Name:____________________________________

EOSC 350 Final Exam

December 19, 2016

Instructions

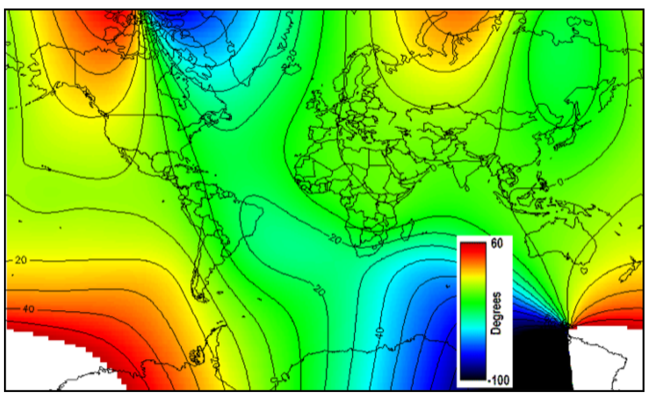
Here are some instructions

- There are 43 Multiple choice worth 1 point each and Short Answer questions worth 60 points. There is one bonus question.
- You will have 2.5hrs to complete the exam.

Multiple Choice (43 points)

1. A map displaying a "Total field magnetic anomaly" can be best described as:
   (a) A map of the amplitude of Earth's magnetic field.
   (b) A map of the distribution of magnetic material.
   (c) A map of the vertical component of the measured magnetic field.
   (d) A map of the horizontal component of the measured magnetic field.
   (e) A map of the component of the measured magnetic field anomaly that is aligned along the direction of Earth's magnetic field.

2. The following map is a map of:



   (a) Total Magnetic field.
   (b) Magnetic field declination.
   (c) Magnetic field inclination.
   (d) None of the above.

3. What is NOT a reason for using a Base Station in a magnetic survey.
   (a) To remove effects from near surface rocks that have variable magnetic susceptibility.
   (b) To correct the data for diurnal variations.
   (c) To correct for disturbances caused by magnetic storms.
   (d) To remove the effects of the IGRF.

4. How does the appearance of a total field anomaly from a long vertically oriented steel well casing change from the south pole (I = -90°) to the north pole (I = 90°)? Assume that the well casing is not remanently magnetized.
   (a) The vertical well casing would produce a positive monopole shaped anomaly at the north pole and a negative monopole shaped anomaly at the south pole.
   (b) The vertical well casing would produce a negative monopole shaped anomaly at the north pole and a positive monopole shaped anomaly at the south pole.
   (c) The vertical well casing would produce positive monopole shaped anomalies at both the north and south poles.
   (d) The vertical well casing would produce negative monopole shaped anomalies at both the north and south poles.

5. Under what conditions is it possible to use a magnetic survey to locate a buried copper or aluminum electrical cable?
   (a) The cable needs to be close enough to the surface so that the induced anomalous/secondary field is measurable.
   (b) The search region needs to be free of other susceptible infrastructure which could greatly complicate the measured response of the cable.
   (c) Both a) and b)
   (d) The cable must be carrying an electric current.

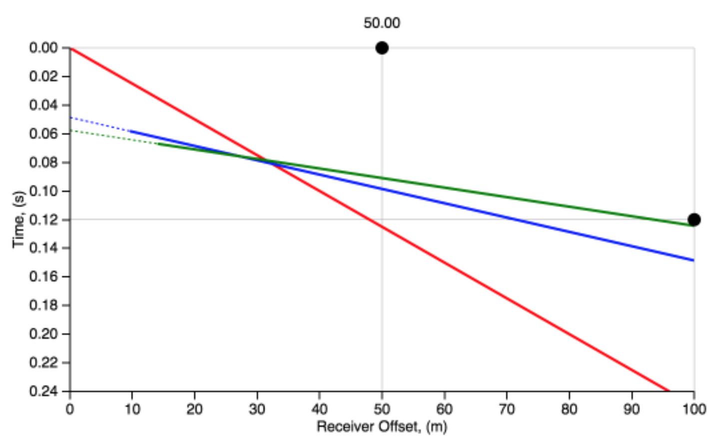
6. The Multichannel Analysis of Surface Waves (MASW) method inverts for which quantity?
   (a) P-wave velocity
   (b) S-wave velocity
   (c) Density
   (d) Young's modulus

7. Before stacking reflection seismic data, a normal move-out correction is applied. This correction is applied to data that is sorted in:
   (a) common shot gathers
   (b) common receiver gathers
   (c) common midpoint gathers
   (d) common offset gathers

8. For a reflection seismic survey where the subsurface has an average P-wave velocity of 1000m/s and we use a 10ms seismic wavelet, what is the best resolution we can obtain?
   (a) 1 m
   (b) 2.5 m
   (c) 5m
   (d) 10 m

9. A seismic survey is conducted in a region with two layers. The top layer is a shale with a density of 2500 kg/m^3 and seismic velocity of 2900m/s. The bottom layer is a sandstone with a density of 2100 kg/m^3 and a seismic velocity of 3000m/s. For a down-going signal, the reflection coefficient for the interface will be
   (a) Positive
   (b) Negative
   (c) Zero
   (d) Not enough information

10. Regarding the figure below, which of the following is correct?



   (a) The dashed vertical line at 50m indicates the cross over distance
   (b) The critical distance is about 30 m
   (c) The red line shows critically refracted signal
   (d) The second layer is clearly visible from first arrival as our data
   (e) All of them are wrong

11. When considering the critical angle between a layer 1 over a second layer 2, with $V1 > V2$, what of the following is true?
    (a) We can calculate the critical angle using Snell's law.
    (b) The critical angle in this case is calculated by another method.
    (c) We need some more information to compute critical angle.
    (d) There is no critical refraction.

12. How does the seismic method differ from the magnetic method?
    (a) Seismic is sensitive to density changes while magnetics is sensitive to magnetic susceptibility.
    (b) The magnetic method is a natural source field while seismic method can use either an artificial or a natural source.
    (c) Collecting seismic measurement requires contact with the ground while collecting magnetic data can be done at the surface or airborne..
    (d) All of the above.

