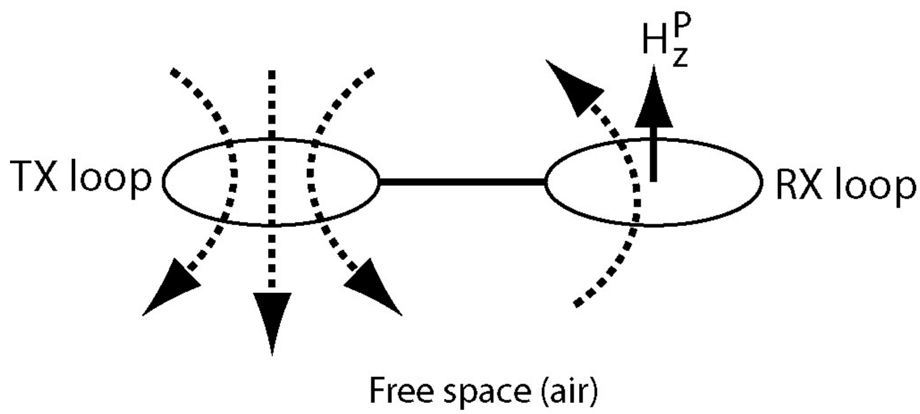
D2 : Ground based loop-loop EM systems

D2.1 Primary magnetic fields

- The transmitter (TX) is a loop of horizontal wire carrying an electric current (I) that oscillates sinusoidally at an angular frequency ω
- Frequency of TX signal is f (Hertz) and $\omega = 2\pi f$
- $I = I_0 \sin(\omega t)$
- Consider the instant in time when I has the maximum value of I_0



- TX loop has area A and is located at the origin (z = 0)

- If the TX is located in a region where σ = 0, a dipolar magnetic field is generated.

- s is the radial distance from TX to RX

- When the TX and RX are at same level (z = 0) can show that $H_z^p = -\dfrac{I_0 A}{4\pi s^3}$

- Why is the sign of H_z^p negative?

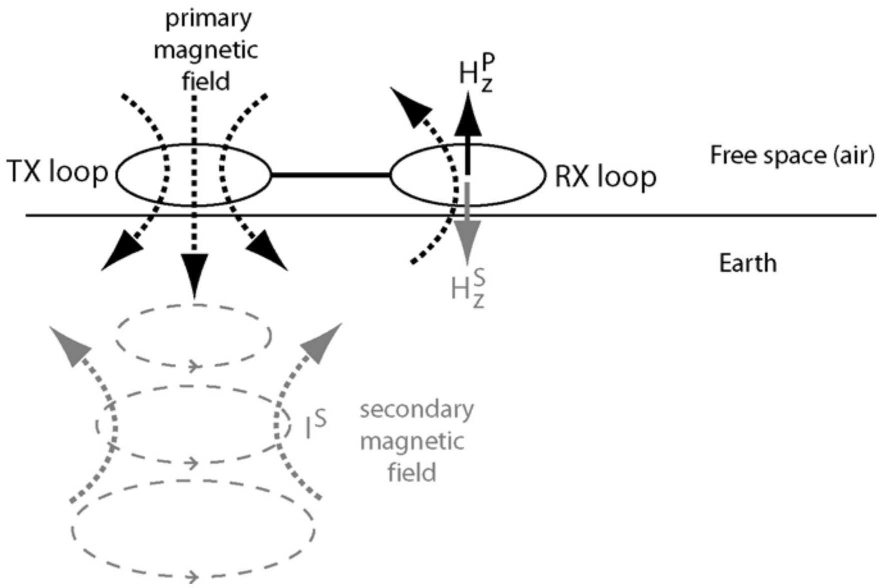
- Remember that the primary magnetic field **oscillates** at frequency ω. The time variation of vertical magnetic field induces a voltage in the RX loop.

- The primary magnetic field is measured by the **voltage induced** in the RX

- Note that the physics of EM induction means that the RX will measure the (time variation) magnetic field that is **normal** to the loop.

- The **primary field** is the only magnetic field detected in the absence of a subsurface conductor.

D2.2 Measurement of apparent resistivity of a halfspace



- Now consider what happens when the TX is placed next to the Earth where $\sigma \neq 0$
- The primary magnetic field produced by the TX extends into the Earth
- As the primary field oscillates, **secondary electric currents** (I^S) are **induced** in the Earth. The secondary currents flow at right angles to the direction of the primary magnetic field.
- Secondary electric currents will dissipate energy as heat through Ohmic losses.
- This loss of energy causes the amplitude of the EM signals to decrease in the Earth. This attenuation occurs with a length scale equal to a **skin depth** (see equation in D1)
- Lenz's Law tells us that the secondary current will flow in the **opposite** sense to the primary current in the transmitter loop.
- As the primary magnetic field oscillates, so does the secondary electric current flowing in the Earth.
- The **secondary currents** will generate a **secondary magnetic field** that is detected at the RX.
- The **total magnetic field** (sum of primary and secondary) at the RX is given by

$$H_z = \frac{IA}{2\pi k^2 s^5}\{9-(9+9iks-4k^2s^2-ik^3s^3)e^{-iks}\}$$

where s is the TX-RX distance and $k = \sqrt{i\omega\mu\sigma}$

Dividing by the primary magnetic field gives:

$$\frac{H_z}{H_z^P} = \frac{2}{k^2 s^2}\{9 - (9 + 9iks - 4k^2 s^2 - ik^3 s^3)e^{-iks}\}$$

