GEOL 384.3 and GEOL 334.3

Lab #9: A table-top Slingram survey

In this lab, you will conduct several small tests of the Slingram EM method using table-top equipment. A Slingram profiling uses a pair of transmitter (Tx) and receiver (Rx) coils connected by a cable and maintained at a fixed distance while moving both of them along the line. Normally, the Tx-Rx spacing is 40 m or 60 m, with penetration depths corresponding to about half of this spacing (Figure 1). Our coil spacing in the lab will be 0.5 m, and the profile will be just over 2 m long.

Figure 1. Slingram survey during the UofS geophysics field school in September 2012.

The oscillating primary magnetic field from the Tx coil induces electric (eddy) currents in the subsurface. These eddy currents generate a secondary magnetic field, which are picked up by the Rx coil. From the recorded secondary magnetic field, its quadrature (90° out of phase with the primary) component is extracted. This quadrature component is sensitive to several physical factors of interest: subsurface electrical conductivity distribution, mineralizations, fluids, fracture zones, etc..

Interpretation of Slingram data is mostly qualitative. From the shape of the anomaly profile, the thickness, dip of the conductive zone can be estimated by using methods studied in the preceding labs or by modeling.

In this lab, we conduct a mini Slingram survey using the same pair of Tx-Rx coils as in lab #8, in a horizontal arrangement on the tabletop in Geophysics lecture room 265 (Figure 2). Between the coils, we place a conductive sheet representing the target. For targets, we can use aluminium sheets, galvanized steel sheets, or aluminium foil. The aluminium foil is probably the best. The target can be oriented vertically or tilted toward one of the coils using notches in a wooden frame (Figure 2).

Figure 2. Transmitter and receiver coils, and the target (aluminum sheet).

In lab 8, we saw how a single coil interacts with itself to produce an impedance that is a function of frequency. We also saw how the signal in the receiver varies with frequency, position, height and tilt, when there is no local conductor (OK, the table has metal parts). The signal in the receiver in the absence of local conductors is called the PRIMARY. The SECONDARY is the signal induced in the receiver coil by the currents in a conducting target. What we measure in the Rx coil is the total signal (PRIMARY + SECONDARY).

In a Slingram survey, the two coils are kept horizontal (axes vertical), with their centers at the same height. It is essential that this relative orientation be maintained. As shown in lab 8, if the separation distance is changed by one percent, the PRIMARY will change by three percent. The SECONDARY (induced by the target) signal is recovered from the total signal by subtracting the PRIMARY, and therefore the three percent error in the PRIMARY will cause a <u>much larger error in the SECONDARY</u> (3% times the ratio of the PRIMARY to the SECONDARY).

In addition to coil spacing, as also shown in lab 8, extraction of the SECONDARY response is strongly sensitive to the equal heights of the coils (slope between the Tx and Rx positions) and their leveling by level bubbles. If there is some topography in a field survey, it will be impossible to keep the coils at the same height, and so a correction will have to be applied. However, in the present lab, we keep the transmitter and receiver at a perfect level and orientations, and so we do not have to worry about the profile slope, and variations in coil separation and orientation.

During the measurements, Picoscope is used to capture the cosine-shaped variations of the transmitter and receiver voltages. From these records, the amplitudes of Tx and Rx voltages and their phase differences are derived by using the procedure described in lab 8. Your primary task in this lab consists in extracting from these records the in-phase and quadrature responses of the secondary signals, as described below.

Extraction of In-phase and Quadrature secondary responses

Harmonic signals are convenient to represent by vectors on the plane (X,Y) in which X is the in-phase amplitude and Y is the quadrature. For example, the oscillating voltage recorded in the Rx in the absence of target (the RRIMARY field) is represented by the green vector **P** shown in Figure 3. This field is advanced with respect to the Tx voltage which we measure in the Picoscope by phase ϕ_P, and this phase angle is represented by the angle of vector **P** relative to the horizontal (in-phase) axis. The length of this vector equals the amplitude of the PRIMARY, P. Similarly, the red vector **R** shows the amplitude and phase ϕ_R of the Rx voltage recorded in the presence of an unknown target.

