not represented in the model; b) missing elevation correction; c) missing terrain correction; d) none of the above. Circle correct answer.
Geology 454 – Environmental and Exploration Geophysics I

Resistiviry Modeling on the Internet Using Tom Boyd’s Programs at


The easiest way to access these programs is through the class web site. Bring up Netscape or Explorer and go to http://www.geo.wvu.edu/~wilson/g252f.htm. You’ll find hotlinks under today’s lecture topic.

Resistivity investigation: Examine the influence of various model and acquisition parameters on the observations of apparent resistivity.

In today’s exercise, you will examine the resistivity response to a horizontally layered earth consisting of 3 layers. When you initially bring up the resistivity modules, you’ll see something that looks like that shown below.

You’ll have three panels. Two displays allow you to control the various acquisition and model parameters; the third shows the apparent resistivities measured in the survey you designed.
The window below shows the earth model window and survey response window. Layer parameters are controlled in the Earth Model window and note that the apparent resistivities are automatically updated with changes to the model parameters. Now that you’ve had a thorough introduction to resistivity modeling using the IX1D software, this may help increase your appreciation of relationships between measured apparent resistivities and the subsurface distribution of layer depth and resistivity. Take a few moments to vary the model parameters and consider their relationship to the apparent resistivity response shown at left. To change the thickness of the layers in the model, just click and drag the layer boundaries.

**Construct the following model**
Res: Top layer 30 Ω-m  
Thickness: Top layer 5 meters  
Res: Middle Layer 10 Ω-m  
Thickness of middle layer 5 meters  
Res: Bottom layer 170 Ω-m

Use a minimum electrode spacing of 0.5 meters, 4 decades, 4 measurements ( spacings) per decade, maximum amperage of 0.5 amperes, and one reading per spacing.
In the survey design window shown below, note that there are several parameters that can be varied. You can select either Schlumberger or Wenner electrode arrays. You can adjust the minimum electrode spacing and the number of decades over which the electrodes are extended. You can adjust the current delivered to the electrodes and the amount of noise you have to contend with by adjusting the standard deviation in the voltage output of the resistivity meter. One can reduce this error by making multiple measurements at a single electrode spacing (see last parameter).

Start with a standard deviation in the operating voltage of 0.021 volts. Drop it to 0.01 volts and note the difference in the space below. How might your interpretation be affected by higher voltage fluctuations?
Increase the number of observations per decade from 4 to 6. In the space below, describe how average over 6 observations per station might change your interpretation.

Increase the maximum amperage to 1A and make similar observations and comments.
In the earth model move the low resistivity interval down to 15 meters. Reduce the voltage deviations to zero, leave everything else the same and examine the influence of changes in the number of decades from 4 to 3 and then to 2. How many decades do you think are needed to accurately assess the distribution of resistivities at the site?

Briefly describe the survey design you would recommend to one of your clients if you were asked to collect a data set to accurately identify and map these three layers.
Read over Tom Boyd’s resistivity survey design page and revise your survey design keeping a need for low cost in mind.

Spend some time looking over the resistivity materials on Tom Boyd’s site. The site provides very practical real-world perspectives on the efficient and effective use of resistivity methods.
Gravity models over a Tunnel

Return to the class site and bring up the gravity modeling module. In this module you can experiment with modeling the effect of various acquisition and model parameters on the anomaly associated with a buried tunnel or cave.

In the model parameters window at right, note that we can vary the station interval, tunnel radius, density contrast, number of observations (at a single station), and the standard deviation or measurement error.

Within the model window, you can click and drag on the tunnel to move it up or down.
In the GM-SYS exercise from last week, we isolated the influence of a cave on gravitational acceleration and evaluated the influence on acceleration of changes in the size of the cave. In today’s exercise, we’ll use Tom Boyd’s software and examine the influence of some other properties relevant to gravity surveys. Start by placing the tunnel at a depth of 15 meters, and reduce the number of standard deviations in the observation error to 0.0 milligals. Note the simple shape of the anomaly and click on the rescale button to get a better view. You’ll see that this 1 meter radius cave produces about an 8 microgal gravity anomaly.

In the window at right I’ve shown the anomaly obtained for a 1-meter radius tunnel with a density contrast of 2.67 gm/cm³. The observations have been repeated three times to reduce the 0.005 mGal error.

Remember you can rescale the plot after adjusting parameters in the model parameter window.
Now let’s bring the tunnel (or cave) a little closer to the surface. Bring it up to 12 meters, 10 meters, and 5 meters.

- Anomaly magnitude = _______ at tunnel depth of __15__ meters.
- Anomaly magnitude = _______ at tunnel depth of __10__ meters.
- Anomaly magnitude = _______ at tunnel depth of __5__ meters.

Now vary the radius of the tunnel while holding it at a depth of 10 meters. Pick your own radii and note the result you obtain below.

- Anomaly magnitude = _______ for tunnel radius of ____ meters.
- Anomaly magnitude = _______ for tunnel radius of ____ meters.
- Anomaly magnitude = _______ for tunnel radius of ____ meters.

In the following, estimate the influence of various acquisition parameters and measurement error for a 1-meter radius tunnel-like cave at a depth of approximately 6 meters beneath the surface. Assume the density contrast is 2.7 grams/cm³ and note the magnitude of the anomaly that is produced by the cave. Gravity anomaly = ______________________

- Before introducing noise or measurement error into your observations, change the station spacing from 1 meter to 10 meters. Note the effect and suggest a possible problem with choosing such large station spacing.

- Now introduce a measurement error of 0.005 milligals (5 microgals). Describe what happened to your data set.

- Reduce your station spacing and note at which spacing you feel confident you can see an anomaly. I can see the anomaly when the station spacing of __________ meters.

- Now increase the number of observations you make at each station and note how many are needed before you can reliably discern the shape of the gravity anomaly.

I need to make _______ observations at each station to begin to see the shape of the anomaly.

Note how the presence of noise increases the time and therefore cost of your survey.
PART 2

The following exercise is an optional one that is designed to take the interested student through the model building process.

Create New Model

In this tutorial we’ll be importing topography, observed gravity and magnetic data and stations elevations from an external file.

From the File Menu click on New Model to activate the New Model Creation dialog window shown below. Note that there are 5 sections in this window. First define the minimum and maximum X-coordinates along the profile line: in this case 0-35 km. The define the elevation range: 0-20km.

Below, you’ll see option buttons for topography, gravity stations, and magnetic stations. Begin by selecting the import from file option under topography.
The **import from file** dialog window will come up (below).

![Import From File dialog window](image)

Click on the **File** button and select *simple.txt* from the open file dialog window. The following screen should appear.

![File dialog window](image)

This window contains a listing of all the data associated with this particular profile or survey line. Click OK and return to the **import file** dialog window.
Select +up since the elevations are positive, and enter 7 in the skip lines field. Accept the default units on X and Z and return to the New Model Creation dialog window.

Repeat the process for the gravity and magnetics option list. Note that the 2nd field (topo) is also the appropriate field for gravity station elevations (Z). Delete column references to the Gxx, Gxy, etc. Also, note that the “Z” field for Magnetics Stations will be 5 and the observed data (Obs) are in column 4.

Finally, enter the earth’s main magnetic field intensity, inclination, and declination by selecting the Change button and filling in the appropriate fields. Click OK to return to the New Model Creation window and then click Create if all looks satisfactory.

The following model window should appear.

![Model Window]

Note that the observed data graphs are not scaled properly. The data run outside the view window. To fix this, right click in the graph window and select auto scale. Your model display window should now look something like that shown below.
For now, turn off the error display. **Right click** and select **Display** (at the bottom), and then from the pop-up list un-check **Grav Err**. Do the same for the magnetic data.

**Model Entry**  
**Tying to Infinity**  
The model we are going to develop represents crustal scale features. In subsequent lab exercises we will work with shallow geotechnical and environmental applications. The same procedures are used; the same theory applies; the skills you are developing have general applicability.

Our model will have a crystalline basement layer with a couple overlying sediment layers.

To begin with we need to extend the edges of our model out to significant distance so that the effect of the edge on the calculated gravity and magnetics in the area of our survey will be minimal. Extending the edges of the models out to a distance of 30,000km on each side does this. To do this, click on **View** and select **2: infinity** from the view list.

Right click on the **Depth** label near the left side of your model window then select **change range** and enter **-1.5km for the minimum** and **6.0 for the maximum**.
You can also increase the size of the model window by left clicking on the divider and dragging the top of the model window up.

