Lab 8: Electromagnetics Part I

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Due: Before your next lab session

Overview

Elementary circuits can be used to simulate the responses for EM surveys. In this lab, you are provided with a Jupyter Notebook that allows you to explore the character of the responses under different conditions. The basic principles for EM induction have been provided in the notes and on the GPG. You will use those notes to accompany the abbreviated text provided here.

Resources

- GPG: https://gpg.geosci.xyz/content/electromagnetics/index.html
- GPGlabs: InductionRLcircuit_Harmonic.ipynb (a two-coil app)
- GPGlabs: FDEM_ThreeLoopModel.ipynb (a three-coil app)

InductionRLcircuit_Harmonic.ipynb

This app uses one coil as a transmitter and the other as a target. The time varying current in the transmitter induces a current in the target loop.

Q1: Magnetic Flux and Coupling

The response in the target loop is fundamentally controlled by how much magnetic flux goes through the target. The diagram on the app indicates: $\mathbf{B_p}$ (primary vertical field) and $\mathbf{B_n}$: (the amount of the field that is perpendicular to the loop)

- The currents induced depend upon the total flux through the loop (Area × $\mathbf{B_n}$):
- Fill in the Table 1.

θ	0	20	40	60	75	80	85	87	88	89	90
$\mathbf{B_p}$											
$\mathbf{B_n}$											
I_s											

Table 1.

- What is the angle of theta that provides maximum coupling; and the value of theta that provides minimum coupling.

Q2: Amplitude of the secondary current.

The current induced in the target depends upon the resistance. To illustrate this keep all parameters equal to their default values but change the resistance as given in the Table 2 and fill in the Table 2. (Note: app slider bar uses log scale)

- Fill in the column of maximum secondary current (max(I_s)) in Table 2.

R (Ω)	max (I_s) (app)	ψ (calc.)	ψ (meas.)	ψ (app)	I_s Real (calc)	I_s Real (app)	I_s Quad (calc)	I_s Quad (app)
1								
10								
100								
10^3								
10^4								
10^5								
10^6								

Table 2.

Q3: Phase of the secondary current

The current in the target is harmonic (same frequency as the primary current) but it is phase shifted. It lags the primary by

$$phase\ lag: \psi = \frac{\pi}{2} + \tan^{-1}(\frac{\omega L}{R})$$

where

- R: resistance (Ω)
- L: inductance (H)
- ω: angular frequency (rad/s); $\omega = 2\pi f$

Calculate the phase lags using the default L and with variable R, and fill in the column of ψ (calc.) in Table 2.

Q4: The secondary current (I_s) is plotted along with the primary current (I_p). Measure the phase shift with a ruler and pencil. How does that phase shift agree with what you calculated from the formula? Put that number in the Table 2 (ψ $(meas.)$).

Q5: Use the formula below and your value of phase lag, ψ, to evaluate what portion of the secondary current is in-phase with the primary and what portion is out-of-phase. Fill in the values in the Table 2 (columns of $I_s\ Real\ (calc.)$ and $I_s\ Quad\ (calc.)$)

$$I_s \cos(\omega t - \psi) = I_s \cos(\psi)\cos(\omega t) + I_s \sin(\psi)\sin(\omega t)$$

- In-phase of I_s: $I_{phase} = I_s \cos(\psi)\cos(\omega t)$
- Quadrature-phase of I_s: $I_{quad} = I_s \sin(\psi)\sin(\omega t)$

Q6: The last plot in the app takes the secondary current and plots the in-phase (real) and quadrature phase currents. At any time, the sum of these two must equal the total secondary current as shown in the above equation. Verify this by filling in below table. You need to compute the amplitude of the secondary current, I_s, for variable time: t=0, T/4, T/2, 3T/4, T.

t	0	T/4	T/2	3T/4	T
I_{phase} (meas.)					
I_{quad} (meas.)					
I_s (meas.)					
I_s (app)					

Q7: Response Curve:

The response curve has a Real (or in-phase) and Imaginary (or quadrature) part. The quadrature curve has a maximum at

$$\frac{\omega L}{R} = 1 \quad or \;\; f = \frac{R}{2\pi L}$$

If we sample the fields below this frequency the quadrature part is larger than the real. If we sample fields above this frequency, then the real part dominates.