In field equipment, the manufacturer calibrates the instrument so that the PRIMARY P and ϕ_P values are known for every coil separation and the secondary is easily obtained. In this lab, we measure a PRIMARY separately, by conducting measurements without target. Thus, the first step of data analysis consists in subtracting the PRIMARY from the total measured signal to get the SECONDARY: vector **S** = **R** – **P** in Figure 3. In the attached worksheet, vectors **P** and **R** are represented by their amplitudes P and R and phases ϕ_P and ϕ_R (shown by angles in Figure 3). These vectors are convenient to describe by their projections onto the axes shown in Figure 3:

$$\mathbf{P} = \begin{pmatrix} P & 0 \end{pmatrix}, \qquad \mathbf{R} = \begin{pmatrix} R\cos(\phi_R - \phi_P) & R\sin(\phi_R - \phi_P) \end{pmatrix},$$

$$\text{and therefore} \qquad \mathbf{S} = \begin{pmatrix} R\cos(\phi_R - \phi_P) - P & R\sin(\phi_R - \phi_P) \end{pmatrix}. \qquad (1)$$

These projection axes correspond to the components of the recorded Rx field being in-phase and 90° out of phase relative to the primary field **P**. These components are obtained by projecting the vectors onto the two unit (basis) vectors shown in the inset in Figure 3: $\mathbf{e}_{\text{in-phase}} = \begin{pmatrix} 1 & 0 \end{pmatrix}$, and $\mathbf{e}_{\text{quad}} = \begin{pmatrix} 0 & 1 \end{pmatrix}$.

The second step of data transformation consists in dividing the components of vector **S** (eq. (1)) by the PRIMARY amplitude P. This operation gives the normalized in-phase ($s_{\text{in-phase}}$) and quadrature (s_{quad}; purple dashed-line arrows) components of the secondary field:

$$\begin{cases} s_{\text{in-phase}} = \dfrac{S_{\text{in-phase}}}{P} = \dfrac{R}{P}\cos(\phi_R - \phi_P) - 1, \\ s_{\text{quad}} = \dfrac{S_{\text{quad}}}{P} = \dfrac{R}{P}\sin(\phi_R - \phi_P). \end{cases} \qquad (2)$$

These quantities are dimensionless and can be expressed in percent. Because they are independent of the strength of the primary signal (P), these quantities should be representative of the currents within the ground.

The $s_{\text{in-phase}}$ component is principally controlled by the resistivity of the subsurface, and s_{quad} – by its induction properties.