Note the scroll bars on the left and across the bottom. You should have a good view of the upper 5-6km in the model.

Also note the presence of the Action Tool Bar (at right).

Take a minute and move the mouse arrow over the buttons on the tool bar. Locate the Add Point, Delete Point and Split Block button.

**Add a surface**

Click the add point button and insert one point on the left edge of the model at \( X = -35,000 \) and \( Z = 3.5\text{km} \), and another on the right edge of the model at \( X = 30,000 \) and \( Z = 3.5\text{ km} \).

Your model window should look like that below.

Note that the coordinates of the mouse pointer are displayed in the lower right corner of the model window. Look at these points to help position each point. You can then precisely define the locations of these points by clicking on the eyeball (the examine function) and typing in the exact coordinates.

Now click on the Split Block button. Click on point 2, release the left mouse button and move over to point 1. Note that the mouse pulls a rubber band across the model. It is tied to point 2 as shown below.
Bring the cross hairs directly over point 1 and click again. A line attaching the two points appears, and a dialog box opens which offers you the choice to **Cancel**, **Accept new block**, or **Accept/Edit new block**. Select **Accept/Edit new block**. The following dialog window opens up.

Change the layer name to **Lower Sediments** and the density to **2.35 gm/cm³**.

Now in the same manner insert another horizon dividing the sediment block into two layers. Place points **First on the left** at \( X = -30,000 \) and \( Z = 2.0 \) km and **on the right** at \( X = 30,000 \) and \( Z = 1.5 \) km.
When the **Copy Block** window appears, change the layer name to **Upper Sediments** and the density to **2.5 gm/cm³**

**Save your Model**

File, then **Save As**

And navigate to your G: drive and save the file there for future access.

You can also save the current view window.

Go to the **View Menu** and select **Edit Views** to activate the **view list** dialog box. From the **View** list select **Startup** and then click on **Repl. W/CView**. Then click **OK** to close the dialog window. You can easily return to these display settings through the **Edit View** window.

---

**Complete your model**

Now return to your model view window. Make adjustments to the display ranges if needed. We will be placing additional points in the horizontal interval –5 to 45km and vertical range 0 to 6km. Next use the **Add Point** command to place anchor points on the two near-surface horizons. As shown below.
Next, add intermediate points as shown below. Note that when you add a point you can move it around as long as you hold down on the left mouse button.

Next, create two new surfaces to truncate sedimentary wedges against the basement surface (lower surface). To do this, click the split block button on the **Action Toolbar** and drag a horizon from the surface sediments to the basement interval forming wedges on both sides of the basement high as shown below.

Nest delete the remnant package of sediments that extend across the basement high. Do this by clicking on the **Delete Surface** button on the **Action Toolbar** and then clicking on the surface you want to delete. When you click on the surface a small window will open up (see next page) and ask you what interval you want to delete. It considers the possibility that you might actually want to merge the unit overlying the basement high with the overlying sediments. **Keep the upper sediments.**
After you delete the upper sediment block, your model should look something like that shown on the next page.

Now use the examine function to check that each layer has the properties you intend them to have.
Click on the **Examine** (eyeball) button, and then click on each layer. The following figure illustrates what you will see.

A footnote to all this is that the block assignments will vary depending on which way you drew your line. So checking these layer properties is an important step. If you start on the left and go right – the new block will be below your line. If you go in the other direction, the new block will default as the interval above the line you just digitized.

To complete your model use the examine-function once more and change the name of crustal rock to basement and change the density of the basement to 2.7 gm./cm³ and define its magnetic susceptibility as 0.005 cgs units.
Calculate the gravity and magnetic fields over your model

Go to **Compute** on your main GMSYS menu bar and then click on **Calculate**.

With a little manipulation (i.e. take notes) you get a result that looks something like that shown below.
GRAVITY COMPUTER LAB

Forward and Inverse Modeling of Gravity Data:
Locating buried glacial channels and evaluating the results of published analysis

During this lab your task will be to reevaluate the model developed by Stewart along profile XX’ (page 29, Figure 7) in the paper "Gravity Survey of a Deep Buried Valley". Below, a series of steps are presented to give you some additional practice with GM-SYS and its usage.

1) Go to the Common Drive and copy the folder Stewart to your network N:\Drive.
2) Start GM-SYS and open the file Stewart.sur from your N:\Drive.

The following model and data windows will appear:

Figure 1: The model and observations (solid dots) shown here and in Figure 2 below are taken from Stewart’s paper.
Stewart’s residual gravity data and depth-model or cross section are plotted below for reference.

Figure 2: A) Gravity anomalies from section XX’ (Stewart); B) Cross section taken from Stewart.

3) Use the examine function (eyeball on the action toolbar) to check the model parameters.
   - The density of the till is __________ gm/cm³
   - The density of the bedrock is __________ gm/cm³
   - The density contrast (bedrock to till) is __________ gm/cm³
   - What should the density contrast be? __________ gm/cm³

   Change the density of the bedrock so that the correct density contrast will be present between the bedrock and overlying till.

   These questions are just here to focus your attention on the details of the model. They do not need to be submitted.

4) Open up a word file and copy this view window (Alt-Prt Scr and then in a word text box Ctrl V) to your word report file. You may want to review the earlier handout on these screen copy and paste procedures; i.e. reset the density to 2.6 gm/cm³.

   At this point, note that there are significant differences between the calculated gravity (the solid line in the upper pane) and the observed gravity (dots at each observation point). The calculated gravity for Stewart’s model does not agree with the observations taken from his residual gravity map along the profile XX’.

   Drop the starting figure into word – the first figure in your lab report! You can discard unneeded figures later.
Before doing anything—ask yourself how the subsurface representation of this cross section could be changed to better fit the observed gravity. In the figure below, I’ve labeled a couple areas (A and B) where significant disagreement occurs.

![Areas of disagreement: A and B](image)

Figure 3: Examine the differences between the observed anomalies (the black dots) and the calculated anomalies (the solid black line) shown in the top pane and consider how the configuration of the bedrock/till horizon could be changed to correct for these differences.

5) Use the move point option and manually adjust the locations of points defining the till/bedrock interface. Note how the gravity anomaly varies. Attempt to eliminate the differences between observed and calculated anomaly.

Note that will holding down on the point and moving it around, your anomaly window will automatically be updated, and the error (difference between the calculated and observed gravity anomaly) will appear as a red line (see below).

![Figure 4: Note that observed and calculated anomalies agree much better in area B after adjustment of bedrock depth.](image)
In the figure below, I’ve eliminated the differences at B.

Figure 5: Anomaly A remains. What can we do to eliminate differences between calculated and observed gravity anomalies in the vicinity of A along the profile?

To eliminate the differences associated with anomaly A, let’s use a different method – inversion. This is the sort of thing you did a lot with in our terrain conductivity and resistivity modeling exercises. The inverse options leave it to the computer to make adjustments in the layer configuration to achieve a better fit between the calculated and observed gravity values.

6) To undertake the inverse operation first click on the INV button on your Action Toolbar (right).

Figure 6: The inversion setup window and action toolbar.
Working with the inversion setup window.

7) **Click on the X button** in the inversion parameters window and select XZ. Doing this will allow both the X and Z values for selected coordinates to be adjusted by the computer.

**Check the AutoDC** check box. This will allow the computer to make bulk-up and down shifts of the entire curve to help improve the fit.

**Click on Constraints** and set the dX and dZ values to 50 feet. This will restrict the distance over which individual coordinate points will be allowed to move.

Lastly **click on the layer points** that you want to free for the inversion. Those points will be highlighted by a cyan colored +.

It is recommended that you zoom in on the surface points between 13000 and 15000 feet along the profile. This will ensure that you actually pick the layer coordinates and not the topographic surface coordinates.

After points have been selected, your model should look like that shown below

![Figure 7: Corner coordinates that are free to move around are highlighted in turquoise. The + sign indicates these points can be adjusted in both the up and down and side-to-side directions to help minimize the difference between the observed and calculated anomalies.](image)

Now **Click GO**.

The first inversion step will be displayed and you will have the option to accept, cancel or go an additional step (see figure top of next page).
Figure 8: the dashed lines show where the surface and calculations were prior to running the inversion.

We need to go a little further so *Click on Next Step*. If this seems to throw the whole model off - *just click undo*. You can undo or back up as many times as you’d like.

Then *click Accept* (you can x out of the inversion setup window). Your model should look similar to that shown below.