- At what frequency does the quadrature peak occur for this problem? (Note: use the default R and L values in the app)

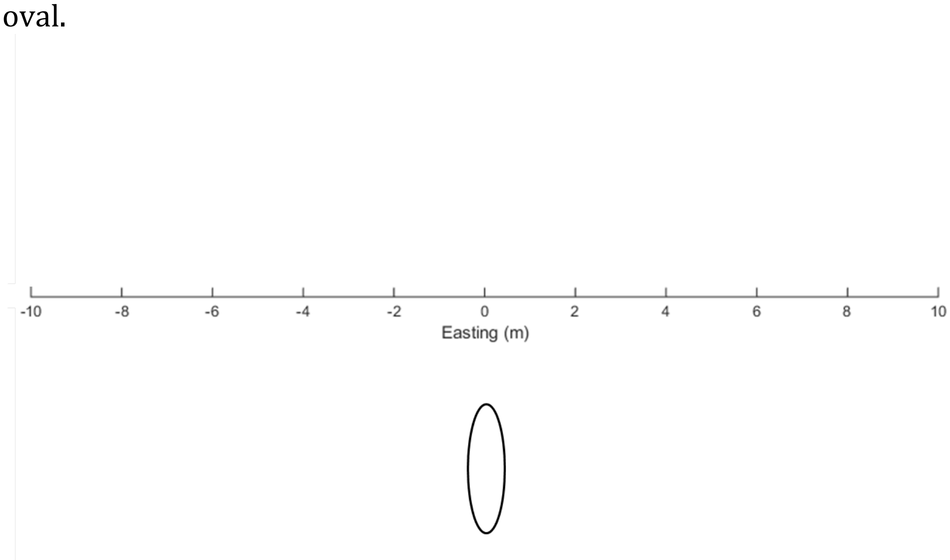
- What is the ratio of Quadrature/Real for frequencies that are a factor of 10 smaller than this, and for frequencies that are an order of magnitude larger?

Loop-loop frequency domain EM system

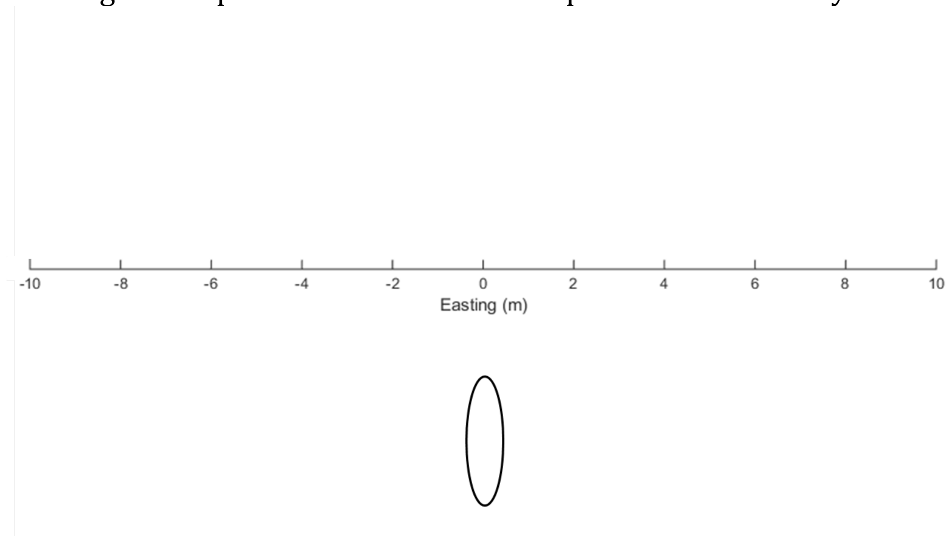
A loop-loop frequency domain EM system (e.g. EM-31) consists of a transmitter (Tx) and a receiver (Rx), which are mounted at the ends of a 3.6m long boom. The Tx carries a sinusoidal (or harmonic) current of frequency f = 9,700 Hz. This generates a time-varying magnetic field everywhere and is called the primary magnetic field $\mathbf{H}^\mathbf{P}$. The primary magnetic field induces currents in the target. We can represent a conductive target by a loop of wire that has a resistance (R) and a self-inductance (L). The induced currents in the target then generate the secondary magnetic field $\mathbf{H}^\mathbf{S}$. The Rx measures both the primary and secondary magnetic fields. EM-31 calculates the ratio $\mathbf{H}^\mathbf{S}/\mathbf{H}^\mathbf{P}$ as the measured data. The Rx is sensitive only to magnetic fields that cross its plane, so the co-planar geometry is one of maximum coupling. If the Rx coil was rotated 90 degrees so that it was perpendicular, then no magnetic field lines would cross its plane and no primary field would be measured.