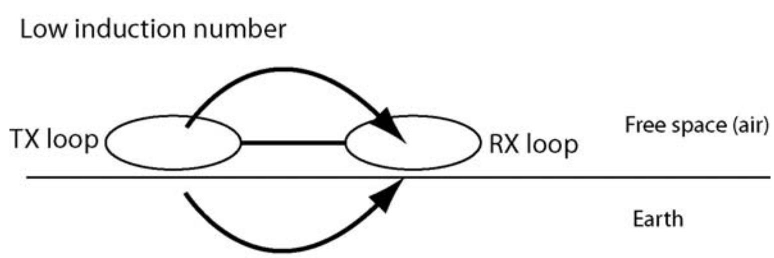
for vertical magnetic dipoles

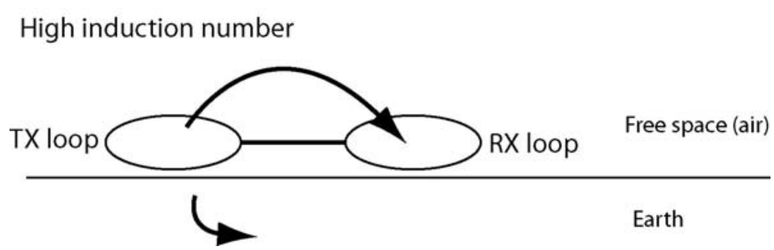
- These expressions for $\left(\frac{H_z}{H_z^P}\right)$ become **much simpler** when ks is either **very large** or very small.

- The **induction number** is defined as $B = \frac{s}{\delta}$

- A **low induction number** corresponds to measuring the magnetic field **very close** to the TX (much less than a skin depth). In this case the EM signals travel from TX to receiver through **both the air and the Earth**.

- A **high induction number** corresponds to measuring the magnetic field a **long way** from the TX (many skin depths). In this case the EM signals travel from TX to RX **through only the air**. Signals that enter the Earth are completely attenuated before they reach the RX.





- The EM instruments discussed in this class use near field measurements (low induction number). When ks << 1 it can be shown that

$$\frac{H_z}{H_z^p} = \frac{2}{k^2 s^2}\left(\frac{k^2 s^2}{2} - \frac{k^4 s^4}{8}\right) = 1 - \frac{k^2 s^2}{4}$$

- This can be rearranged as

$$\frac{H_z}{H_z^p} = 1 - \frac{k^2 s^2}{4} = 1 - \frac{i\omega\mu\sigma s^2}{4}$$

- Setting the imaginary parts of this equation to be equal gives

$$\mathrm{Im}(\frac{H_z}{H_z^p}) = \frac{\omega\mu\sigma s^2}{4}$$

- Re-arranging, gives an expression for the **average conductivity** of the ground

$$\sigma = \frac{4}{\omega\mu s^2}\mathrm{Im}(\frac{H_z}{H_z^p})$$

- All the quantities on the right side of this equation can be measured.

- H_z^p is the primary magnetic field. This is typically measured when the instrument is calibrated at the start of a survey.

- H_z is the total magnetic field measured at a survey point.

D2.3 Instrumentation

- A range of instruments are available commercially to make these measurements.
- One of the leading manufacturers is Geonics Ltd (www.geonics.com)

Geonics EM38

- Instrument has s = 1 m and is widely used in agricultural studies.
- Frequency = 14.6 KHz
- http://www.geonics.com/html/em38.html

Geonics EM31

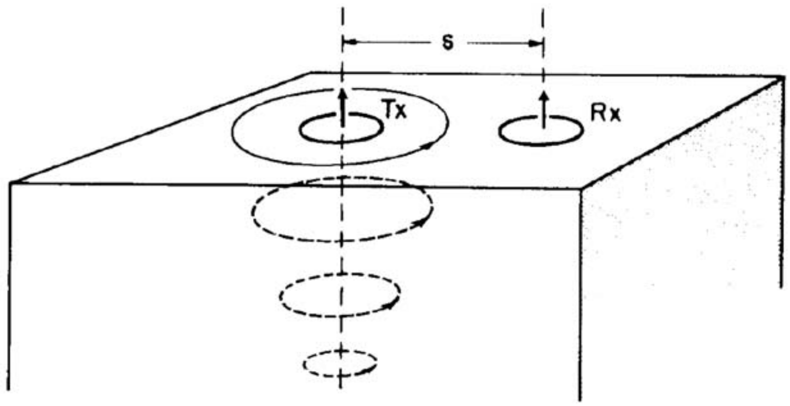
- Instrument has s = 3.6 m and is used in environmental studies.
- TX and RX dipoles are mounted on a rigid boom
- Frequency = 9.8 KHz
- Measurements with dipoles vertical and horizontal can give information about variation of conductivity with depth.
- Additional information about the variation of conductivity with depth can be obtained by measuring with the EM31 at different distances above the surface (z = 0 m, z = 1 m, z = 2 m)
- http://www.geonics.com/html/em31-mk2.html

Geonics EM34

- Used in hydrogeology and environmental studies for deeper penetration.
- Instrument has TX and RX loops connected by a cable.
- The spacing can be set at s = 10 m, 20 m or 40 m
- Frequency is 6.4, 1.6 and 0.4 kHz with s = 10, 20 and 40 m respectively.
- Need to orient the TX and RX prior to each measurement.
- Used in both environmental studies and mineral exploration.
- http://www.geonics.com/html/em34-3.html

D2.4 Depth of investigation

- Just as with DC resistivity measurements with a Wenner array, it is important to understand the depth to which the measurement of subsurface conductivity extends.