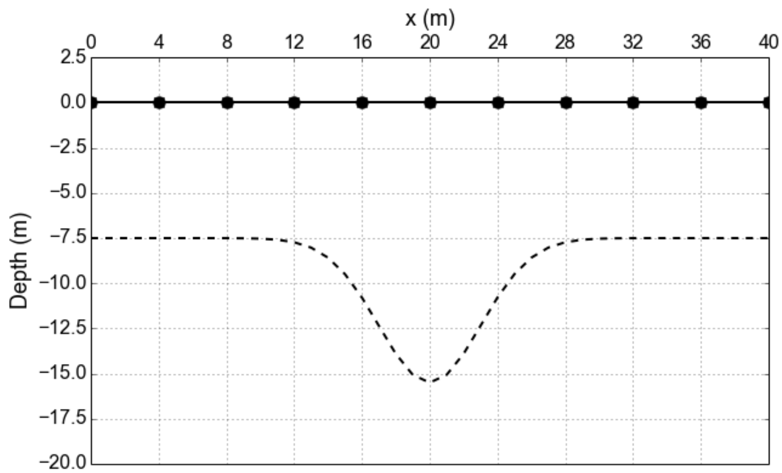
13. Which statement is NOT true?
    (a) A P-wave is a body wave.
    (b) An S-wave is affected by water saturation of medium
    (c) A Rayleigh wave travels along surfaces and interfaces.
    (d) A Love wave is a surface wave.

14. Why is GPR used in glacial environments?
    (a) The skin depth for GPR signals in ice is very large.
    (b) The wavelength is very short so the resolution is high.
    (c) Fewer data can be collected in glacial environments and this results in chearper surveys.
    (d) GPR can easily differentiate layers of ice and snow.

15. Of the following, which is NOT a processing step used in GPR?
    (a) Travel time to depth conversion
    (b) Topographic correction
    (c) Gain correction
    (d) Stacking
    (e) They are all potential processing steps.

16. You were going to perform a GPR survey after a period of extended drought. However, you needed to postpone your survey for 2 weeks due to significant rainfall. The near-surface soils are now saturated with water. Which or the following statements is INCORRECT?
    (a) The near-surface conductivity and relative permittivity are larger after the rainfall.
    (b) The penetration depth of the GPR signal may now be smaller.
    (c) The resolution of near-surface features is now better.
    (d) GPR signals now propagate more quickly through the Earth.

17. Above, we see a two-layer model with a concave interface. A zero-offset GPR survey configuration is used to map this interface. Why are these types of features hard to interpret in radargram data?



(a) There are locations along the interface in which no reflected signal is measured by the receiver.

(b) The station spacing shown in the figure is too large to be effective.

(c) A single interface returns multiple reflected signals, which could be interpreted as multiple objects.

(d) Some reflected signals come in at an angle and are therefore hard to observe.

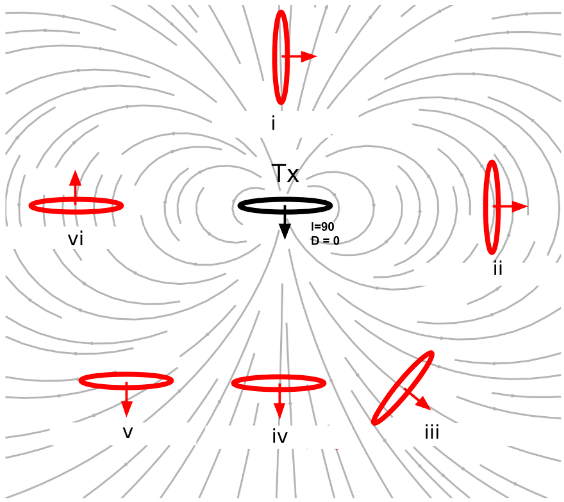
18. When a GPR wavelet reaches the interface of a perfect conductor:

(a) All of the wavelet is reflected

(b) Some of the wavelet is transmitted and some of the wavelet is reflected

(c) All of the wavelet is transmitted

(d) Not enough information



19. Consider a zero-offset GPR survey. In some cases, the slope of the radargram signature at sufficient offset can be use to estimate the propagation velocity. For which of the following objects is this possible?
    (a) A point reflector
    (b) A thick pipe
    (c) A rectangular block
    (d) All of the above

Use the following figure to answer the next two questions.

20. Which receiver loop(s) are perfectly coupled with the transmitter loop?
    (a) i and ii
    (b) iii, iv and vi
    (c) iv, v and vi
    (d) ii and iii

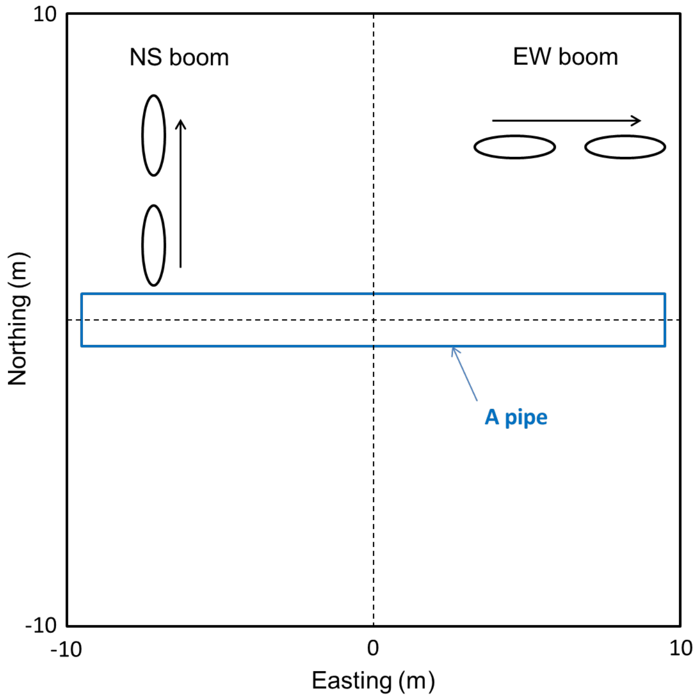
21. Which receiver loop(s) are null-coupled with the transmitter loop?
    (a) i and ii
    (b) iii, iv and vi
    (c) iv, v and vi
    (d) ii and iii

22. The voltage recorded by the receiver coil of a frequency-domain EM system will be proportional to what?
    (a) The strength of the magnetic field normal to the loop
    (b) The rate of change of the magnetic field normal to the loop
    (c) The strength of the magnetic field parallel to the loop
    (d) The rate of change of the magnetic field parallel to the loop

23. Which statement regarding the computation of the apparent conductivity from the data obtained by EM-31 is INCORRECT?
    (a) To compute apparent conductivity we assume a homogenous half-space model.
    (b) The apparent conductivity is not necessarily identical to the true conductivity of the earth.
    (c) To compute apparent conductivity of EM31 data, we only need the imaginary component of the fields measured.
    (d) The apparent conductivity calculation for EM31 data assumes that the coil spacing is much greater than skin depth.