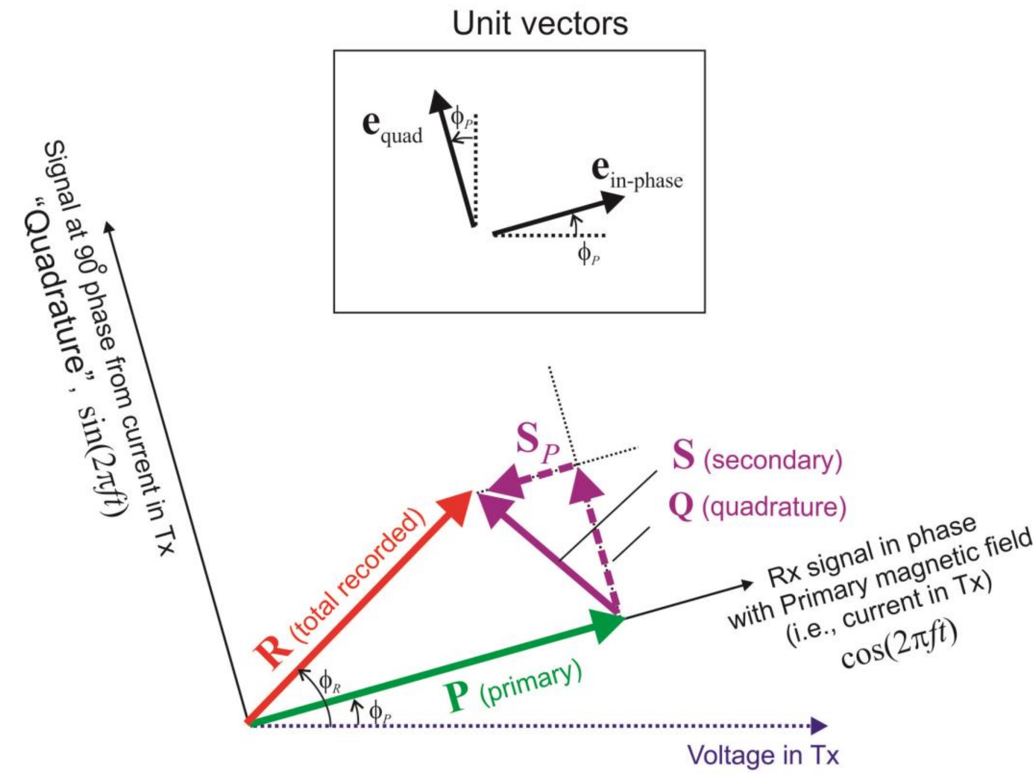

Figure 3. Harmonic oscillatory signals represented by vectors. Vector **P** (green, primary) is the voltage in the receiver coil recorded in the absence of metal targets. This signal is in phase with the current in the transmitter. **R** (red) is the total voltage recorded in the receiver, and **S** = **R** – **P** is the secondary voltage produced by the subsurface targets. This secondary voltage is decomposed into $\mathbf{S}_P$ (secondary, in-phase with **P** and <u>principally be due to resistivity</u>) and **Q** (quadrature; <u>produced by the inductance of the medium</u>).

Note that although this Figure show $\phi_r > 0$ for clarity (counter-clockwise measurement of all angles), in reality, the Tx current lags the voltage, and therefore, you will have $\phi_r < 0$ in your data.

Identification of characteristic frequency

We also saw last week that the transmitter and receiver coils have characteristic frequencies f_c, which are produced by their inductances and resistances. The target also has an inductance and resistivity, and therefore it also has a characteristic frequency, which depends on the conductivity and the dimensions of the target. Since our objective is to determine the characteristics of the target, we need a way to remove the effects of the transmitter. This is one of the purposes of subtracting the primary.

The identification of the critical frequency f_c is similar to what was done in lab 8. At frequencies much lower than f_c ($f \ll f_c$), the RESISTIVE LIMIT (plateau of 90° phase) is approached (Figure 4). At frequencies $f \gg f_c$, the INDUCTIVE LIMIT (plateau of amplitude) is approached. The Quad response peaks at f_c (Figure 5).

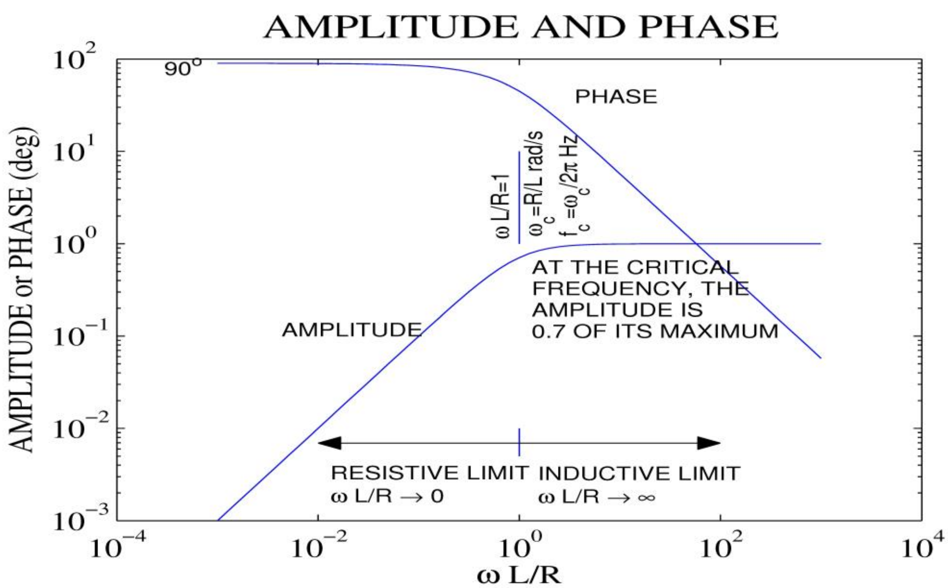

Figure 4. Amplitude and phase of the recorded signal **R**. From these graphs, the characteristic (critical) frequency f_c is the frequency at which the amplitude equals $1/\sqrt{2} \approx 0.707$ of its maximum level (plateau), and the phase equals 45°.