Figure 9: a good match between calculated and observed gravity has been obtained. Note how the model (in lower pane) has changed.
You can also use the move point option to fine tune your model or test out other ideas. Inverted points will remain highlighted until you select another function from the toolbar.

8) Finally, display the error between the calculated and observed gravity by clicking on Display and then checking off the Grav, Err item in the list.

9) Make another copy of your screen and place it in your word lab report file.

If desired, you can click on the examine button and assign different color and texture schemes to enhance the appearance of your model for presentation.

![Graph Showing Calculation Error](image)

Figure 10: Lithology patterns and colors have been added to our model to make the display more informative. V marks the deepest point in the bedrock valley along this cross section. The valley is modeled to be about 580 feet deep in this area.

10) Now let’s explore the relationship of these anomalies to the predictions based on Stewart’s equation $t = 130g$.

Place your mouse arrow on the gravity value observed over the deepest valley along the profile marked by the V in the figure above. For your reference, note the values below.

The gravity anomaly $g_v$ at this point is __________ milligals
The predicted value of $t = 130 g_v$ is __________ feet.

Bring your mouse arrow down into the model window and rest it on the valley floor. Read the depth of the valley floor off the coordinate values listed in the lower right of your GM-SYS window.

The depth to the valley floor is __________ feet.
Calculate the depth to the valley at this point and ask yourself how well it agrees with the value in the model. Recall what the assumptions of Stewart’s formula are and answer the following (do not hand in).

Why do you think there is a disagreement between the model depth and the simplified estimated based on Stewart’s formula?

11) Use the examine function and change the density of the till to –0.6 gm/cm³ and the density of the bedrock to 0 gm/cm³ to make the model agree better with the assumptions implicit in the Stewart formula.

Make a note of Stewart’s assumptions here for your own reference.

The density contrasts in our model fit the assumptions made by Stewart, but our model is more realistic than that assumed by Stewart in developing the formula used to provide a rough estimate of valley depth. The Stewart formula provides a quick estimate of valley depth that you can do in your head or using a calculator. A quick and easy estimate, but one that will always have some error unless the valleys are in fact ________ in width, in which case they would not be valleys! But in this case, the disagreement is really large and the reason for that is partly due to our incorrect use of Stewart’s formula. Do you know why the estimate we made using Stewart’s formula is not properly calculated?

To gain some additional perspectives, right click on the gravity window and click on set DC shift. Then click on absolute and OK. The value in the absolute shift box should be 0.

Note that this will shift all the calculated values into the negative (see below). This is what we would expect, since we are employing a negative density contrast. Positive anomalies are not possible in such a model. The DC shift represents the anomaly in absolute terms rather than relative terms. For the purpose of comparing our result to Stewart’s estimate we need to compare the un-shifted negative anomaly in the model to the value calculated using Stewart’s formula. Doing this will change the minimum value from the -1.2 milliGals in Figure 10 to the ~ -3.8 mGals in Figure 11.

Now if you recalculate, you will get a much larger estimate of valley depth. To make proper use of Stewart’s formula we have to remind ourselves where his formula comes from. Another assumption it makes is that there is only one density and it refers to the density contrast between the bedrock and till. The contrast is also negative. It has to be in this single non-zero density model. If the density contrast were positive it would flip all the anomalies around.
Basically Stewart looks at anomalies in his area and considers their value relative to some 0 mGal reference. That point might be an area where there are significant exposures of bedrock and the depth to bedrock there would, of course, be 0!

![Class display]

Figure 11: Actual value of the anomaly has been shifted into the negative. V notes location of deepest valley in the model.

Now repeat the comparison at point V and for future reference, fill in the blanks below as part of the in-class activity. (Do not hand in).

The gravity DC corrected gravity anomaly $g_v$ at this point is ____________ milligals
The predicted value of $t = 130$ g using the model anomaly at this point is _________ feet.
The depth to the model valley floor is ____________ feet.

Did the method work a little better?

Why do you think there is still an error in the depth estimate?
Hopefully you’re seeing that rapid computations of possible depths (in the case) to the geologic features producing a given gravity anomaly have a lot of assumptions and will be in error depending on how well model honors those assumptions.

Again, these questions are just here to focus your attention on the details of the model and do not need to be submitted.
12) Our last task for the day will be to examine the potential effects associated with model layers that have **limited** extent in and out of the cross section, rather than the default **infinite** extent of the models we’ve been working with. Did you realize that? The cross section looks really nice, but it is a 2D representation of a 3D feature. The anomalies that you have been calculating are for valleys that extend in and out of the cross section to infinity! To get an even better estimate of the anomaly over one of these valleys using the computer model, we need to limit the extent of these valleys in and out of our cross section. Let’s work through this.

**First - Set the DC Shift back to Automatic.**

What we mean by **infinite extent refers to the extent of the layers in and out of the model cross section viewed on the computer screen.** By default, the layers are assumed to extend out to plus and minus infinity in and out of the plane of the section.

As opposed to taking the default infinite extents, we can limit the extents in and out of the plane of the section to approximate the valleys length in and out of the cross section and examine the effect on the calculated anomaly.

To do this use the examine function and click on the Glacial Till layer in your model. Then check the 2 –3/4 D box. When you do this, note that an additional two tabs appear across the top of the Block Parameters window: a Y+ Block and Y- Block (see Figure 12 below).

Click on the Y+ tab and change units to feet, set density at 0 and set the length to 1000 as shown below. **The density in this case (0) refers to the density of the material out beyond the limits of the till – i.e. that of the bedrock.**

![Figure 12: Y+ and Y- Block parameters control layer extend normal to the cross section.](image)
Note that I’ve also set the color and pattern to indicate that the bedrock comes up to the surface and bounds the valley out of the plane of the section. Right? If the Valley isn’t there, then the bedrock must be. Although not necessarily true, it is consistent with the simple model we are working with. If we knew more about the local geology we could introduce additional layers, make the model more complex and realistic and obtain more accurate results.

For the Y- Block assign a negative value to the length. Basically the negative sign tells the computer that the block extends into the screen. If you leave the units in kilometers set the extent to -0.3048km. The sign should be intuitive: negative block – negative extent.

![Figure 13: Setting up the Y- block model dialogue window. The density is 0 gm/cm$^3$ because we assume the bedrock has a reference density of 0 gm/cm$^3$. The till has a density of -0.6 gm/cm$^3$ relative to the higher density bedrock. It may be a little difficult to appreciate that we can play around with the relative density contrasts rather their absolute values. If you don’t believe this, experiment and put the actual densities back in. The geophysicist, in this case is interested only in the relative gravity anomaly. If you leave the DC shift off, you will get the same answer!](image)

Now you should see that the anomaly is much less pronounced (Figure 14). The calculated and observed anomalies no longer match. The match we have in Figure 10 for example is very good – for INFINITE valleys. But valleys aren’t infinite. To get a match between calculated and observed anomalies for valleys that have lengths in and out of the section similar to those we encounter in Wisconsin we have to repeat the inversion process. What do you think will happen to those valleys when we run additional inversions?
Figure 14: Valleys extend about 650 feet in total length. This would be 0.1 kilometer for the Y+ block and –0.1 kilometer for the Y- block. V notes deepest valley in the model.

Figure 15: In this model the extent in and out of the section is a little larger than that Figure 14. An additional inversion has been undertaken. As you can see, the narrower valley must be deeper to produce the same anomaly as the infinite one.
At this point, in the valley model that you’ve developed, reset the DC Shift to absolute so that the anomalies will all be negative and adjust the gravity scale range as needed.

At point V (e.g. Figure 14), consider the following (do not hand in).

What is the maximum negative value of the gravity anomaly for the deepest valley (the valley at V) when calculated for a valley that extends significant distances in and out of the plane of the section (effectively to plus and minus infinity)?

__________________ milligals

What is the anomaly at V when the valley width is reduced to 2000 feet (i.e. 1000 feet on either side of the survey line)?

__________________ milligals

What is the anomaly at V when the valley width is reduced to approximately 650 feet (i.e. 0.1km on either side of the survey line)?

__________________ milligals

These questions are here to help you focus on issues to be addressed in the lab report and do not need to be submitted.

Questions to answer and submit
1. You observe a residual gravity (gravity anomaly) with positive and negative values that extend from +2 milligals to -2 milligals. Use Stewart’s formula (t=130g) to estimate the depth to bedrock.