Q8. Assume the Tx-Rx separation is 4 m and that the loops are oriented horizontally on the surface (the Easting axis). The data point is plotted at the midpoint between the Tx and Rx. For four observation points at Easting = -4, -2, 0, and 4 m, do the following. Four diagrams are provided below for you to draw your answers.

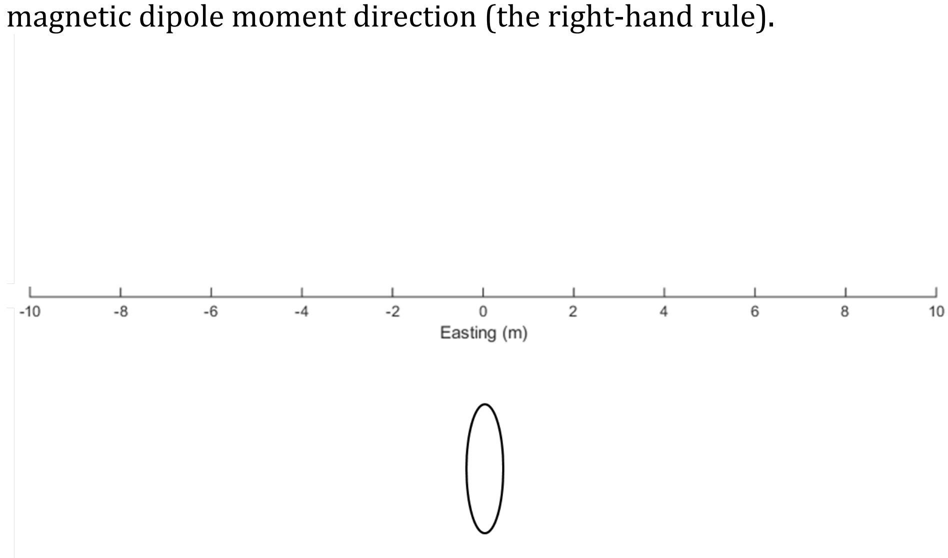
a. Sketch the Tx loop using an oval as if you are looking down from the side. The Tx loop carries an increasing current flowing in the clockwise direction when looking from above. Label the direction of the current in your Tx loop. Draw a short arrow at the center of the Tx loop to indicate the magnetic dipole moment direction (the right-hand rule). Sketch the Rx loop using another oval.



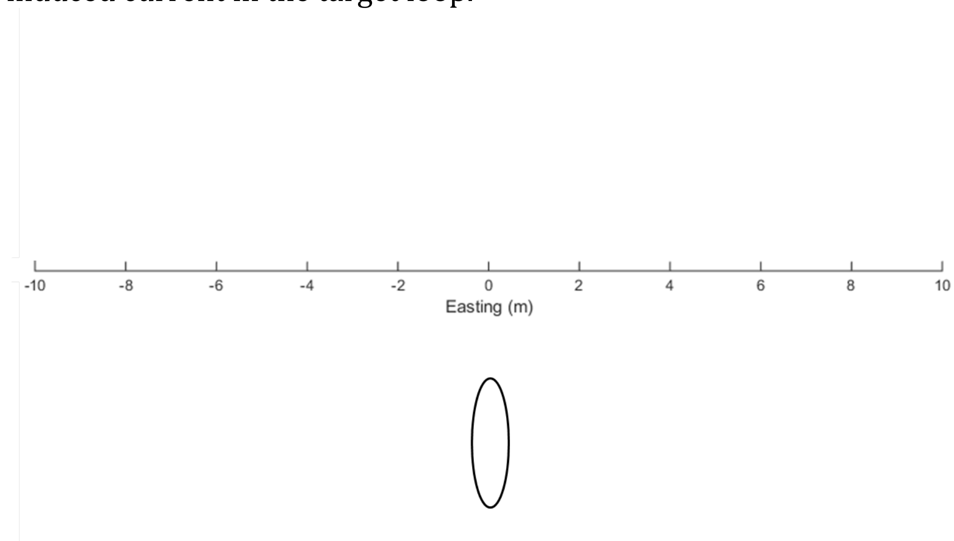
b. Sketch the primary magnetic field lines from the Tx due to the current. Label the direction of the magnetic field lines. Make sure they are consistent with the magnetic dipole direction and the loop current direction you had in **a.**