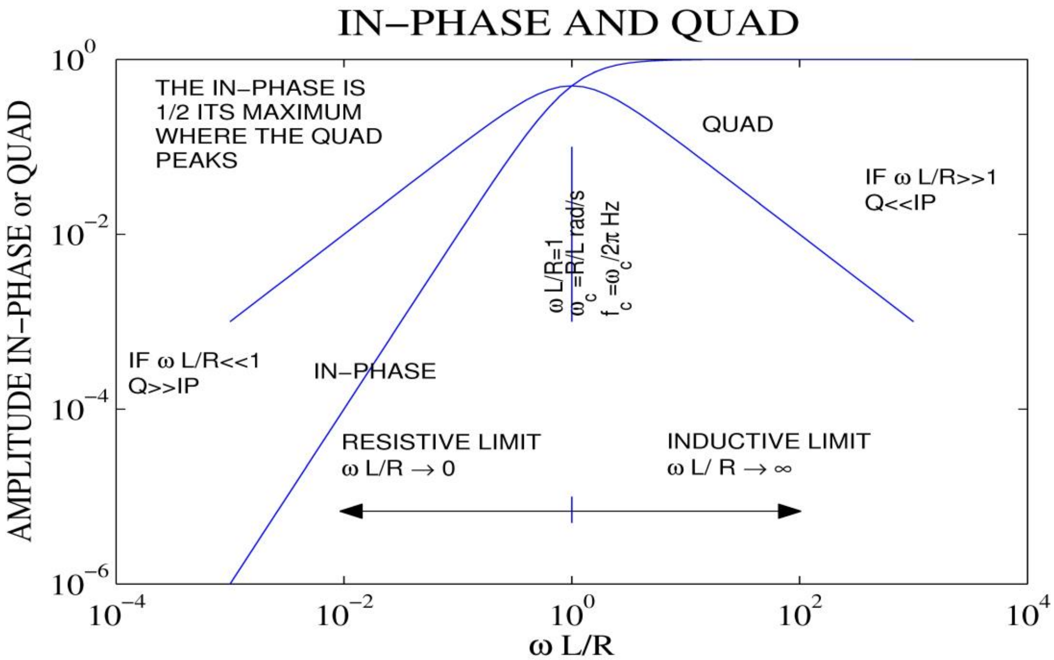

Figure 5. In-phase and Quad secondary voltages in the receiver. From these graphs, f_c is the frequency at which the Quad peaks and the In-phase response equals ½ of its highest (plateau) level.

Physically, the characteristic frequency f_c is the halfway point between frequencies at which resistance dominates and at which induction dominates (Figure 4). This frequency can be calculated for simple targets, such as a coil of wire, a sphere, or a flat sheet. For a flat sheet, the time constant and f_c equal

$$\tau = \frac{\mu\sigma hD}{4}, \qquad f_c = \frac{1}{2\pi\tau} = \frac{2}{\pi\mu\sigma hD}, \tag{3}$$

where μ is the magnetic permeability, σ is the conductivity, h is the thickness and D is the dimension (length or height).

For the aluminium sheets we use, these formulas give τ = 4 ms and f_c of about 40 Hz. Your measurements may differ from this because the above formula for τ is approximate. The galvanized steel sheets have a critical frequency of about 250 Hz and the aluminium foil about 4000 Hz.

For a target like a metal sheet, the critical frequency f_c is proportional to the product of conductivity, thickness of the target, and its size. Therefore, from an f_c measurement, we cannot solve for the conductivity or thickness of the target, only for the product of all three parameters. Of course, if we have the thickness and D from another survey, say from a mag survey, we could calculate the conductivity. This is typically how the ambiguity is resolved – by utilizing other kinds of information.