2. In Figure 3 the bedrock depth is approximately 200ft below the surface near point B. How deep (on average) is bedrock in the model you revised to minimize error between the calculated and observed gravity in this area. Present a figure showing your result. Label and put a caption on it that answers this question.

3. Reduce the extents of the valleys in and out of your model section to ±1000 feet. Make the changes to the Y+ and Y- blocks and then apply. How does the calculated g over the deepest valley differ from that obtained for the infinite valley? Include a figure illustrating this result, label it and include a caption that states your result.

4. Conduct an additional inversion and note by how much the valley depth has increased to retain a match between the calculations and observations. Note differences with reference to figure used to illustrate answer to problem 3.

5. Use Stewart’s formula to estimate depth over this deeper but narrow value. Note how it differs from the value you obtain in your model (problem 4). Show calculations in your submitted work.

Submit your responses on ____________ .  

Date to be announced
Some Perspectives on Edge Effects

The equation \( t = 130g \) assumes that ________________________________________________
______________________________________________________________________________
______________________________________________________________

Just what is an edge effect and how significant could it be? Here are some examples to help you appreciate the potential significance of edge effects in the application discussed by Stewart.

- **Example 1:** In the simple example below the edge of a glacial valley is represented by a vertical 200 foot high wall separating low density glacial till to the left and high density bedrock to the right. The glacial valley extends to infinity in all other directions.

1. Use Stewart's formula and compute \( t \) using a value of \( g \) from the extreme left hand side of the model.

2. Over what distance - right or left of the valley edge - does the anomaly drop from 0 to its maximum value?

3. Over what distance is this transition significant?
• **Example 2:** Valley depth equals 500 feet.

1. Use Stewart's formula and compute $t$ using a value of $g$ from the extreme left hand side of the model.

2. Over what distance - right or left of the valley edge - does the anomaly drop from 0 to its maximum value?

3. Over what distance is this transition significant?

• **Example 3:** Valley depth equals 750 feet
1. Use Stewart's formula and compute $t$ using a value of $g$ from the extreme left hand side of the model.

2. Over what distance - right or left of the valley edge - does the anomaly drop from 0 to its maximum value?

3. Over what distance is this transition significant?

- **Example 4: The unseen edge**
Computing the gravitational fields of simple geometrical objects - The Half-Plate, Sphere, Ring and Sector – using scientific analysis and plotting software

In today's lab there will be opportunities to ask additional questions about the gravity lab assignment designed around an evaluation of Stewart’s gravity model. The remainder of the period will be spent providing you with background in the use of a scientific plotting, math and statistical analysis software package. The software you will learn to use today is called PsiPlot. PsiPlot is similar to EXCEL. The following instructions are meant to take you step-by-step through the computation and plotting of variations in the gravitational acceleration associated with the semi-infinite or half plate.

Remember that the relationships derived for simple geometrical objects represent gravitational acceleration vs. X/Z, where X is distance along the surface and Z is depth to the object. Z may be depth to the center of the object, depth to surface or depth to midpoint, depending on the object being modeled.

In lab today we will compute the response of the half-plate, which is

\[ 2G \rho t \left( \frac{\pi}{2} + \tan^{-1} \frac{x}{z} \right) \]  

Eqn. 6:47

Remember that in this case, Z represents the depth from the surface to the midpoint or center of the plate. By way of analogy to the glacial valley applications, Z will represent half the depth of the glacial till. In this explicit form, you are actually able to evaluate the extent of the edge effects. X in this example is the distance, positive or negative, from the edge of the glacial valley.

GETTING INTO PSI- PLOT

PsiPlot runs in the windows environment. There should be a PsiPlot shortcut icon on the windows display. If you cannot find a shortcut icon on your login screen go to START PROGRAMS and then to PSI-Plot. Click on PSI-Plot to open the program.
When the PSI-Plot window opens up, click on **FILE** then on **NEW Sheet**.

**SpreadSheet Window**

Go to **Data - Fill Selection - Algebraic**

Enter the following values into your **Fill** window.
When you click OK or Enter, the following data will appear in Column 1 of your spreadsheet.

These values should run from -3000 to +3000. Click on the Fill1 Column Label and type in X, then Enter. Your window will now look like that below. In general you can label your columns with any desired column name.

Now go to MATH Transform. You'll get the following window.
Highlight the equation window (click on it) and enter the following

g=2*6.732E-11*(-600)*500*((PI/2)+ATAN(X/700))*1E5

Your math transform window should look something like that shown below.

For future reference, you can get help on Math Functions from the HELP button on the top menu bar. Click help and then do a search on **math** (see below).

The window under **math functions** (below) provides a nice summary of the short hand notation for various math functions. Note the definition for **atan**.
In the formula \( G = 2 \times 6.732 \times 10^{-11} \times (-600) \times 500 \times ((\pi/2) + \text{ATAN}(X/700)) \times 10^5 \)

* represents multiplication

6.732E-11 represents 6.732 \times 10^{-11}, and 1E5 is 1 \times 10^5 or 100000.

Brackets are used to insure the appropriate order of multiplication, division, and addition, etc.

\( \pi \) stands for \( \pi \).

In this example \( t = 500 \) and \( z = 700 \).

After entering the formula into the equation window and clicking OK, your spreadsheet will contain the additional column G (see below) containing the accelerations due to gravity across the fault step.
Plotting

TIME TO GRAPH YOUR DATA!

Let's plot X vs. g.

Click on PLOT (a menu drops down)
Click on 2D Curve > (menu opens to right)
Click on XYLines (2D XY-Lines window opens up)

Note that in this case, X >> defaults to x, and
Y >> to G.

Click on ADD CURVE>>, then OK

Notice X and Y defaults in window at right.

Click OK ….

The following plot will appear.

Plot 1
ODDS and ENDS -

Move the mouse arrow down into the plot area and Click it in an empty area of the plot. Note that the plot will be highlighted (eg. square dots appear on the plot margins). You can resize the plot by clicking on the highlighted edge or corner points. You can move the plot around by clicking within the bounds of the plot and dragging it to a desired location. Try it. To close your plot, move the mouse over to the upper left corner and click on the design. Then click on CLOSE, then click on NO (you don't want to save it). This will return you to your spreadsheet.

Now let’s try another one

PLOT

2D CURVE

XYLINES

but, this time click on STYLE>> and select another symbol. Click on COLOR>> and select another color. Double click on the little window next to Symbol Size:, and enter 0 (only the line will appear).

Don't forget to click on ADD CURVE, then OK.

Note that the plots default to a landscape layout. Let's change that to portrait. Click on FILE (Menu drops down - note variety of selections. Experiment later.) Click on Printer Setup. Click on Portrait, then Click on OK

Resize the graph to fit in the upper third of the sheet.

Double click on the graph title **Untitled1 or whatever**. Type in any title you'd like. Do so now, and also note the other options in this window, including Font, Size, Italic, etc. Click on OK.

You can change axis labels the same way.

**Note the tool box off to the right.**

Click on abc

Bring the cross hairs over to a suitable place on your graph. Hold down the left mouse button and drag open a rectangular box to place a label. When you release the left mouse button, a text format window will open up. You can enter a relevant label as you did for the title and axes above. Click on OK when done.

Click on your label, and move it around.
Click on an open space within the graph. Note that the graph is highlighted. Now
Click on the label you entered above. Note that the graph remains highlighted.
You will have to push it back.
Go to VIEW (a window drops down).
Click on Push Back
Now click on your label. There you have it.

This has just been a basic run through on some of the options available through PSI-
PLOT. The best way to learn PSI-Plot will be to experiment.

To complete our PSI-Plot overview, change windows back to your spreadsheet. Click on
window then click on SHEET UNTITLED2. You should now be back in the spreadsheet.

**Plotting your graph:**
Click- on FILE
PRINT - (IT'S GONE)

**Notes on Plotting Tips**
Saving your files
There is probably no need to save the plot files, as they are fairly easy to generate. If you wish to save, go through the normal FILE, SAVE AS process. PSI-Plot graphs are saved as ___PGW files, and the spreadsheets are saved as ___PDW files. Use a file name that means something to you. If you save, copy your files to your own diskette. Clean your files from the Z:\apps\g252 directory when finished.