- The secondary current flow induced in the Earth is a set of horizontal loops, as shown above. This pattern can be derived from Faradays and Lenz's Laws (McNeill, 1980)

- At low induction number the secondary current flows in a set of **horizontal loops**.

- These current loops can generate additional secondary currents in adjacent loops. However, at low induction number this doesn't happen, which simplifies the physics (McNeill, 1980).

- The secondary current is induced from the surface to a depth equal to a skin depth. However at low induction number depth of investigation is limited by geometric factors, not the skin depth.

- The functions Φ_V and Φ_H shows how conductivity at different depths contributes to the average conductivity measured by the instrument. These functions are called the **relative response**.

$$\Phi_v(z) = \frac{4z}{(4z^2+1)^{3/2}};$$

- Note that z is depth in Earth **normalized** by the TX-RX distance. $z = \frac{d}{s}$

- The vertical coil configuration (V) has **zero sensitivity** at z = 0, and **maximum sensitivity** at z = 0.4

- Horizontal coil configuration (H) has a relative response Φ_H that has a maximum value at z = 0 and then decreases monotonically with increasing z

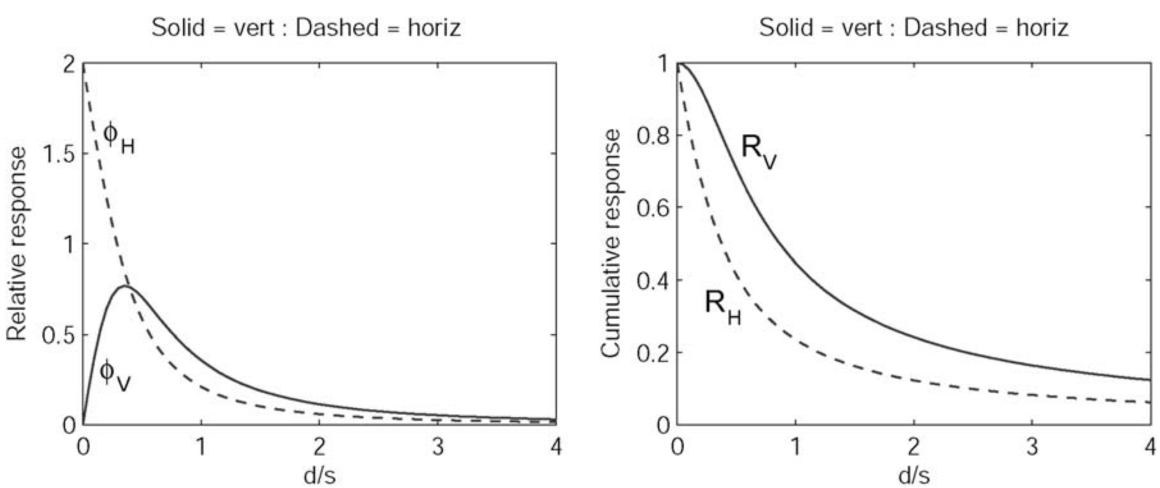
$$\Phi_H(z) = 2 - \frac{4z}{(4z^2+1)^{3/2}}$$

- **Question** : Can you use a sketch of the magnetic fields to explain the differences between $\Phi_H(z)$ and $\Phi_V(z)$?

- Can integrate these functions to get the **cumulative response**, which is defined for the two coil configurations as:

$$R_V(z) = \int_z^\infty \phi_v(z)dz \; ; \qquad R_H(z) = \int_z^\infty \phi_H(z)dz$$

$$R_V(z) = \frac{1}{(4z^2+1)^{1/2}} \; ; \qquad R_H(z) = (4z^2+1)^{1/2} - 2z$$



- The cumulative response functions are the sum of the contributions from all layers **below** a depth *z*

- The vertical coil configuration gives the greatest depth of penetration.

- Horizontal coil configuration is most sensitive to shallow structure

- Horizontal coil configuration is less sensitive to misalignment of the TX and RX coils.

- Note that in the EM31 the TX and RX are rigidly fixed to a boom. However in the EM34 they are only connected with a cable and must be oriented for each measurement.

- In summary Exploration depth for horizontal coils ~ 0.75s
  Exploration depth for vertical coils ~ 1.5s

	Horizontal dipoles	Vertical dipoles
EM38 (s=1 m)	0.75 m	1.5 m
EM31 (s=4 m)	3 m	6 m
EM34 (s=10 m)	7.5 m	15 m
EM34 (s=20 m)	15 m	30 m

- These depths are taken from Geonics TN6 by McNeill (1980) and represent the depth at which the peak response occurs.

- The instrument is sensitive to greater depths (as deep as 6m for the EM31 vertical dipole)

Calculation

- Consider the depth extent of an EM31 survey in a region where the subsurface resistivity is 100 Ωm. The TX frequency is 9000 Hz.

- Show that the numbers above confirm that the TX-RX spacing limits the depth of investigation, rather than skin depth.

D2.5 Measurement of apparent conductivity of a layered Earth

- To calculate the conductivity that would be measured over a layered Earth, need to average the contributions from each layer.