Usually, we profile at multiple frequencies and try using this information to get the characteristic frequencies of the various targets. The characteristic frequency is important because it depends on the dimensions and conductivity of the target. However, for only one metal sheet used as target in this lab, the characteristic frequency will be close to the one in the absence of a target, that is, the f_c of the PRIMARY response.

Induction number

The INDUCTION NUMBER N is another important characteristic of the EM response which we are testing in this lab. For an isolated target, the induction number is the ratio of the characteristic dimension of the experiment h to the skin depth δ:

$$N = \frac{h}{\delta}. \quad (4)$$

For a tabular target, the characteristic dimension h is its thickness. The induction number describes how the EM response depends on the increasing thickness h. At low N, the response of the sheets simply adds up with increasing h, so that you can in principle differentiate between targets of different thicknesses. By contrast, at higher induction numbers ($\delta \ll h$), the EM response saturates, and the addition of further sheets does not increase the response.

At 10 kHz, the skin depth in aluminum is half a mm, which is comparable to the thickness of one sheet. This means that at all frequencies, the induction number is low when only one sheet is present, but with two or more, there is no significant change in response. Galvanized steel stays at low induction numbers until several sheets are combined. For foil, many sheets are required to achieve a large N and to saturate the response.

Assignments

To perform Slingram profiling, we need to: A) measure the response function for the PRIMARY field, B) select the appropriate (one or multiple) frequency for profiling, and C) perform profiling across the geological strike of the target. Step A) was performed prior to this lab, and the PRIMARY response of the voltage in Rx coil to the voltage in Tx can be found in the NO TARGET table on the first page in the worksheet. To obtain easily readable values, the R_{Primary} column in this table contains the Rx voltage scaled to the level of Tx voltage equal 1000. Note that this page in the worksheet also contains the original data table imported from `.dat` file produced by our instrument.

1) **Plot the values of R_{Primary} and ϕ_P from the NO TARGET table. Compare them to the expected responses in Figure 4.** Later, these quantities will be used as P and ϕ_P to obtain the response function by eqs. (2).

2) From these plots, **determine the critical frequency f_c for the primary field**.

You should find that the f_c is not much above 500 Hz, and so we will do a Slingram profile at 500 Hz. Set this frequency in the function generator, and set the transmitter and receiver coils up at the center of the table, with their axes vertical, and the centers 50 cm apart. The midpoint of the two coils should correspond to profile position x = 150 cm. Set the metal target sheet vertically at an end of the modeling table.

3) **Acquire a profile** along the modeling table by moving the holder with the target over the coils. Use 20-cm or longer intervals far from where the coils are and 5-cm intervals near the coils, as suggested but not strictly required in the "Slingram" page of the worksheet.

   Similar to the NO TARGET table, **transfer the results** from the `.dat` file obtained from the instrument into columns R (recorded amplitude scaled to Tx voltage = 1000) and ϕ_R (recorded phase) the table Vertical Target (second page in the worksheet).

4) Using Excel or Matlab/Octave, **calculate the last three columns in this table.** Start from the auxiliary column for phase differences and finish with final values of in-phase and quadrature responses.

   For the primary field (amplitude P and phase ϕ_P), use the values from table NO TARGET at frequency 500 Hz. **Express the fractional values of $s_{\text{in-phase}}$ and s_{quad}** (by eqs. (2)) **in percent**.

5) **Plot the values of $s_{\text{in-phase}}$ and s_{quad} in two ways:**

   a. as functions of the position of the target along the table, and

   b. the same but using as distance the <u>target position in cm divided by the coil separation in cm</u> (50 cm).

6) **Describe the shapes of the responses** with respect to their symmetry and relation to the position of target (x = 150).

For comparison, Table "Tilted Target" shows results of a previous profile with the same target but tilted at 30° toward point x = 0. The position of the tilted target should be measured at the top of the sheet (i.e., the <u>deepest</u> point of the target in a field experiment).

7) **Repeat the above calculations and plots for the tilted target**.

8) **GEOL334 only: Discuss how the lateral positions and shapes of the amplitude and phase responses relate to the dip of the target.**

Hand in:

Brief answers to the questions highlighted in **bold** above with figures embedded in a Word or PowerPoint document by email.