Superposition Principle
For additional practice try plotting the response of a buried sphere where

\[
g_{\text{sphere}} = \frac{G \rho \pi R^3}{3 Z^2 \left( X^2 + 1 \right)^{3/2}}
\]  

(Eqn. 6:53). Do for the same range of X as used in the above example. Use a \( \rho \) (or \( \Delta \rho \)) of -2.0gm/cm\(^3\), Z = 200m and R = 100m. This will yield the following formula

\[
g_{\text{sphere}} = (10^5) \times ((6.732 \times 10^{-11}) \times (-2000) \times (1.3333 \times \pi \times 100^3)) / ((200^2)^((x/200)^2+1)^{1.5})
\]

Your formula window will look like that below, which will be too small to display the entire equation.
Plot GS (see below).

Add G and GS together and plot.

This is just a graphical use of the superposition principle which can basically be stated in the following way: the net gravitational acceleration associated with two or more objects equals the vector sum of the accelerations produced by each object.

In our applications we are always looking at the vertical component of the acceleration due to gravity and therefore our summation is a scalar sum of the vertical components.
PsiPlot is a useful plotting and scientific analysis tool that you may find uses for in this and other classes. There are various statistical and data analysis options that can be used in your data analysis (see below under Data and Math).

You will also find numerous plotting options to accommodate display of just about any kind of data (see below).
Excel Exercise

_In this exercise, we'll repeat the computations for the fault step using Excel._
Bring up Excel from the _start programs_ task bar.

First type X into the first cell of Column A. Then type in the numbers –3000 and –2900 in the second and third cells of column A as shown below and select both cells. Cell selection is done simply by left-clicking the mouse and dragging down over the cells to be selected – in this case cells 1 and 2. When you lift up on the left mouse button, a black square will mark the lower right hand corner of the selected cells.

Left click on the black square, hold and drag down the page. Note that to the right of the column the current cell value will appear in a box.

Continue to drag the box down to cell 62 and note accompanying current cell value. It should read 3000. We now have the column of x values needed for our computation.
Next in Column E type in G, Density, Pi, and Z, and then in column F, type in the corresponding values for these parameters (see below).

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</thead>
<tbody>
<tr>
<td>1</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-3000</td>
<td>G</td>
<td>6.73E-11</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-2900</td>
<td>Density</td>
<td>-600</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-2800</td>
<td>Pi</td>
<td>3.14159</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-2700</td>
<td>t</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-2600</td>
<td>Z</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-2500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-2400</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In column B type in \( g \) in cell B1, and in cell B2 type in the following – 
\[=2*F2*F3*F5*(F4/2+ATAN(A2/F6))*100000 \] (see below)

Now click in cell B2 and do edit copy or CTRL C to copy the cell. Left click on the lower right corner of the cell, hold and drag down to cell B62. When you lift up, note that cells B2 through B62 will be filled with the numeric values of \( g \) corresponding to the various distances along the profile – X as shown on the next page.
Plotting in Excel

On the Excel toolbar across the top click on the Chart Wizard (below).

That will bring up the Chart Wizard Chart Type window (next page).
Make sure you select XY Scatter as the standard type and highlight the appropriate sub-type as shown above. Then click next. The following will appear.
There may be some differences between Excel versions. Note that Excell recognizes the data in columns 1 and 2 and automatically graphs the function in Step 2. If this does not happen, we can select the columns to be graphed under the series tab.

Click Next and then fill out the title and axis labels (below)
Click Next again to get the following window.

We are going to save the graph to the current spreadsheet, so just take the default (shown above) and click Finish. The Chart or graph will appear in your spreadsheet as shown below.

You can left click and hold to adjust the location of the graph. There are additional options than can be used to adjust the graph properties. For example, note that the x labels are plotted within the body of the graph. To get them to plot above the graph, double click the x-axis to bring up the following format axis window.
Under the **tick mark labels** option list, click **High** then **OK**. Your plot will appear as shown below.
Excel is very powerful because of the manner in which equations are designed. To illustrate this, change the value of the density in cell F3 from –600 to –400 (remember the units here are in kg/m³).

Note what happened to your graph. The computed values of \( g \) changed. They were all recomputed and automatically re-graphed. You could do this for \( t \) and \( Z \) as well. In this manner, you can easily compare the results obtained for different values of your model parameters.

**Computing the terrain correction using Excel.**

At the bottom of the page click on Sheet 2, and type in the following:

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Elevation at measurement point</td>
<td>2840</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Elevation of sector</td>
<td>2640</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Replacement Density</td>
<td>2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Elevation difference ( Z )</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 ( G )</td>
<td>6.73E-11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 ( P_i )</td>
<td>3.14E+00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 ( R_i )</td>
<td>3.90E+02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 ( R_o )</td>
<td>8.95E+02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Terrain effect of this sector</td>
<td>2.77E-01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note that in the formula window the individual cell references do not have $ signs as were used in the formula in the preceding example. Cell references in EXCEL can be either absolute or relative. The absolute reference is useful, because it allows us to refer back to a specific cell and avoids having that value change when a formula cell into which it is entered is copied. The absolute reference is fixed reference. Whether a reference is fixed or absolute depends only on how you refer to it. The following table illustrates various absolute references.

<table>
<thead>
<tr>
<th>Formula</th>
<th>Result when formula is copied</th>
</tr>
</thead>
<tbody>
<tr>
<td>=2*$A1</td>
<td>The column remains constant – fixed</td>
</tr>
<tr>
<td>=2*A$1</td>
<td>The row remains constant – fixed</td>
</tr>
<tr>
<td>=2*$A$1</td>
<td>The row and column remain constant – fixed</td>
</tr>
</tbody>
</table>
Since we aren’t copying the formula window, we do not need to worry about absolute versus relative cell referencing.

Study the formula used to calculate the acceleration due to gravity of the material in an individual sector of the F-ring.

\[=2\times B5\times B6\times B3\times ((B8-B7 + (B7^2+B4^2)^{0.5} - (B8^2+B4^2)^{0.5})/8)\times 100000\]

Note how the value changes as you change the density from 2670 to 2000. Compare to value of sector 1 mentioned in class. Last week.
MAGNETIC
COMPUTER LABS
You have gained considerable experience by this time in the analysis and interpretation of gravity data and the use of the modeling software GMSYS. You’ve also had an opportunity to review basic principles regarding the basic characteristics of gravitational fields and interpretation of their origins.

You’ve also learned to answer questions about the geologic significance and origins of gravity and, using the computer as an analytical tool. The computer provides a means of extracting more detailed answers about the configuration of geologic intervals producing density and susceptibility contrasts and thus gravity and magnetic anomalies, respectively. Calculations can be done in the FORWARD and INVERSE direction.

Based on our prior modeling experience with terrain conductivity, resistivity and gravity data, you know that the FORWARD modeling approach allows you to test out a specific idea or geologic interpretation. Until recently, most model studies consisted of repeated forward modeling steps. This procedure consists of making an initial geological guess about the configuration of density or susceptibility contrasts believed to be producing the observed anomalies, making a forward calculation, and then comparing the calculated values to the observed values. The modeler attempts to minimize the differences between the calculated and observed values by modifying the layers and densities of the model in a geologically acceptable manner to yield a closer match between calculated and observed values. This is an iterative process. It is repeated until one gets a result that is both consistent with other available subsurface information, and until the model calculations yield anomalies very close to those observed along the survey line or profile.

In the last couple decades, the computational power of computers has advanced so much that it is now possible to let the computer perform repeated modifications to the model such that the error between calculated and observed anomalies along the profile are quickly minimized. As you know, that process is referred to as INVERSE modeling. The computer makes modifications, recalculates and gauges the effectiveness of these modifications on the basis of whether a reduction or increase of the difference between the observed and calculated values has been achieved.

Some of the modifications of the model made by the computer during this "inverse" process may not be consistent with the local geology. So even though the computer has taken some work out of the task for you, the interpreter still has to judge the merits of the solutions obtained by the computer. The interpreter must ask, "Is the result obtained by inverse modeling process consistent with the local structural style of deformation or with the configuration of stratigraphic, metamorphic or igneous boundaries observed at the surface or inferred from other geophysical
data? Is it correct to assume, for instance, that density contrasts (or susceptibility contrasts) are constant across your model?" Your biggest mistakes these days could be to place too much faith in the results obtained by the computer.

"What were your assumptions? Are they correct?"

Remember also that programs are not perfect. They may contain errors and produce erroneous results. Learn enough about the physics of these different fields so that you have a common sense or intuitive grasp of what to expect. Check your results by making simple computations based on simple geometrical approximations. The use of the comparative process we developed using simple geometrical objects offers an important reality check or "common sense" perspective on results obtained by the computer.