24. The apparent conductivity calculated from an EM 31 survey does NOT depend upon the transmitter
    (a) Frequency
    (b) Height
    (c) Orientation
    (d) Strength

25. The electrical conductivity of a sedimentary rock depends upon
    (a) Porosity
    (b) Pore fluid content
    (c) Shape of the pores
    (d) All of the above



26. You have been contracted to locate buried copper and steel pipes near the old expo site in Vancouver. The pipes are oriented E-W, as shown above. Several data sets were collected: EM-31, GPR and magnetics. Data were aquired along the north-south line over the pipe, as shown in the figure below. Which combination of data sets would be best for detecting both pipes and distinguishing between the copper and steel pipes?
    (a) GPR-EM (EW boom)
    (b) GPR-EM (NS boom)
    (c) Mag-GPR
    (d) Mag-EM (NS boom)
    (e) (c) and (d)

27. The secondary magnetic field in an EM survey is
    (a) The magnetic field arising from induced currents within the Earth
    (b) The amplitude of magnetic field measured by the receiver
    (c) Dependent upon the orientation of the receiver
    (d) All of the above

28. Consider the EM-31 instrument. Which of the following statements is FALSE?
    (a) The ratio of secondary field to the primary field can be split into in-phase and quadrature phase components.
    (b) The quadrature phase data can be converted to an apparent conductivity.
    (c) The in-phase data can be used to find metallic objects.
    (d) It measures multiple frequencies
    (e) None of the above.

29. EM methods are often used to locate mineralized rock formations. However other rock types, like clays and water-saturated rocks, can also have high conductivities. Which of the following additional surveys can be the most useful in solving the ambiguity to distinguish mineralized rocks from clays and water-saturated rocks?
    (a) S

    eismic reflection or refraction

    (b) D

    C resistivity

    (c) M

    agnetic

    (d) N

    one of the above

30. A time-varying magnetic field
    (a) Generates an electric field only in conductors.
    (b) Generates an electric field everywhere.
    (c) Generates a secondary magnetic field only in resistive bodies.
    (d) Generates currents everywhere.

31. The geophysical contractor you hired suggests that your target won't be seen using an instrument operating at 9,800 Hz because the target is deeper than the penetration depth. A good suggestion would be to:
    (a) Use a wider spacing between the transmitter and receiver.
    (b) Consider a different method altogether because the ground conductivity seems too high for investigation with EM methods.
    (c) Use an instrument with a higher frequency.
    (d) Use an instrument with a lower frequency.

32. Which of the following statements is CORRECT
    (a) The "in-phase" datum is always different from the "real"
    (b) The "out-of-phase", "quadrature" and "imaginary components" can sometimes differ
    (c) The "real" and "imaginary" are the same
    (d) The "quadrature" and the "real" are different

33. Which of the following statements is INCORRECT? A sounding curve from an EM system is:
    (a) The measured response from a single Tx/Rx pair as a function of time
    (b) The measured response from a single Tx/Rx pair as a function of frequency
    (c) The measured responses from a transmitter and receiver that are progressively separated about a point of symmetry
    (d) Can be measured from an aircraft or on the ground

34. Searching for targets with very low conductivity (like voids for example) is difficult with EM induction techniques because:
    (a) Currents induced within resistive materials will be small, making it difficult to detect secondary EM fields.
    (b) Skin depth of the targets will be very small.
    (c) Only measurements of the in-phase component will have large amplitudes
    (d) Coil spacing would have to be unreasonably small before there is any chance of obtaining measurable values.

35. Conductivities of earth materials are often expressed in mS/m. A value of 10 mS/m corresponds to what resistivity?
    (a) 100 ohm-m
    (b) 10 ohm-m
    (c) 1 ohm-m
    (d) 0.01 ohm-m

36. A company performed a two-loop survey (like the EM-31) over a two-layered Earth. The company then provided you with the apparent conductivities from both the vertical and horizontal dipole orientation measurements. You are tasked with computing the actual conductivity of the two layers. What additional information do you need to know?
    (a) The thickness of the first layer.
    (b) The height of the instrument above the surface.
    (c) The coil spacing of the instrument.
    (d) All of the above.

37. List these events in the correct order:
    1. Time varying magnetic fields generate electric fields in the earth
    2. Secondary currents generate secondary magnetic fields
    3. Time-varying transmitter current generates a time varying magnetic field
    4. Currents are generated in a conducting material

    (a) $3 > 1 > 4 > 2$
    (b) $3 > 1 > 2 > 4$
    (c) $1 > 3 > 2 > 4$
    (d) $1 > 3 > 4 > 2$

38. Of the following options, which is the BEST definition of apparent resistivity
    (a) Measured voltage divided by the known current.
    (b) The resistivity of the ground between the current and voltage electrodes.
    (c) The resistivity of a uniform Earth which reproduces the observed voltage.
    (d) The same as the true resistivity in most circumstances.

39. In a sounding mode, the DC array
    (a) Keeps the same geometry but is translated laterally along the surface.
    (b) Requires a buried current electrode.
    (c) Keeps the same geometry but is symmetrically expanded about a fixed point.
    (d) Employs a combination of (a) and (c).

40. After the generator for a DC survey is turned on, a volume of Earth material experiences an IP effect. Which of the following statements is true?
    (a) The charges associated with the IP effect are built up instantaneously and they are the same for all rocks.
    (b) The charges take time to build up and the time for build-up is the same for all rocks.
    (c) The charges take time to build up and the time for build-up can vary between rock-types.
    (d) The charges are built up instantaneously but their magnitude differs because of rock-type.

41. An IP datum can have units of
    (a) mV/V
    (b) msec
    (c) mrad
    (d) All of the above

42. Induced polarization refers to
    (a) The polarization of the electric field in the earth that has been induced by the transmitter current.
    (b) The development of polarization charge that occur when an electric field is applied.
    (c) The magnetization set up inside the earth when a current is applied.
    (d) The polarization that arises from the time varying current from the direct current generator.