- At low induction number McNeil (1980) showed that for a two layer model with conductivity σ_1 and σ_2 where the upper layer has a thickness *d*, the average conductivity measured by vertical dipoles is

$$\bar{\sigma}_v = \sigma_1(1 - R_v(z)) + \sigma_2 R_v(z)$$

- Note that $z = d/s$ where s is the TX-RX distance. With the dipoles horizontal

$$\bar{\sigma}_h = \sigma_1(1 - R_h(z)) + \sigma_2 R_h(z)$$

D2.5.1 Depth sounding with a loop-loop EM system

- These equations are evaluated in the figure below. Increasing the value of *s* corresponds to deeper exploration. In principle could use a system to measure depth variation of conductivity in a similar way to the Wenner array

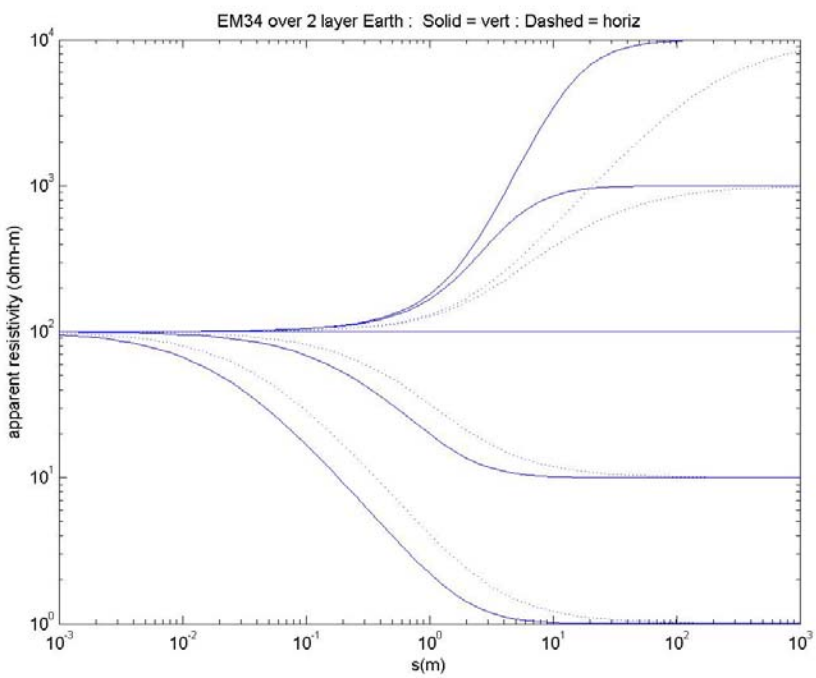
- However, a wide range of *s* values is difficult to implement because this requires a wide dynamic range for the RX. This method is not used at present (although possible with an instrument such as Geonics EM34)

- Often the depth character of the near surface is modelled by loop-loop EM systems using measurements from two different instruments, each with a different spacing s.

- Equations derived above are not valid at high values of conductivity (e.g. seawater). This is because the low induction number assumption is not valid.

- Figure below shows a 2 layer Earth with the TX and RX placed on the surface at z = 0. The upper layer has ρ_1 = 100 Ωm and is 1 m thick. The lower layer has resistivity values ρ_2 = [10000, 1000, 100, 10, 1 Ωm]

- Conductivity is the reciprocal of resistivity ($\sigma = \frac{1}{\rho}$)