As we continue to build on the computer modeling and interpretation experience provided by the computer labs we’ll use a combination of methods (gravity and magnetic) to investigate a subsurface problem. As with some of our previous labs, you have to come up with an interpretation given the observed geophysical data along the profile, and some general information about the local geology and the type of objects you are looking for.

The remaining two labs provide one final subsurface mystery for you to solve -

Brief statement of the problem

In this lab we will be looking for buried metallic drums. We suspect that drums of radioactive material suitable for making a “dirty bomb” have been secretly buried to avoid being found. Simple excavation (back-hoeing) of the area is ruled out since accidental rupture of the drums would release radioactive materials into the local groundwater system and atmosphere. Clean up would be extremely hazardous, difficult, and expensive.

For the purpose of an initial reconnaissance of the area, you decide to run both gravity and magnetic surveys over the site. In the three columns below you are given the observation points in feet along the profile, and the observed gravity anomaly (milligals) and magnetic anomaly (gammars or nanoteslas) at those points. Once the source areas are located you may later decide to run resistivity or terrain conductivity surveys to delineate the vertical and lateral extent of contamination plume(s) associated with leakage from the buried drums.
Lab Discussion and Questions

You’ll find the model folder for this lab - *Maglab* - on your H:\drive. Copy the folder to your G:\drive, and then bring up GM-SYS. The default view should look like something like the following.

The upper window contains magnetic data collected along a transect across the site. A large magnetic anomaly was located at about 210 feet along the profile and additional observations were taken at 5 foot intervals across this feature to improve resolution of anomaly details.

The geology of the site consists of a thin veneer of alluvium overlying basalt bedrock. The basalts are magnetic and surveyors quickly realize they are unable to determine whether the anomalies are due only to the bedrock or to a combination of bedrock and buried metallic containers. They realize that because of the large contrast between the density of the alluvium and bedrock, a gravity survey should reveal the configuration of the bedrock. Once the bedrock geometry is known, they will be able to compute the contribution to the magnetic anomaly that is due solely to the bedrock configuration. The investigators collect gravity data at the same stations occupied during the magnetic survey.

For this exercise we will assume that available geological data from the area suggest that the density of the alluvial fill is approximately 1.8 g/cc, and that the density of the basaltic bedrock, is 2.8 g/cc.

The geophysicists realize the gravity and magnetic anomalies can be simulated using only two layers: one representing the alluvial fill and the other representing the basalt bedrock.

Now open up the gravity data windowpane so you can see the variations in residual gravity anomaly.
Starting Model

What is the best way to start? Since we don't know anything about the configuration of the bedrock, we will have to run through an inverse modeling process to determine bedrock depth from the measured gravity anomalies across the area.

Note that we could use Stewart's technique other authors on your reading list use a similar approach; it is not really a novel idea) to approximate the depth or thickness of the alluvia along the profile. So you could also put in a rough guess of depth using the plate approximation and make a FORWARD calculation to see how well you did. Then you could invert to “fine tune” your model.

Consider the value of the residual gravity anomaly shown at approximately 150 feet along the profile.

The residual anomaly is purposely shifted to negative values (remember the ideas associated with Stewart’s area). The minimum anomaly in this case is roughly –0.32 milligals. Using the plate approximation, what would be the thickness of the alluvium at that point, assuming that edge effects had minimal effect on the estimate?
Another approach is to take full advantage of our computational resources and determine the bedrock configuration through inverse modeling of the gravity data. We start by putting in a flat layer, with corner coordinates located or defined about every 20 feet or so across the area. Initially they could all have the same depth – *perhaps one derived from the plate estimate*. Then we could use the INVERT option, freeing only the Z coordinates this time. The computer will automatically raise and lower the corner coordinates defining the bedrock relief until a match between the calculated and observed gravity is obtained. You could then let the program shift the X values around, however, with corner coordinates spaced at 20ft intervals this should not be necessary.

First – select the INV process from the Action Toolbar (see below).

Recall from the previous gravity lab that there are several parameters to specify in the **Inversion Setup** window. In this run, we will free only the Z coordinates. Under **constraints** we’ll specify dX and dZ values of 5 feet. Recall, that this parameter restricts the adjustments in X or Z that the computer can make in trying to improve the fit between calculated and observed gravity values. Check the AutoDC level.

Your **Inversion Setup** window should look like that shown at right.
Finally select the points you want to free during the inverse computations. Your final view window should look like that above.

The inversion process can leave a pretty rough or jagged looking surface. I always like to smooth it out so that it looks more realistic from a geologic point of view. From your action toolbar select Pick individual vertices and move them slightly being sure not to degrade the fit between the calculated and observed gravity. It is usually possible to smooth out some of the irregularity this way.

When completed, your model will probably look similar to that shown below.
How did the inverse modeled bedrock depth compare to that obtained using the plate approximation?

Now bring down the magnetic windowpane. Based on the gravity modeling, you now have an approximate idea of the bedrock configuration. You can use this bedrock model as a starting point in your analysis of the magnetic data. Available geological data indicate that the bedrock is magnetic with relative susceptibility (susceptibility contrast) between the basalt bedrock and alluvia of -0.006. Your profile is normal to magnetic north, and the total field intensity of the Earth's main field at the site is approximately 55,000 nanoteslas (or gammas). The inclination of the Earth's main field is 65 degrees. These parameters have already been set in the model (see Profile >> Set Mag. Field). They are important parameters that should be correctly assigned in any magnetic modeling effort. At this point your modeling window will look like that shown below.

At this point, click on the examine button in the Action Toolbar and assign a value of –0.006 for the magnetic susceptibility (see below).
Assuming that the bedrock lithology is homogeneous, and that the susceptibility contrasts are constant across the profile, the calculated magnetic anomaly should be the anomaly due to the bedrock alone.

You will note that there is significant disagreement between the observed and calculated magnetic values between 180 and 230 feet along the profile. **Why do you think this disagreement exists?**
Don’t try and eliminate this disagreement by adjusting the depth to bedrock. We have good agreement between the computed and observed gravity values which indicates that our representation of bedrock depth must be fairly accurate. Recall that the main reason for collecting the gravity data was to get a firm grasp on the bedrock configuration. The disagreement between calculated and observed magnetic field intensity is not associated with errors in our bedrock model; the differences are associated with the presence of magnetic materials other than the basalt bedrock: the drums of radioactive waste we’ve been hunting for.

You can adjust the model coordinates further to try and achieve a better combined-fit between gravity and magnetic calculations and observations in the regions outside of the major differences between magnetic observations and calculations. Just be sure not to try and adjust bedrock coordinates in the vicinity of the large magnetic anomaly between 180 and 230 feet along the profile. However, I think you will see that calculated magnetic anomaly matches the magnetic field pretty well in areas outside the high amplitude anomaly near the center of the profile.

In this figure, the bedrock configuration has been established through the inverse gravity modeling procedures. The magnetic field associated with the bedrock is shown by the solid (computed) line in the upper Magnetic display pane. The observations (solid points) suggest the presence of magnetic objects not associated with bedrock at approximately 215 feet along the profile.
Lab Computations and Questions:

This lab has two parts to it. Parts 1 and 2 will be presented in a single write-up. As part of the current lab I recommend that you begin to write the general introduction and background section. In addition, you can also write up a general discussion of the gravity modeling results and preliminary magnetic modeling results, i.e. the contribution to the local magnetic field associated with bedrock. Basically you can set the stage for the final modeling exercise which will consist of determining the location and number of drums buried at the site.

Now is also a good time to consider a couple questions within the context of our discussions of the regional and residual fields. These concepts were discussed under gravity methods. The computation of the residual played an important role in Stewart’s work. You can also consider the magnetic observations as consisting of regional and residual components.

Questions to think about

A. The difference between the observed magnetic anomaly and calculated bedrock anomaly represents what kind of anomaly?

Residual or regional?

B. What kind of magnetic anomaly is represented by the calculated field associated with the bedrock?

Residual or regional?
MAGNETIC COMPUTER LAB

Part 2

In Part 1 of this lab exercise, we undertook an analysis of gravity over the data from the suspected burial site to define depth to bedrock. This step was necessary as a precursor to the interpretation of the magnetic data because the bedrock is itself magnetic and represented by basalt with susceptibility of 0.006 cgs units. Since our objective is to find buried metallic containers at the site, being able to discriminate or separate out the contribution of the bedrock topography to the magnetic anomalies observed in the area is critical to accurately pinpointing the location of the buried containers of radioactive debris.