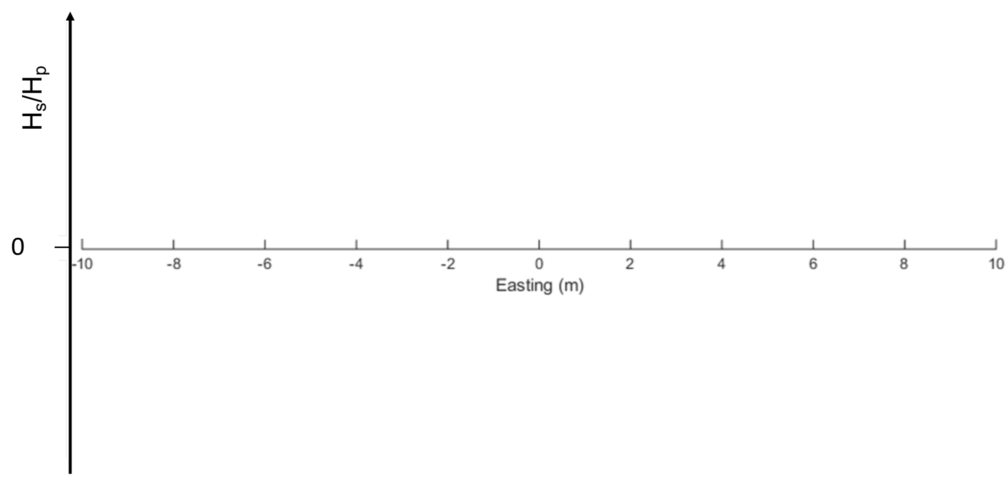
c. Sketch how the field lines interact with a target loop buried 4 m below the surface at Easting = 0 m. Label the direction of the induced current in the target loop. Draw a short arrow at the center of the target loop to indicate the magnetic dipole moment direction (the right-hand rule).



d. Sketch and label the direction of the secondary magnetic field lines due to the induced current in the target loop.



e. In the diagram below, qualitatively sketch the data profile based on your answers above. Use the sign convention that the observed data is positive when the secondary field is in the same direction as the primary field at the receiver.



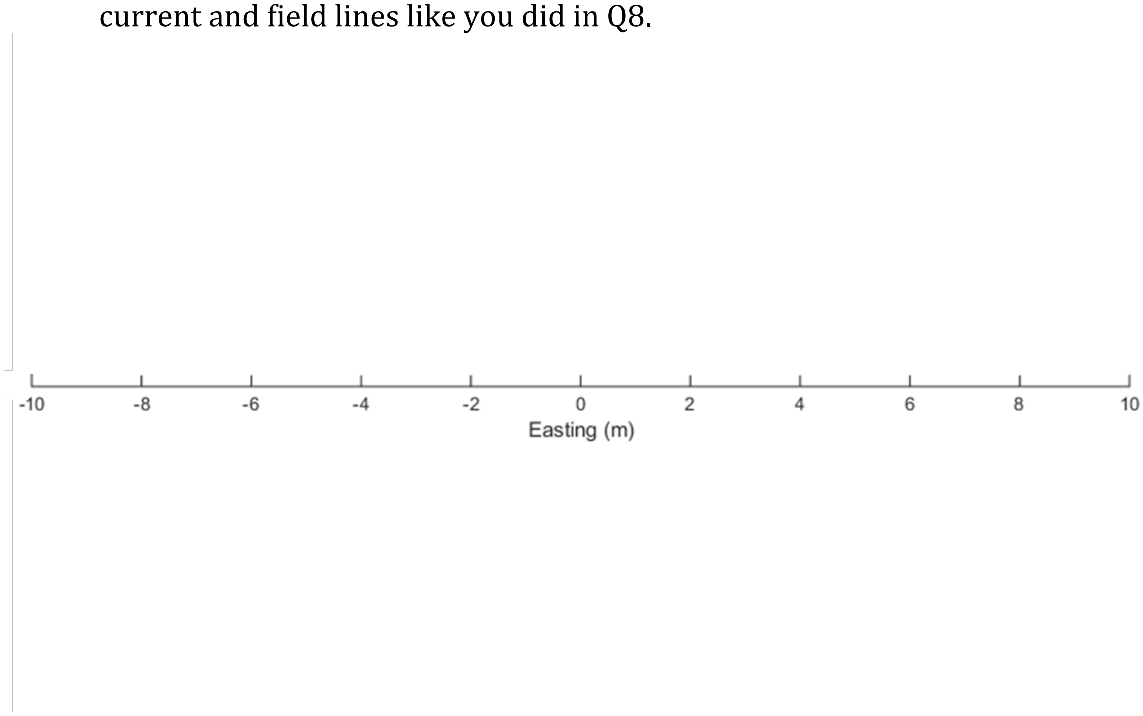
Q9. The above work is geometrical and applies equally well to the Real and Imaginary portions of the recorded data. That is, both Real and Imaginary transect plots will have the same characteristic shapes. Their relative amplitudes however are determined by the properties of the target and the frequency of the instrument. More precisely it is the dimensionless quantity $\boldsymbol{\alpha = \omega L/R}$. Launch the notebook "**EM_ThreeLoopModel.ipynb**" from gpgLabs. Run the cells from the beginning to the section of "**Run FEM3loop Widget**" using the defaults. Look at Plots 1 and 2.