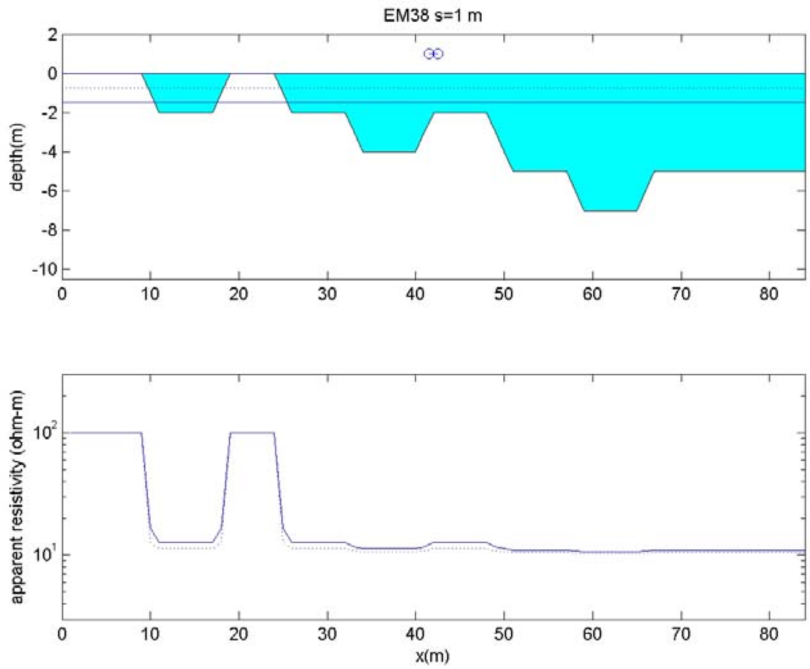


- Generated with MATLAB script : **em_sounding_2_layer.m**

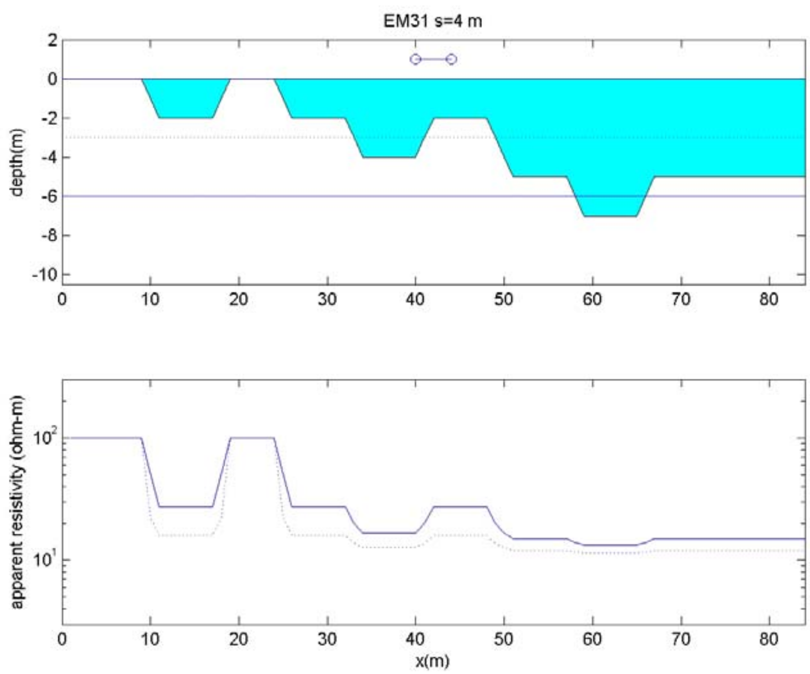
- Solid lines are for vertical dipoles and dashed lines are for horizontal dipoles

D2.5.2 Profiling with a loop-loop EM system

- Horizontal lines show the exploration depth for s = 1 m (Geonics EM38) and s = 4 m (Geonics EM31) with horizontal (dashed) and vertical (solid) coil orientation.
- Blue layer, ρ = 10 Ωm ; White layer ρ = 100 Ωm



- With small s value, this survey has a very limited depth of exploration.
- Can only measure the resistivity at the surface.



- Deeper exploration of the same model is possible with s = 4 m using an EM31

- Everywhere on the profile can see that resistivity increases with depth.
- To see this, compare the vertical and horizontal measurements.
- MATLAB script : **em_profiling_2_layer.m**

Sample calculation 1

- An EM31 survey takes place where a surface layer of glacial till is 4 m thick.
- The resistivity of the till is 25 Ωm
- The crystalline bedrock has a resistivity 400 Ωm
- The EM31 is placed on the ground at z = 0 with dipoles oriented vertically.
- What resistivity value will the EM31 read?

Sample calculation 2

- An EM34 survey is being used to map the depth of the water table in a sand layer.
- The TX and RX are placed on the surface of the Earth at z =0.
- Dry sand has a resistivity of 800 Ωm and the wet sand has a resistivity of 100 Ωm.
- The EM34 gives a reading of 350 Ωm when s = 20 m
- What is the depth of the water table?

Multiple layer models

- This approach is simple to extend to multiple layers.
- Conductivity values $\sigma = [\sigma_1, \sigma_2, \sigma_3]$ with interfaces at depths $d = [d_1, d_2]$
- These depths are normalized to give $z_1 = \frac{d_1}{s}$; $z_2 = \frac{d_2}{s}$; $z_3 = \frac{d_3}{s}$

- Can show that:

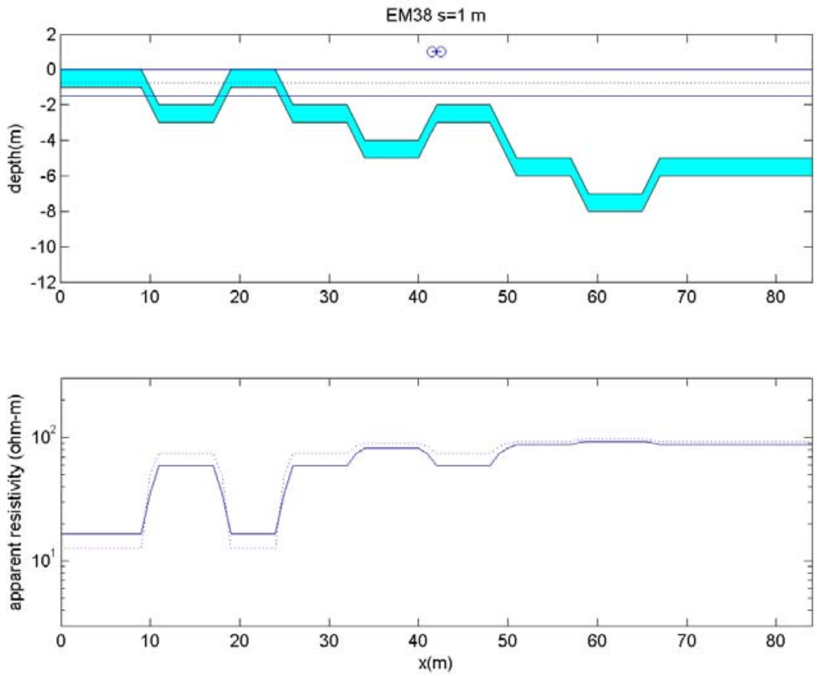
$$\bar{\sigma}_v = \sigma_1(1 - R_v(z_1)) + \sigma_2(R_v(z_1) - R_v(z_2)) + \sigma_3 R_v(z_2)$$