Now that the bedrock effect has been determined, we are able to relate features unexplained by the magnetic field of the bedrock to buried metallic debris at the site.

Today's exercise will not take much of your time, but I would urge you to take the additional time to prepare your lab report.

Procedures

- Copy the MaglabP2 folder from the common drive to your G or C:\Drive
- Get into GM-SYS and Open the file MaglabP2.sur. Your start-up window should look like that below.
• For starters check individual layer parameters. Then zoom in on the object labeled drums. We will use one object to represent the cluster of drums.

• Assign a susceptibility of 0.55 to the drum body and check off the 2 and 3/4D check box as shown below. We’ll assume that the drums are 5 feet long, and that they are stacked on their side. We’ll also assume that our profile goes directly over the buried drums (the peak of the anomaly observed on the survey map). Thus the strike length - into and out of - the cross section will be 2.5 feet.

• Open the Y+ folder and define the strike-length of the drums into the section as 2.5 feet (below). Set susceptibility to 0, the susceptibility of the surrounding alluvial deposits.
• In the Y- folder define the length as –2.5 feet (that is 2.5 feet out of the plane of the section). Set the susceptibility to 0. This represents the susceptibility of the materials beyond the ends of the drum, i.e., the susceptibility of the alluvium.

• Click OK

• The location of the body shown in the starting model is the result of a rough guess. I placed an object beneath the peak of the anomaly and made some minor adjustments to its location. Your startup window should look something like that shown below.

![Image](image.png)

• Try and fine-tune the location and size of the buried cluster of drums by running an inversion. Click on the inversion option in the action toolbar and set up the inversion parameters.

• **Inversion parameters** –
  
  Free both X and Z coordinates.
  
  Set dX to 5 and dZ to 5.
  
  Zoom in on the drum cluster and free **only** the three points that outline the cluster for inversion.

• The inversion process may actually weaken the match, but click **next step** a few times and note where the coordinates start to drift.

• Exit the inversion window and then begin to manually adjust the locations of the cluster boundary.

• You’ll probably want to zoom out a bit before making manual adjustments. Zoom in or out to suit your interests.

• The resulting adjustments – after some tinkering – may look like that on the following page.
• Beware of the perfect match associated with various configurations of very flat drums.

• Now that you have a fairly good idea where the drums are located, we can make a rough estimate of how many drums are buried at the site. This estimate assumes that we know something about the size of the drums. To make things easy we'll assume the drums have a cross sectional area of 4 ft$^2$.

• In our approach thus far, we have assumed that the drums producing the anomaly are clustered together in one area. To estimate the number of drums we simply calculate the cross sectional area of the derived triangle and divide it by the cross sectional area of a single drum (4 ft$^2$). To calculate the area of this triangle you’ll want to examine the x and z coordinate locations using the eyeball. Write down these coordinates and plot them on a sheet of graph paper at one-to-one scale so you can measure the base and height of your triangle.

• Show your triangle plot. Remember that the area of a triangle is 1/2 the base times the height. Discuss your results.

• Discuss possible limitations of the result you obtained. In your discussion, also consider the relative influence of depth of burial. Remember that a buried drum has a magnetic field that is roughly equivalent to a simple dipole field. The magnetic anomaly produced by the drum will diminish with increased depth of burial ($r$) as $1/r^3$. Drums buried deeper at the site may not be resolvable. Compare the relative magnitude of an anomaly associated with a drum buried 7 feet beneath the surface to one buried 20 feet beneath the surface. Could there be more drums there than you suspect?

• Illustrate your model by choosing fill patterns for the objects in your model. Also check the plan view to make sure your model has been correctly defined (see example figure below).
Model display: Configuration of the bedrock surface separating basalt from alluvia was defined through modeling of the residual gravity data across the site. The cluster of buried drums is modeled as a triangular shaped object with 5 foot strike length. Magnetic calculations and observations are shown in the center pane.
Your Lab Report:
Points will be allocated on the following:
5  Abstract and report structure

Abstract:
- Present a brief description of what you did and the results you obtained (~200 words).

5  Background:
- Provide some background on the data we’re analyzing, i.e.:
  - Describe what it is you are looking for.
  - Why was the gravity survey necessary?
- Along with the above discussion points, summarize the physical properties associated with the model such as densities and susceptibilities. What contrasts did you use?

17  Results (present in order listed below):
1. Illustrate the configuration of bedrock that you derived from the inversion of the gravity data. 3 points for figure plus accompanying discussion.
2. Discuss the comparison of the magnetic anomaly associated with bedrock to the total magnetic anomaly survey across the profile. Use a figure to illustrate the bedrock magnetic field (calculated in MagLab1) and note parts of the magnetic anomaly that are not explained by the bedrock field. Relate these features to the concepts of regional and residual fields (see Part 1). 4 points for figure plus accompanying discussion.
3. Discuss the results of magnetic modeling undertaken in lab to define the location and extent of the buried drums. Illustrate your result. 3 points for figure illustrating the drum cluster you derived and brief comment.
4. Present analysis of the triangular body associated with the cluster of drums: i.e. show the 1:1 scale graph of the triangle; present your calculation of the cross sectional area of the body, and your calculation of the number of drums. 4 points for graph, plus calculations/analysis and statement of results.
5. Discuss the possibility that you may have missed some drums. Be specific. How might the \(1/r^3\) variation of the magnetic field of a dipole (i.e. the drum) affect your ability to detect a buried drum? \(r\) is distance from the dipole-center to magnetometer. 3 points for using specific example.

5  Conclusions:
- Summarize the highlights of results obtained from your investigation of the site. Discuss the approach used, the rationale behind it, your findings along with shortcomings and limitations of the possible interpretations.

32 Total points

ASSIGNMENT IS DUE __December 9th (Thursday) __
The procedures for opening up MAGIX model files are reviewed in Part 1 of the magnetic lab section of this manual. If you have questions refer back to that discussion. Open up the file maglab2.MGX in the Z:\apps\programs\magix directory.

1) A magnetic survey has been conducted over a waste site where drums of highly toxic materials have been buried. Total field intensity measurements were collected on a 1-meter grid of points over the burial trench, which is oriented roughly N45°E. The regional field associated with local geological features in the bedrock and nearby cultural magnetic sources were estimated and removed. Several isolated magnetic anomalies are observed in the remaining residual anomaly. You select a profile along the axis of the trench across one of these features to develop and inverse subsurface model. Computer modeling allows you to estimate the depth and approximate size of the object(s) producing the residual anomaly.

<table>
<thead>
<tr>
<th>measurement x (m)</th>
<th>measured field intensity (nT)</th>
<th>measurement x(m)</th>
<th>measured field intensity (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>16</td>
<td>346.40</td>
</tr>
<tr>
<td>2</td>
<td>0.32</td>
<td>17</td>
<td>206.70</td>
</tr>
<tr>
<td>3</td>
<td>0.84</td>
<td>18</td>
<td>66.19</td>
</tr>
<tr>
<td>4</td>
<td>1.68</td>
<td>19</td>
<td>-14.84</td>
</tr>
<tr>
<td>5</td>
<td>2.99</td>
<td>20</td>
<td>-43.84</td>
</tr>
<tr>
<td>6</td>
<td>5.38</td>
<td>21</td>
<td>-46.18</td>
</tr>
<tr>
<td>7</td>
<td>9.28</td>
<td>22</td>
<td>-39.50</td>
</tr>
<tr>
<td>8</td>
<td>15.97</td>
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<td>-31.41</td>
</tr>
<tr>
<td>9</td>
<td>27.62</td>
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<td>48.15</td>
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<td>11</td>
<td>84.09</td>
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</tr>
<tr>
<td>15</td>
<td>396.70</td>
<td>30</td>
<td>-5.88</td>
</tr>
</tbody>
</table>

Drums buried in the trench are believed to be roughly 1.2 meters high with a diameter of .6 meters. The effective magnetic susceptibility of this type of drum is generally .55 cgs units. The intensity of the earth’s magnetic field at the site is 55000 gammas and its inclination is 65°. The strike direction is -40 degrees (N40W) and the profile direction is N50°E (check the Edit)
Geometry Graphically parameters). Assume that the drum (or drums) were placed in the trench on their side and that the profile crosses the center of the anomaly. Hence, the in and out extents will be 0.6m.

The purpose of this exercise is to learn to use the MAGIX option INVERT to determine the X and Z coordinates of the buried drum(s). You will probably want to INVERT from the INTERPRET menu. This will allow you to gauge the effectiveness of the inversion attempts, visually as they are being performed. Based on your previous experience with MAGIX, you probably already have a good idea about where to start. But this time you are doing things in reverse.