a. Evaluate for the default settings. Use the diagram in Plot 1 to evaluate the theoretical ratio of Real/Imaginary amplitudes for this example. Now use Plot 2 to see if your recorded data are in accordance with that number.

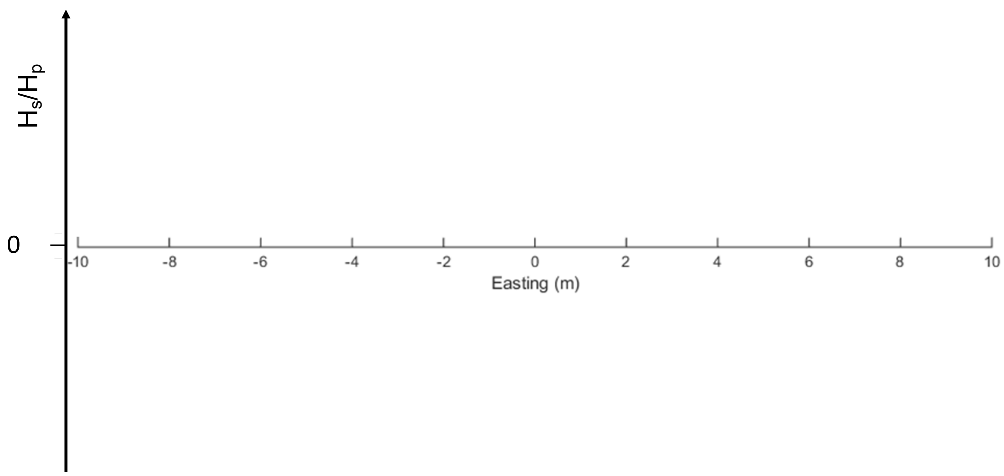
b. Repeat Part (a) using R = 20000 (now we have a poor conductor). To do so, adjust the slider for the resistance R.

Q10**.** Return the sliders to the default parameters (or rerun the cell to restore the default). Then change the inclination and the declination of the target to be I = 0 and D = 0.

- Sketch the Tx, Rx and the target loops for the datum at x = 0 m and draw the current and field lines like you did in Q8.