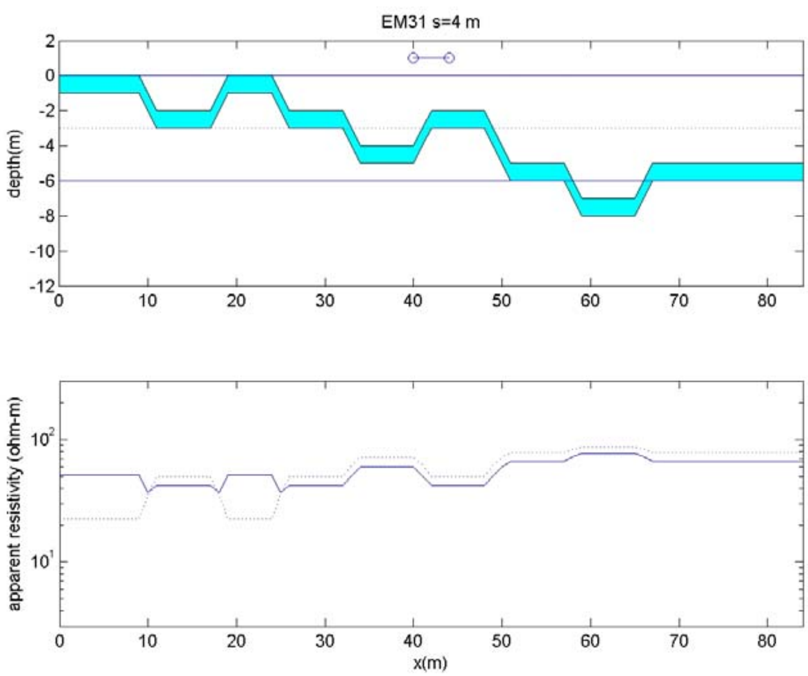
$$\bar{\sigma}_h = \sigma_1(1 - R_h(z_1)) + \sigma_2(R_h(z_1) - R_h(z_2)) + \sigma_3 R_h(z_2)$$

- In the following example the model consists of blue layer (ρ = 10 Ωm) in white halfspace (ρ = 100 Ωm)

- This survey has limited depth of exploration, as expected for s = 1 m

- This EM38 survey detects an increase in apparent resistivity with depth in some areas and a decrease in others. To see this compare the horizontal and vertical dipole measurements. Remember that vertical dipoles sample deeper in the Earth than horizontal dipoles.


EM38 s=1 m
depth(m)
apparent resistivity (ohm-m)
x(m)


EM31 s=4 m
depth(m)
apparent resistivity (ohm-m)
x(m)

D2.6 : Applications of loop-loop EM surveys

D2.6.1 Mineral exploration

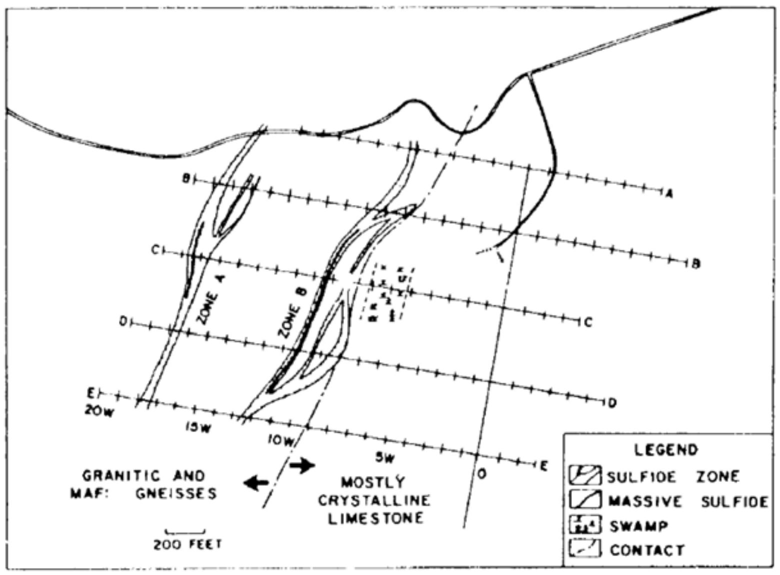


FIGURE 17. Geologic map of the Cavendish test site and the grid of traverse lines used in geophysical studies (after Ward et al [3]).

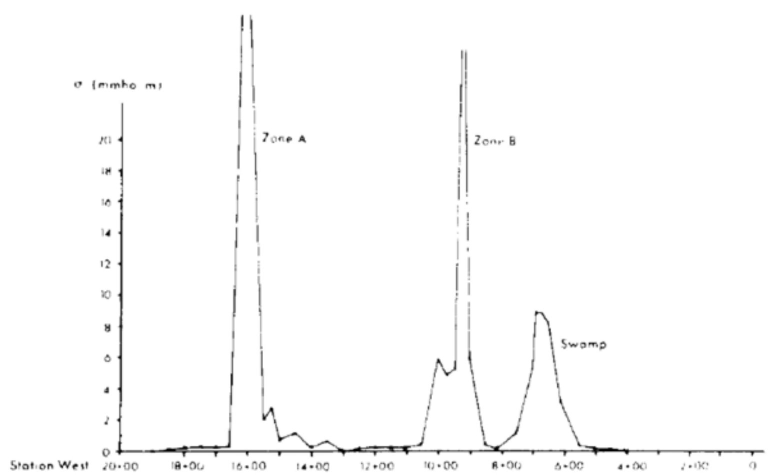


FIGURE 18. EM31 survey of Cavendish test range Line 'C'.

- Figures above show a test of the EM31 at the Cavendish test site (McNeill, 1980). The bedrock is high resistivity gneiss and limestone. Two zones of sulphide mineralization are crossed on Line 'C' and show a high conductivity.