1. Make a starting guess about the X and Z locations of the object(s) using the half-maximum technique noted in the text and described below. Just as with gravity, magnetic anomalies associated with simple geometry (sphere, vertical and horizontal cylinder, etc.) have characteristic shapes. In this example, we have one or more drums buried at a depth of a few meters. Hence we might approximate the arrangement of drum(s) by a sphere. The vertical magnetic anomaly associated with a vertically polarized sphere, is easily represented analytically, and yields \( X_{1/2} \) (the distance from the peak where the anomaly falls to half its maximum value) = 0.5 \( Z \) (depth to center of the sphere). Hence \( Z = 2X_{1/2} \). The earth’s main field is inclined at 65°, and you are looking at the total field anomaly rather than the vertical field anomaly. Although the similarities are rough, the half-maximum estimate will give you an approximate initial estimate of depth to the center of the object. Also, the anomaly is asymmetrical, so in this case, taking the average of the \( X_{1/2} \)’s on both the left and right sides of the anomaly may provide more accurate depth estimation.

Plot off the observed magnetic data, and mark the 1/2 max positions on both sides of the anomaly.

Place a drum sized object at that depth near the anomaly peak.

2. Make a FORWARD calculation, plot your result. HOW ACCURATE WAS YOUR GUESS?

3. Now let the computer calculate where and how deep the drum is. Running the INVERT option on a closed body like the drum can be kind of tricky. The program does not always behave the way you would like it to. For instance, it will not maintain the cross section of the drum. So when you run INVERT the object may become quite distorted and look nothing at all like a drum. In many instances the sides of the object may even cross over each other. Do not despair.

   a. You might save time by representing the object as triangular in cross section. Even though we know the drum is circular (or rectangular) in cross section (assuming that it hasn't been crushed) it is probably far enough beneath the surface so that differences between the details of the model and the actual shape of the drum will not have only minor effect (recall Magnetic Lab Part 1). Also, it is impossible to cross the sides of the triangle.

   b. Start by FREEing only the X coordinates. This will yield the approximate horizontal location of the drum(s).

   c. Run INVERT and look at the result. Did the calculations converge close to the observed anomaly? Do you need to make another iteration? Describe your initial success or failure.
d. Don’t forget that you can **Set Auto Recalc** and adjust the positions of coordinates by hand. Since you have just completed an inversion of the X coordinates, you might try **EDIT BODY** and move the body manually up or down to see if the match between calculated and observed magnetic field intensity improves.

   e. Now **FREE** the Z coordinates and **unFREE** the X coordinates. Iterate again and determine whether you are heading in the right direction; i.e., are you converging to a viable solution. It is better to go in small steps. Sometimes the program solutions start to diverge and multiple iterations do not improve the result. If this happens, it is best to use your own judgment and relocate the BODY back to a more reasonable starting position.

   Complete the inverse process until the convergence is reasonably good and **SAVE** or **REPLACE** your model. There is no reason to repeat the INVERT process to obtain 0 error.

   The above steps are probably the hardest part of the exercise.

**Complete this exercise by answering the following:**

1. What is the cross sectional area of the object you derived? Estimate the volume by multiplying this times the total extent in and out. Now evaluate your result. Do you have one drum or two? How can you tell?

2. Compare the depth to the center of the inverse model you just derived with the initial estimate made using the half-maximum technique for the sphere. How close were they? Describe as a difference in feet.

**DON'T FORGET TO PLOT YOUR RESULTS AND SAVE AS NEEDED**

Lab 2 is due _________________.

Late labs will receive a letter grade reduction
Magnetic Computer Lab
Comparing Total Field and Vertical Gradient Measurements

Part 4 (to be revised)

Use file maglab4.MGX for today's lab.

In some of the papers on your reading list you have run across the mention of the vertical gradient technique. Vertical gradient data is the combination of two independent measurements made at the same point on the earth's surface, but at different elevations, for instance 2 and 3 meters above the surface. The vertical gradient is calculated by subtracting the measurement at the higher elevation (also, presumably, the lower field value) from the measurement made closest to the surface. This generally will give you a positive value, but in some instances may yield negative values.

This computer lab is designed to provide you with a better understanding of the uses and limitations of the technique, and also addresses the basic issue of resolution as distinct from detectability.

**Detectability** - implies only that the presence of one or more objects can be inferred from the data. In other words, the anomaly is large enough to be discriminated from background noise in the measurements. We have referred to the sensitivity of the instrument as being the deciding factor in some of the gravity and magnetic homework and test problems. However, sources of variation unrelated to the local subsurface zone-of-interest make instrument precision an ideal limit. Variability in the earth’s magnetic field due to the lack of terrain and elevation corrections, local cultural features, variations in the solar wind, etc., make detectability an issue which is site dependent.

**Resolution** - has a more specific connotation and refers to the ability to distinguish the presence of individual objects, and assumes that they are detectable within the context of a particular site. In Magnetic Lab 1, you added a second drum, and depending on where you inserted the drum, you noticed a specific affect. If you placed the drum immediately below the first, you noticed that the anomaly remained bell-shaped but increased in amplitude. You could not resolve the second drum. You might have been able to infer its presence by noting the change of anomaly amplitude, but there was no evidence of a second peak. If you placed a second drum at the same depth to the left or
right of the first drum, you may or may not have observed a second peak. Whether you did or did
not depended on how far the drums were separated.

**Vertical gradient** - measurements are often employed in shallow subsurface applications because of
their ability to improve resolution of individual objects or to locate their edges more precisely.

The vertical gradient is often expressed in terms of the vertical gradient of the vertical component
of the earth’s magnetic field.

\[
\frac{\partial F_E}{\partial r} = \frac{\partial}{\partial r}\left(\frac{2M \cos \theta}{r^3}\right) = -\frac{6M \cos \theta}{r^4} = -\frac{3F_E}{r}
\]

**Assignment:** In today’s lab we will take a critical look at the improvements that can be gained from
the use of vertical gradient measurements as opposed to total field measurements. We will consider
the simple case of two drums, and determine the limit of resolution using both total field and
vertical gradient measurements. Two drums are already entered for you in the model file
`maglab4.mgx`. Each of you will be assigned a depth. Undertake the following experiment:

- In SET DATA PARAMETERS examine the settings and change the data set name to your
  name.
- Compute the magnetic anomaly associated with an isolated drum at your assigned depth.
- Make a depth estimate from the total field anomaly using the half-amplitude relationship.
- Place a second drum in the model at the same depth, and separate the two drums sufficiently
  far apart so that two separate peaks, one over each drum, are still observable.
- Estimate the depth to each of the drums using the \(X_{1/2}\) rule for the buried dipole. Make your
  measurement of \(X_{1/2}\) on the sides where the overlap of anomalies from each drum is least.
  Note that \(X = 0\) does not coincide with the center of the composite anomaly but with
  individual peaks.
- **Plot the model** and calculations and note the actual separation between drums and average
  estimated depth derived from the half-max relationships.
- Bring the two drums closer together until you lose any hint of the double peak.
- Make another depth estimation using \(X_{1/2}\) measurements of the combined field. In this case,
  \(X = 0\) corresponds to the center of the combined anomaly.
- **Plot your model**, mark down the actual spacing between drums and note the average
  estimate of drum depth from the half-max relationship.
- Go to the edit data menu and select **mag gradient** as your data type. Return to **Interpret** and
  move the two drums closer together until you loose evidence for the two drums with the
  vertical gradient.
• Plot the model and calculations. Note that this is the vertical gradient plot and note the separation between drums on your plot.

**Answer the following questions:**
Make sure you present your results and computations and describe what you've done. Don't make the reader go hunting for your work or have to figure it out on his or her own.

1. How good are the X<sub>1/2</sub> depth estimates obtained from the total field measurements? Describe for the three cases worked in lab.
2. What is the horizontal resolution limit for the total field measurements at both depths? Recall, this measurement is made at the point where 2 separate peaks can be resolved. Express as a ratio of sensor-to-drum-center distance.
3. What is the horizontal resolution limit for the vertical gradient measurements at both depths? Again - this measurement is Express as a ratio of sensor-to-drum-center distance.
4. Do vertical gradient measurements improve spatial resolution of individual drums?

*Show your work and refer to numbered, labeled and captioned figures In your write-up.*

**Assignment DUE:** __________