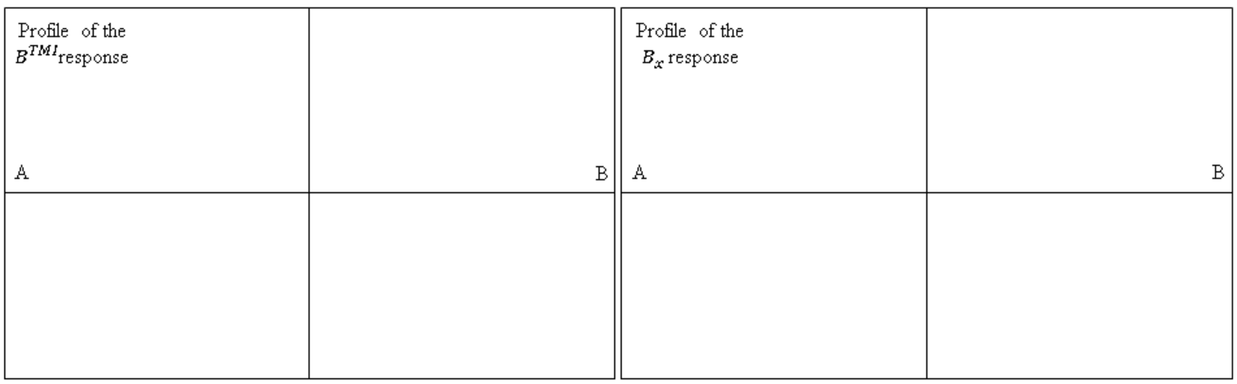
43. The chargeability of Earth materials is dependent upon
    (a) The pore structure of the material
    (b) The surface to volume ratio of the grains that make up the soils or rocks.
    (c) The electrical conductivity of the fluids in the pores.
    (d) All of the above.

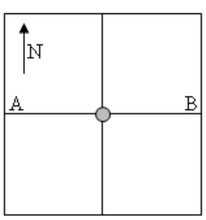
Short Answer (60 Points)

Magnetics (8 points)

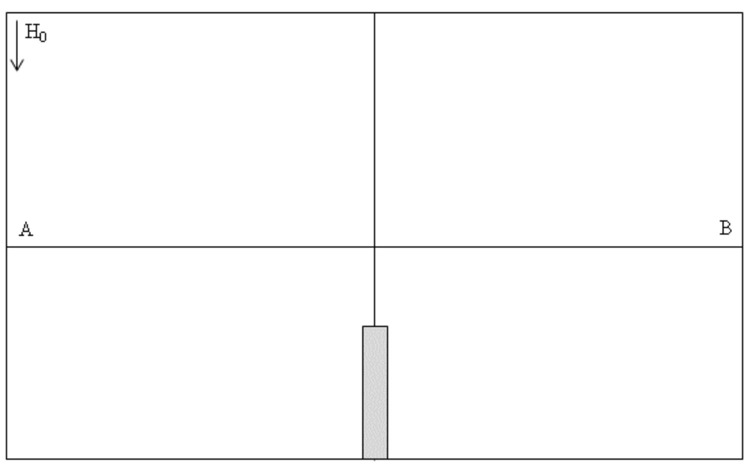
44. To locate an abandoned steel-cased well, a total magnetic field survey is conducted at 2 m above the ground. Assume that the inclination of the inducing field is 90°.

    (a) (3 pts) In the below diagrams, sketch the anomalous magnetic field lines (bottom), a profile of the total field anomaly (top left) and the x-component of the magnetic field (top right) along a profile line over a susceptible well that extends to depth.





Map with profile line



Secondary magnetic field lines

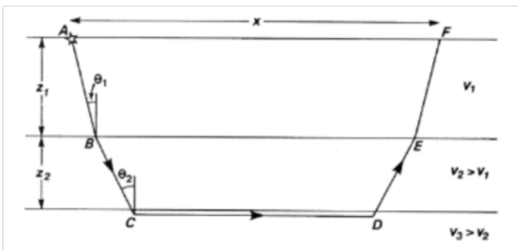
(b) (1 pt) Why might such an anomaly be referred to as a monopole anomaly?

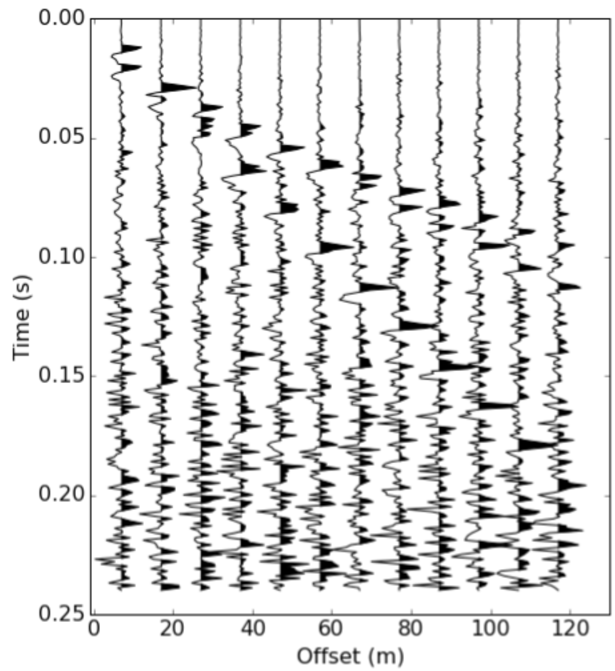
(c) (1 pt) Based on total magnetic field data collected over the pipe, how would you estimate the depth to the top of the pipe?

(d) (3 pts) If you were to design a survey to detect all pipes within a 100m x 100m area what station and line spacing do you need and thus how many data need to be collected? How would these factors change if you knew that all pipes were at least 2 meters below the surface?

Seismic (8 points)

45. Consider the three layer geological model shown below. The EOSC350 TA team performed a seismic refraction survey with single shot and obtained shot gather shown below. Answer following questions. (Hint: v1<v2<v3)





(a) (1 pt) Estimate the velocity of the first layer velocity (v1; m/s)

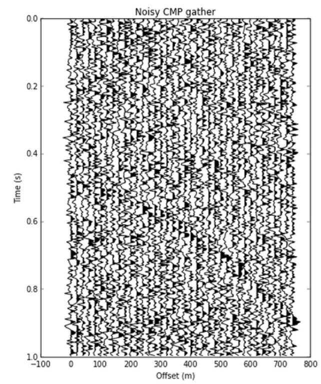
(b) (1 pt) Estimate the velocity of the second layer

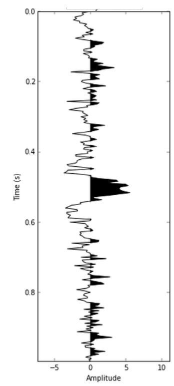
(c) (1 pt) Estimate the velocity of the third layer

(d) (1 pt) Compute the incidence angle θ_1 and critical angle θ_2 shown in the left panel of above Figure.