- Note that a swamp also shows up as a zone of low resistivity (high conductivity)

- The mho is a unit of conductivity and is "ohm" spelt backwards.

- 20 milli-mhos = 0.02 S/m = 50 Ωm

D2.6.2 Environmental geophysics

- EM instruments are commonly used to pinpoint areas of interest, which are than explored further using DC resistivity and/or ground truth (drilling or digging).

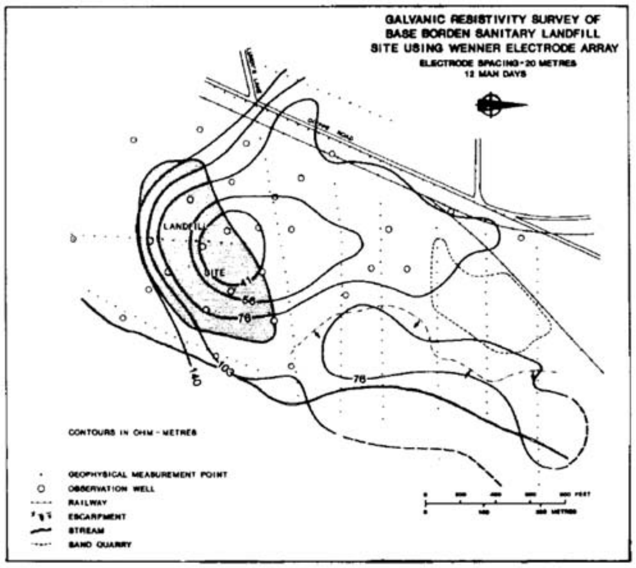


FIGURE 20(a).

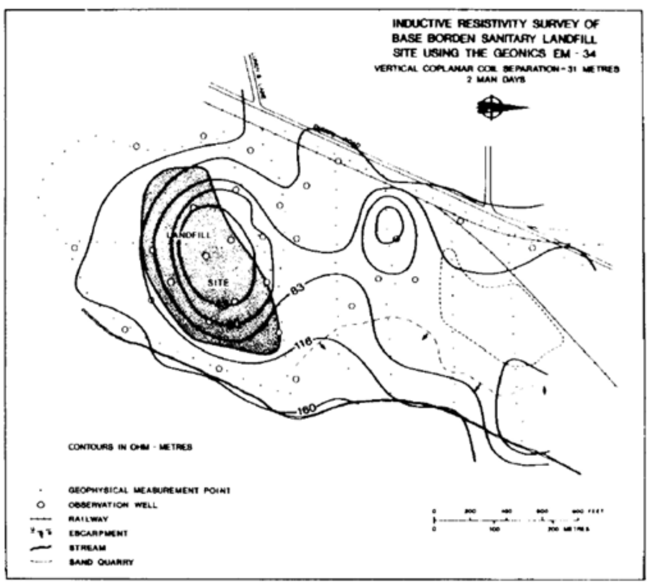


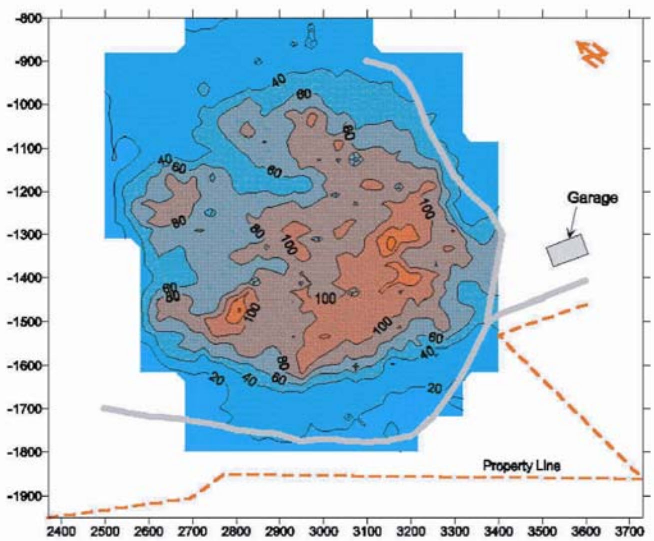
FIGURE 20(d).

- Comparison of EM34 and DC resistivity Wenner array for mapping a contaminant plume.

- The EM34 survey took 2 days, in contrast to 12 days for the Wenner survey.

- In addition, the EM34 does not require direct contact with the ground through the electrodes, since it couples inductively.

- These maps are made by measured ground conductivity on a grid of points and contouring the results. Many instruments use a built-in GPS system, thereby removing the need to independently survey the grid points.



Electromagnetic terrain conductivity map (in mS/m) of Laurel Ridge Landfill, Lily, Kentucky (in feet). The higher conductivity values (>40 mS/m) represent areas of buried waste.