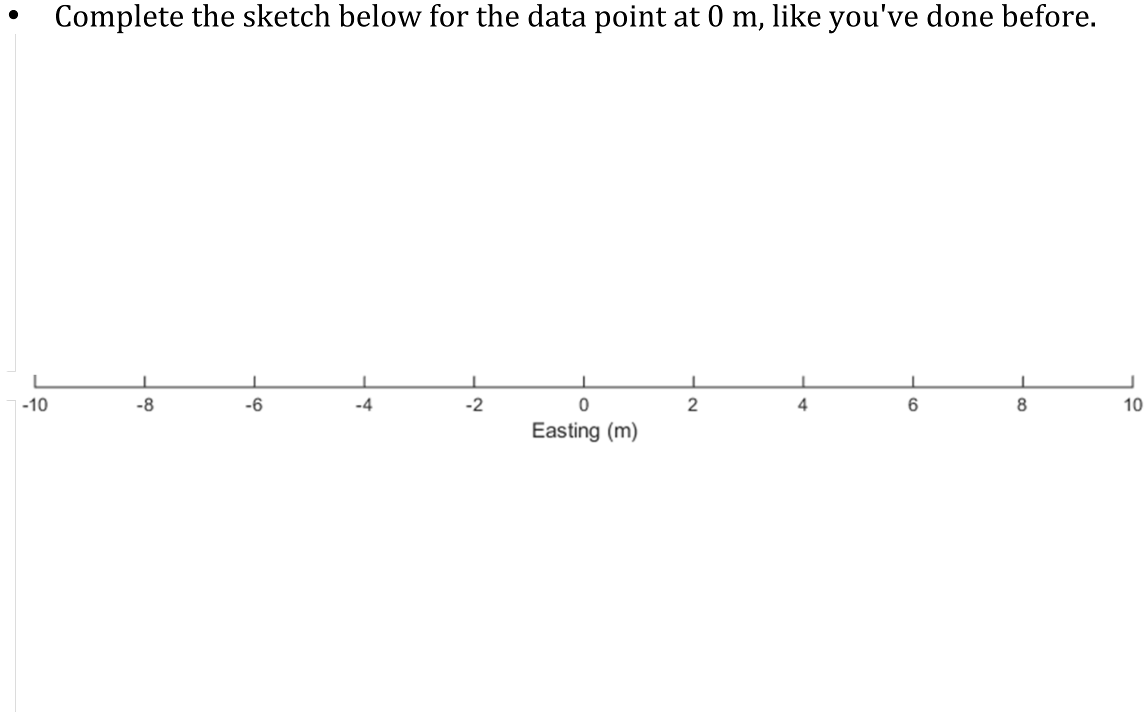


- Draw the expected data along the profile. Does your sketch match the notebook result?

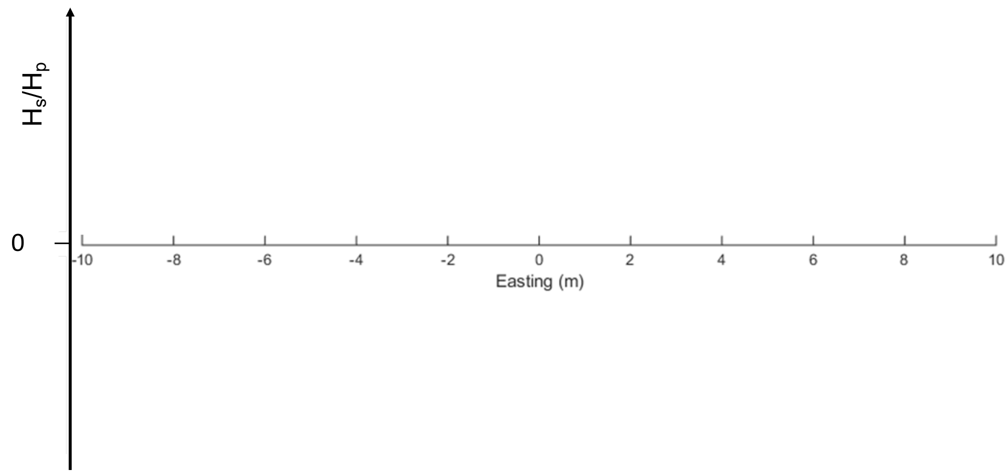


Q11**.** Now change the inclination and declination of the target to be I = 90 and D = 0.

- Complete the sketch below for the data point at 0 m, like you've done before.



- Draw the expected data along the profile.



Q12**.** Return the sliders to the default settings (I = 0, D = 90). Examine how the data changes with the depth of burial of the target. Investigate the depth, z = 2 to 10 m in steps of 2 meter increments.

a. How does the amplitude of the anomaly change as a function of depth?

b. What are the most significant changes in the character of the anomaly?

c. How are the zero crossings of the data along the profile affected?

Q13. Return to the default settings. Now alter the data acquisition strategy. Slowly increase the station and line spacing (dx). Look at both the profile plot and the map views.

a. What is the largest station spacing that can capture the anomaly?

b. What factors do you need to consider when choosing station spacing?

Q14. We can expand the concepts of EM coupling to more complex geometries, such as a pipe made of a series of small conductive loops. Run the section of "**Pipe Widget**" for modeling the pipe to answer the following questions. The app plots data for two orientations of the EM-31: north-south (NS) and east-west (EW).

a. Look at the profile line plot (bottom plot). Which of the two boom orientations gives a response most similar to the default set-up for the 3-loop problem in Q8?

b. Explain why you choose that orientation (you may want to use a sketch).

c. Adjust the depth of the pipe. What happens to the anomaly?