(e) (1 pt) Estimate the thickness, z1, of the first layer.

46. The normal incidence trace below (right) was generated from the noisy data on the right.



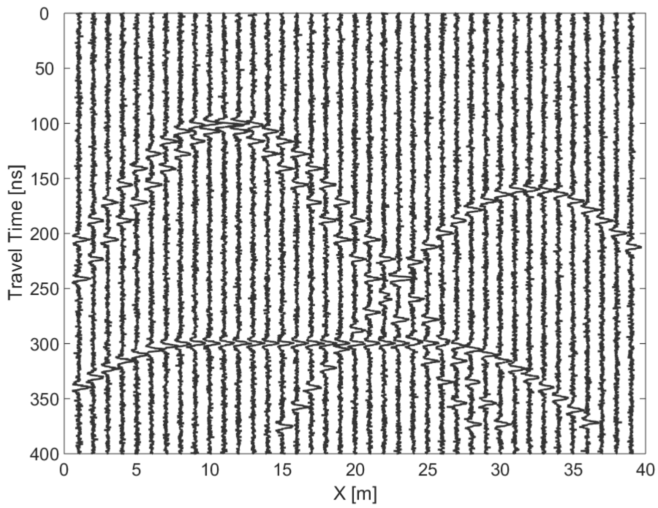


(a) (1 pt) What is a CMP gather? Using a geologic model consisting of a single layer over a half-space, sketch 3 ray-paths to support your explanation.

(b) (2 pts) There are two main processing steps used to obtain the single seismic trace, shown on the right, from the noisy CMP gather. Name and describe these two steps. Your explanation will be helped with use of a travel time equation.

GPR (8 points)

47. Below we see a radargram for a zero-offset GPR survey. Buried beneath the ground are 3 pipes and a large concrete block.



(a) (1 pt) Label the anomalies due to the pipes and due to the block.

(b) (2 pt) Use the right-most pipe signature to determine the velocity of the host medium and its relative permittivity.

(c) (2 pt) Using the two-way travel time formula, what is the depth and horizontal location of the right-most pipe?

(d) (1 pt) What is the depth and horizontal margins of the block?

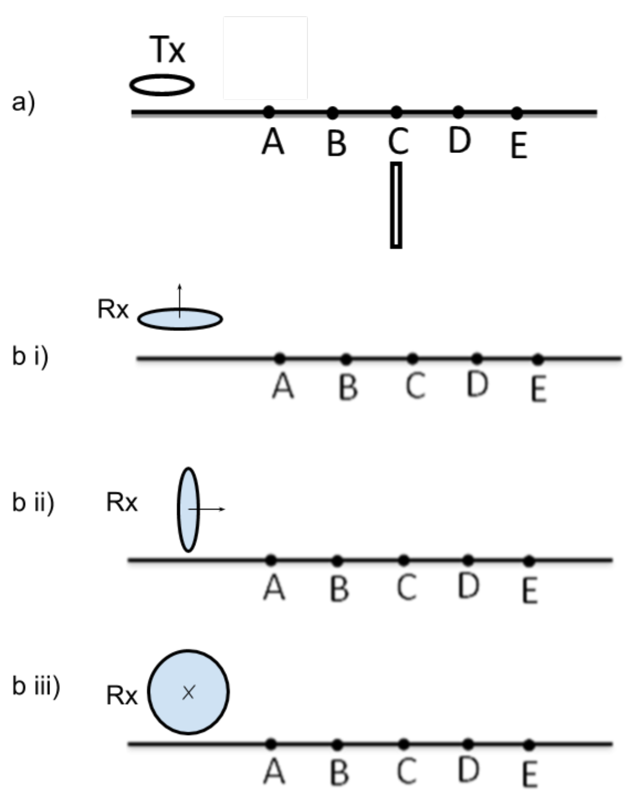
(e) (2 pt) In this figure, we are able to distinguish the signals from two pipes which are close together. At what separation distance would we be unable to differentiate their responses. (Assume an operating frequency of 250 MHz).

EM (13 points)

48. An electromagnetic survey is carried out over a shallow buried foundation. The rebar in the foundation wall makes it act like a vertical conducting plate. Assume that the survey is carried out along a line perpendicular to the strike of the wall. Rather than using an EM31 with a fixed separation between the transmitter and receiver, for this experiment the transmitter will remain fixed and only the receiver moves. A sketch of the relative location of the transmitter and foundation is provided in the diagram below. The transmitter is oriented horizontally (vertical magnetic dipole). Assume the transmitter has an increasing current going clockwise when looking from above.

    (a) (2 pts) On the diagram provided, sketch the primary magnetic field. Indicate the direction of the induced currents in the plate and sketch the resulting secondary magnetic fields.

    (b) (3 pts) For each of the three situations below (i, ii, iii) the receiver orientation is different. The normal to the loop is provided by the vector. Sketch the data you expect to record at points A to E and generate a profile curve. Provide information on how you decide what is positive and negative.



49. The data plots are from and EM31 instrument acquired at the Expo site. The frequency of the coils is 10^4 Hz and the coil separation is $4m$.
    (a) (1 pt) The instrument provides two numbers: what are their names?

    (b) (1 pt) Which one can be converted to apparent conductivity? Using a formula explain how those numbers can be obtained.

    (c) (1 pt) What criterion must be satisfied for those numbers to be valid?.

    (d) (2pts) What is the maximum conductivity of the ground that allows this to be valid?

    (e) (1.5 pt) What two criteria do you use to find locations where you have confidence in the numerical values of the provided apparent conductivity (Circle two on the map and label them “A”

    (f) (1.5 pts) What two criteria do you use to find locations where you think there might be buried metallic objects? Circle two on the map and label them “B”

DC Resisivity (12 points)

50. You have three exploration problems and you can use a Wenner array (see Figure) in a sounding mode, a profiling mode, or a profile-sounding mode. All measured voltages are converted to apparent resistivities.

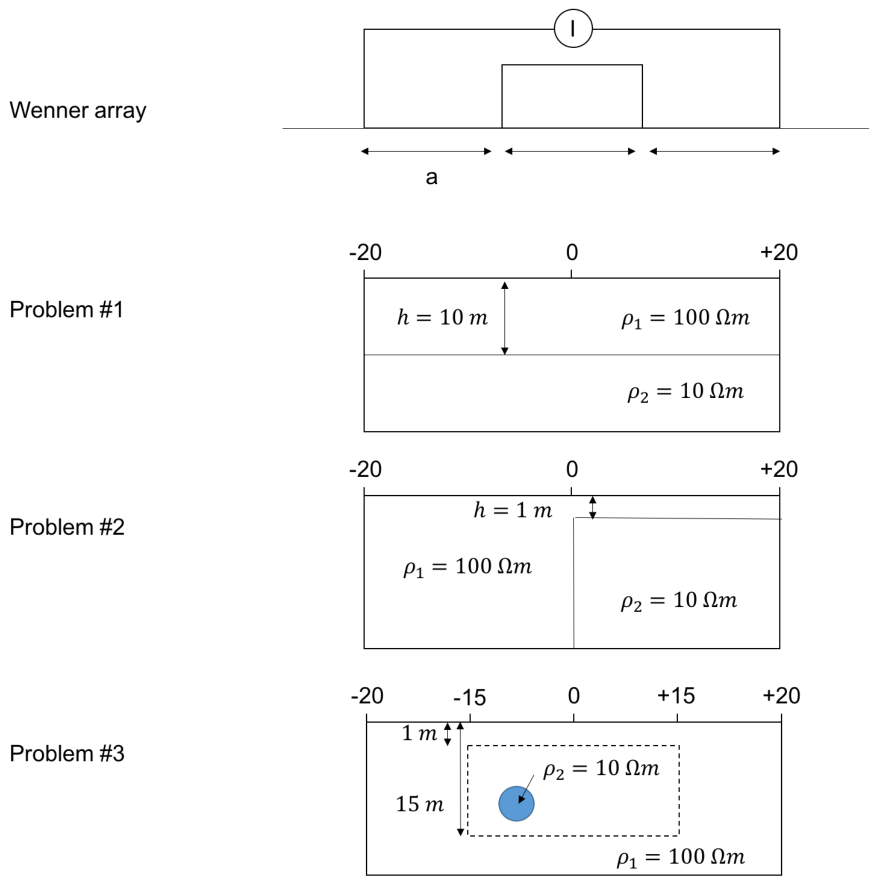


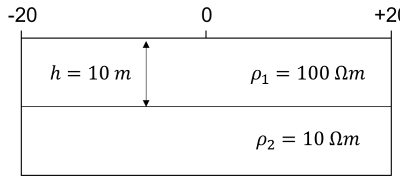
Figure 1: Wenner array and three different resistivity models.

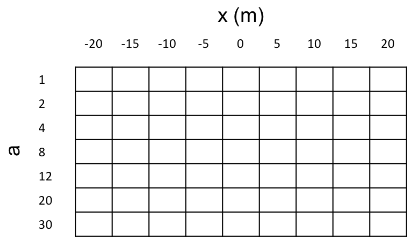
For each of the three scenarios:

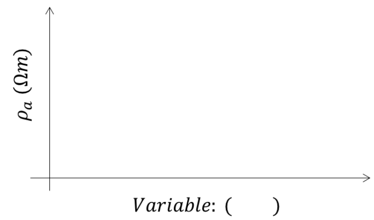
- Delineate a cost effective DC survey (sounding, profiling, or profile-sounding) that efficiently answers your problem.
- Fill in the table (x: column, a: row), that outlines the spacing (a) and center location (x) of your Wenner array (that is, fill the appropriate boxes with an "X"). Explain how your parameters are chosen.
- Sketch the data (apparent resistivities) that you would expect to see if you carried out the survey. Make sure to label all axes.

(a) (2 pt) For a Wenner array, what is an approximate relationship between "a" and the depth of penetration?

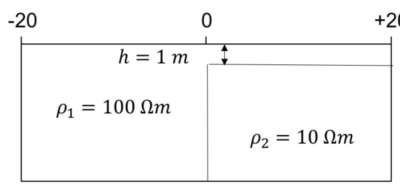
(b) (3 pt) The goal is to find the depth to the top surface of a water table, which is expected to be about 10 meters deep.

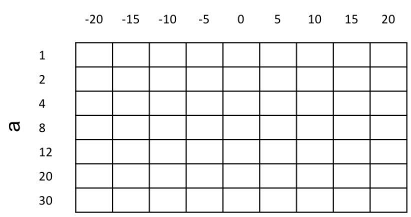


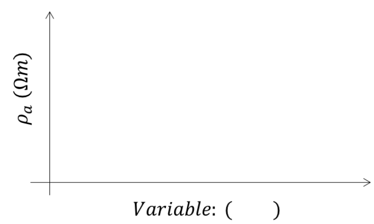




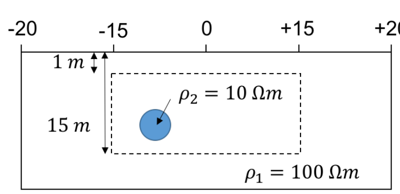
(c) (3 pt) Your goal is to locate a vertical contact that separates two rock units. The ground is covered by an overburden that is about a meter thick. You know that the contact is striking north-south but its location in the x-direction is undetermined.

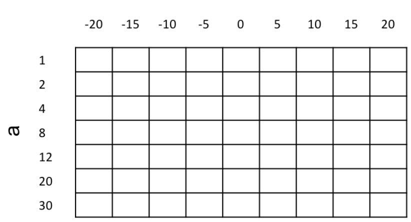


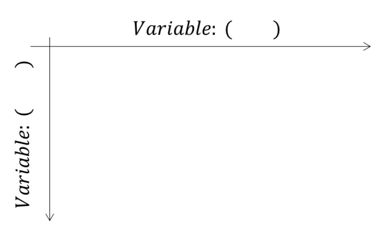




(d) (4 pt) Your goal is to find a buried pipe that is a meter in diameter and at unknown depth, somewhere between 1-10 meters. The pipe is striking north-south; its location in the x-direction is also unknown but is $-15m < x < 15m$







IP (5pts)

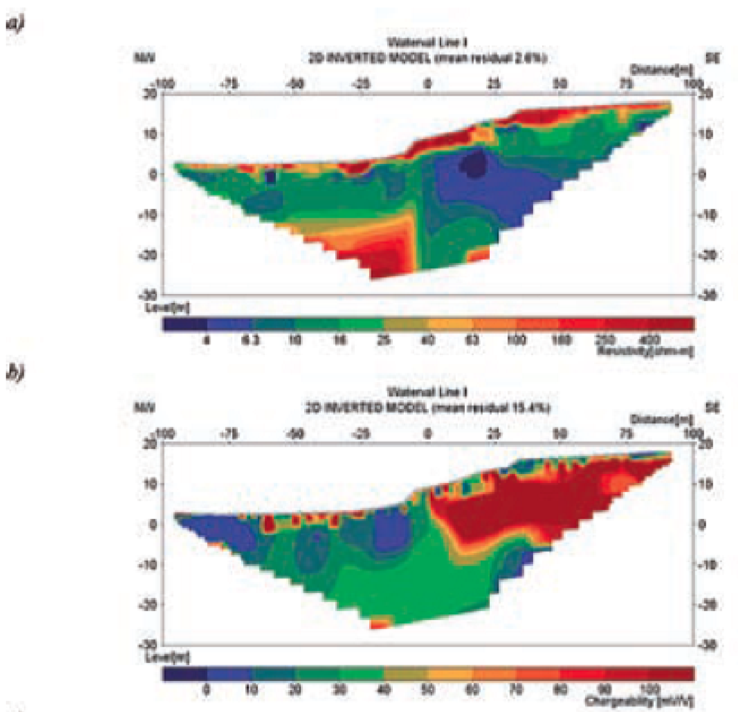
51. The resistivity (top) and chargeability (bottom) models shown were recovered by inverting DC and IP data collected over a waste deposit in South Africa. Note that on the top plot, red is more resistive, and on the bottom plot, red indicates a more chargeable material. Several known geologic units are likely to be present. The granitic basement is overlain by sediments and cut by a fault. The surface layer is composed of gravels. Using this background information and what you've learn in the case study, answer the following questions.

    (a) (2 pts) In the table below, rate the various units as high or low conductivity an high or low chargeability.

Material	Resistivity	Chargeability
Surface rocks/gravels (well drained)		
Granitic basement		
Waste		
Leachate		

    (b) (2 pts) Why might the (i) waste and (ii) leachate take on the physical properties indicated in your table?

    (c) (1 pt) On the figure below, indicate regions of waste material and locations of leachate.



Synthesis (6 pts)

52. In 2014, the dam wall of the tailings pond at Mt. Polley Mine failed, sending 10 million cubic metres of water and 4.5 million cubic metres of slurry into Polley Lake. An independent panel was assembled to investigate the breach.

    ”The Panel concluded that the dominant contribution to the failure resides in the design. The design did not take into account the complexity of the sub-glacial and pre-glacial geological environment associated with the perimeter embankment foundation. As a result, foundation investigations and associated site characterization failed to identify a continuous GLU [Glaciolacustrian] layer in the vicinity of the breach and to recognize that it was susceptible to undrained failure when subject to the stresses associated with the embankment” – Panel Report, 2015

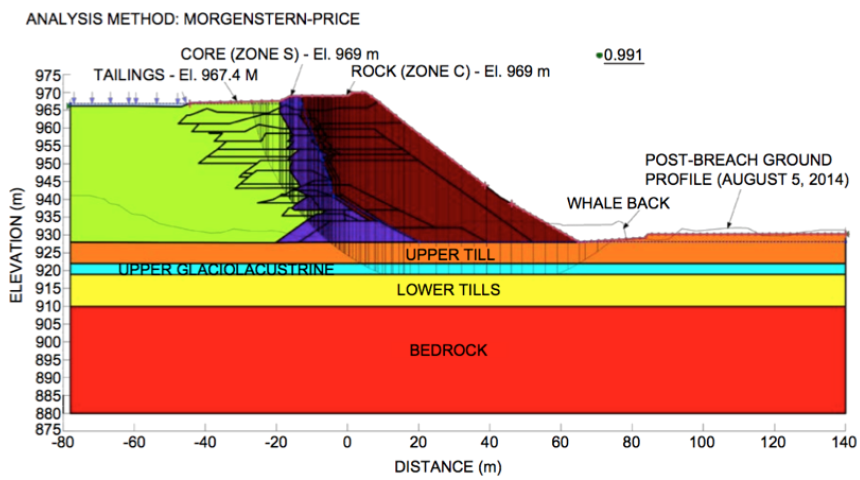


Figure 2: Cross section through the section of the Mt. Polley Dam that failed.

Prior to construction of the dam, boreholes were drilled, but the complexity of the GLU was discontinuous and drilling did not adequately characterize the hazard it posed.

Suppose you were tasked with characterizing the depth and thickness of the GLU prior to the construction of the dam.

(a) Suppose that the resistivity of GLU is much lower than the resistivity of the tills. (That is, GLU is a conductive layer) Which survey would you choose? What important factors about the site might influence the choice of this survey?

(b) Suppose that the resistivity of GLU is much greater than to the resistivity of the tills. (That is, GLU is a resistive layer). Which survey would you employ? What important factors about the site might influence the choice of this survey?

(c) Suppose that the GLU has a higher seismic velocity than the tills. Which survey would you use? What important factors about the site might influence the choice of this survey?

(d) Suppose that the GLU has a lower seismic velocity than the tills. Which survey would you choose? What important factors about the site might influence the choice of this survey?

Bonus (1 point)

53. (1pt) What is the name of the cookies handed out on the last day of class?
    (a) Peanut butter and chip
    (b) Monster
    (c) Chocolate delight
    (d) Oatmeal chocolate chip

It was pleasure to have you attend 350.

Good luck with your careers.

Formula Sheet

Constants

$$\mu_0 = 4\pi \times 10^{-7} \text{ H/m} \qquad \varepsilon_0 = 8.85 \times 10^{-12} F/m \qquad c = 3 \times 10^8 \text{ m/s}$$

Magnetics

magnetization	$\mathbf{M} = \kappa \mathbf{H}$
magnetic permeability	$\mathbf{B} = \mu \mathbf{H} = \mu_0 (1 + \kappa) \mathbf{H}$
dipole moment	$\mathbf{m} = \mathbf{M} \times Vol.$
depth half-width relationship	monopole: $z \sim \frac{1}{2} x_{1/2}$, dipole: $z \sim x_{1/2}$
magnetic charge density	$\tau = \vec{M} \cdot \hat{n}$
magnetic field from a dipole	$\mathbf{B} = \frac{\mu_0 \mathbf{m}}{4\pi r^3} [2cos(\theta)\hat{\mathbf{r}} + sin(\theta)\hat{\boldsymbol{\theta}}]$

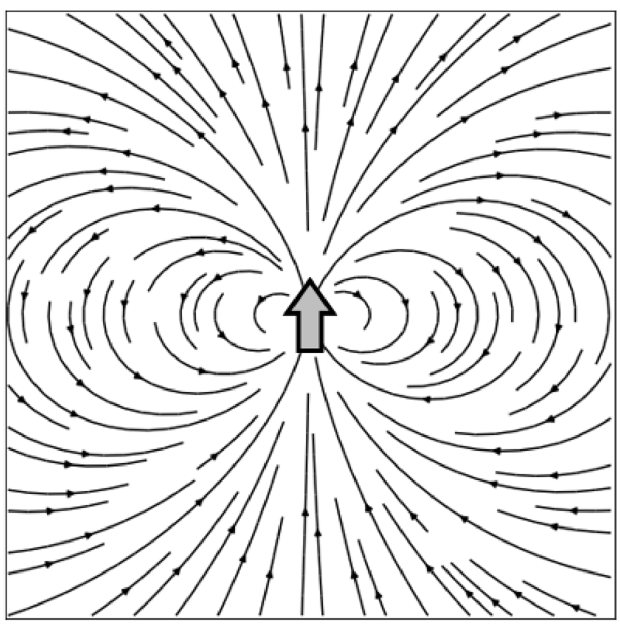


Figure 1: Magnetic field due to vertical magnetic dipole

Seismic

velocities $v_p = \sqrt{\frac{K + 4/3\mu}{\rho}}$ $\quad v_s = \sqrt{\frac{\mu}{\rho}}$

general $Z = \rho v \quad R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad T = \frac{2Z_1}{Z_2 + Z_1}$

general $d = vt \quad \lambda = vT = \frac{v}{f}$

Vertical resolution $L = \frac{\lambda}{4}$

Refraction arrivals $t = \frac{x}{v_2} + 2z\frac{\sqrt{v_2^2 - v_1^2}}{v_1 v_2} = \frac{x}{v_2} + t_i$

Cross-over distance $x_{cross} = \left(\frac{v_1 v_2}{v_2 - v_1}\right) t_i = 2z\sqrt{\frac{v_2 + v_1}{v_2 - v_1}}$

Refraction Angles $\frac{\sin\theta_1}{v_1} = \frac{\sin\theta_2}{v_2}$

Refraction Angles (for three layers) $\frac{\sin\theta_1}{v_1} = \frac{\sin\theta_2}{v_2} = \frac{\sin\theta_3}{v_3}$

Reflection hyperbola $t(x)^2 = t_0^2 + \frac{x^2}{v^2}$ x=distance from Tx to Rx

GPR

Reflection coefficient: $R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}$

Transmission coefficient: $T = \frac{2\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}$

Pulse length (Δt) and central frequency (f_c) of wavelet: $\Delta t = \frac{1}{f_c}$

GPR signal velocity: $v \approx \frac{c}{\sqrt{\varepsilon_r}}$

GPR wavelength: $\lambda = \frac{V}{f_c}$

Vertical resolution limit: $L > \frac{\lambda}{4} = \frac{V}{4f_c}$

Horizontal resolution limit: $L > \sqrt{\frac{Vd}{2f_c}}$

Refraction Angles $\frac{\sin\theta_1}{v_1} = \frac{\sin\theta_2}{v_2}$

Skin depth (quasi-static) $\delta = 503\sqrt{\frac{1}{\sigma f}}$

Skin depth (wave regime) $\delta = \frac{0.0053\sqrt{\varepsilon_r}}{\sigma}$

Velocity of light $c = 0.3 m/ns$ or $3 \times 10^8 m/s$

DC

Resistance & resistivity $R = \frac{\rho L}{A}$

Electric Potential for a homogeneous earth:

Single Electrode $V = \frac{\rho_0 I}{2\pi r}$

Four Electrode Array $\Delta V = \frac{\rho_0 I}{2\pi}\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}} - \frac{1}{r_{AN}} + \frac{1}{r_{BN}}\right)$

Apparent Resistivity:

Single Electrode $V = \frac{\rho_a I}{2\pi r}$

Four Electrode Array $\rho_a = \frac{2\pi\Delta V}{I}\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}} - \frac{1}{r_{AN}} + \frac{1}{r_{BN}}\right)^{-1}$

Wenner Array $\rho_a = \frac{2\pi a\Delta V}{I}$

IP

Intrinsic Chargeability $\eta = \frac{V_s}{V_0}$

IP datum (sample a chanel) $d^{IP} = \frac{V_s(t)}{V_0}$

EM

skin depth	$\delta = 500\sqrt{\frac{\rho}{f}}$
angular frequency	$\omega = 2\pi f$
apparent conductivity for EM31 ($s \ll \delta$)	$\sigma_a = \frac{4}{\omega\mu_0 s^2} Im\left(\frac{H_s}{H_p}\right)$
expansion of $H_s\cos(\omega t - \psi)$	$H_s\cos(\omega t - \psi) = H_s[\cos(\omega t)\cos(\psi) + \sin(\omega t)\sin(\psi)]$
phase lag	$\psi = \frac{\pi}{2} + tan^{-1}\left(\frac{\omega L}{R}\right)$
induction number	$\alpha = \frac{\omega L}{R}$

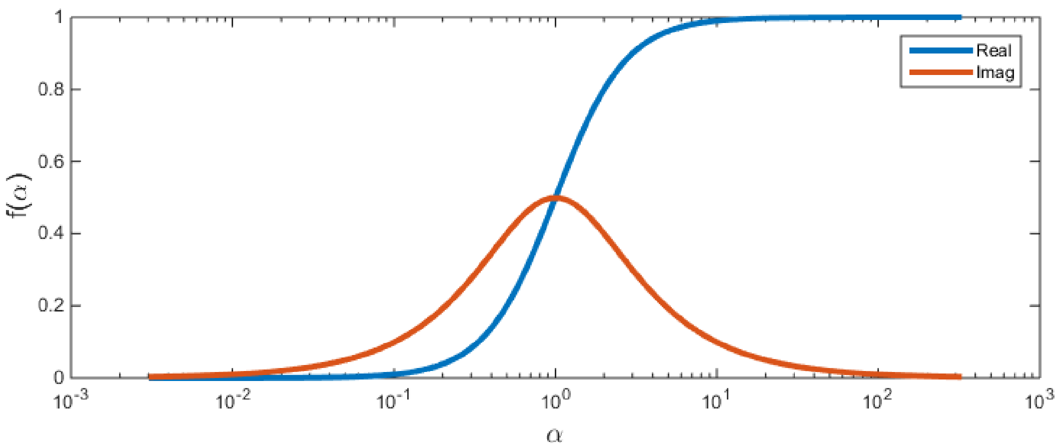


Figure 2: Frequency EM: Response function curve