- Example of mapping the horizontal extent of a landfill with EM data

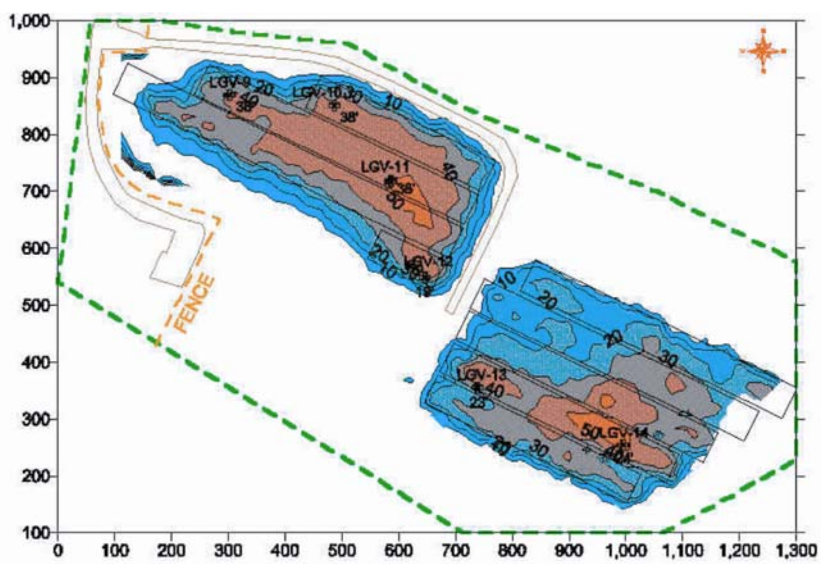


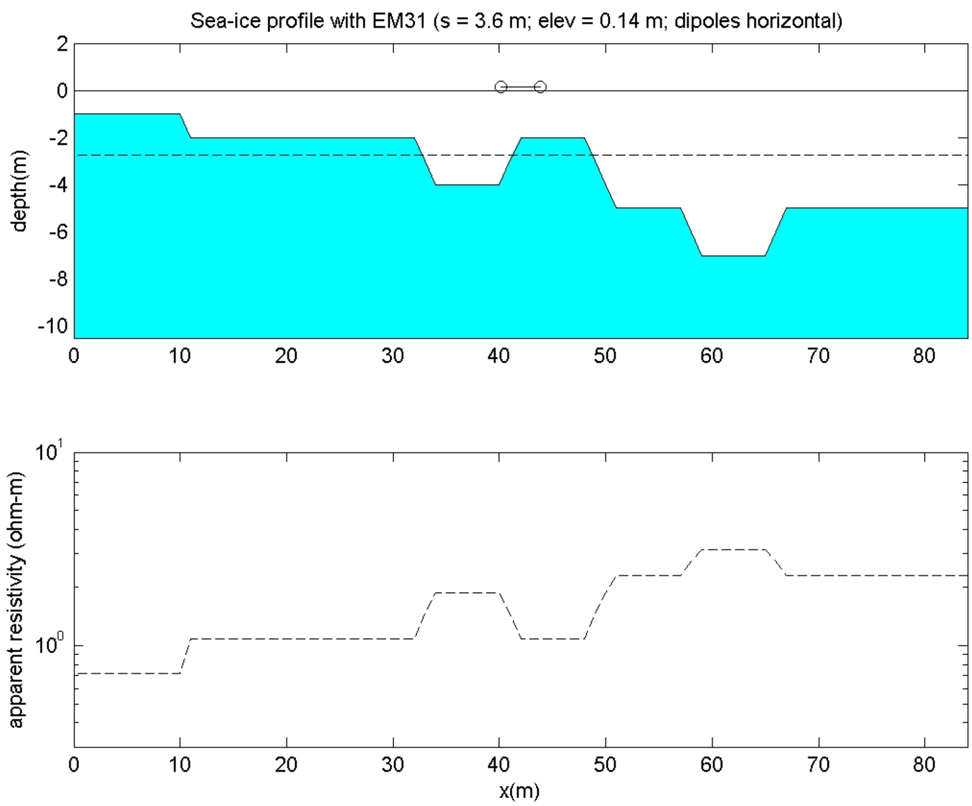
Figure 4 Waste thickness map (in feet) based on apparent terrain conductivity for Amelia County Landfill, Winterham, VA showing depth of waste (in feet) from gas extraction borings.

- Estimate of thickness of waste layer using EM instrument. Requires assumption of the layer conductivity

- Both above figures are from Hutchinson et al, (2000)
- In environmental surveys such as this one, the data is often explored further with boreholes and piezometers to find the cause of the high conductivites (high sulphide content, chlorides, metallic debris, etc)

D2.6.3 Sea-ice thickness

- Ice has a high resistivity and seawater has a very low resistivity.
- This allows EM31 measurements to be used to measure sea-ice thickness.



- Equations developed in D2.5 are not exact in this case because the high conductivity of the seawater means that the induction number is not low.

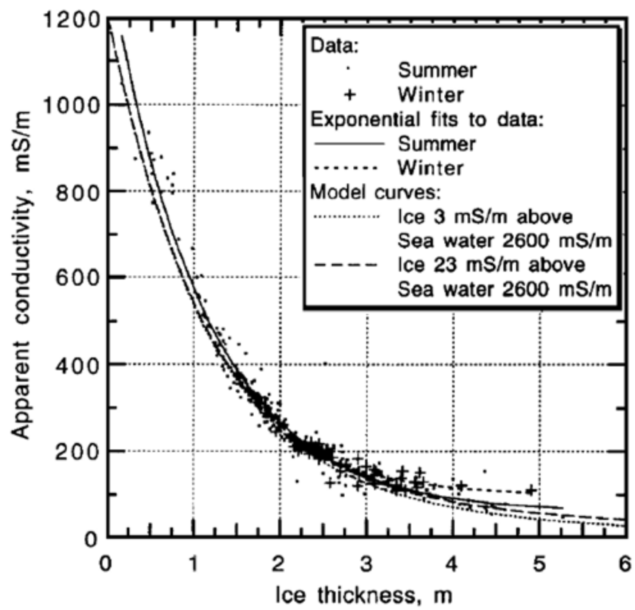
- Method described by Kovacs and Morey (1991) and Haas et al., (1997).

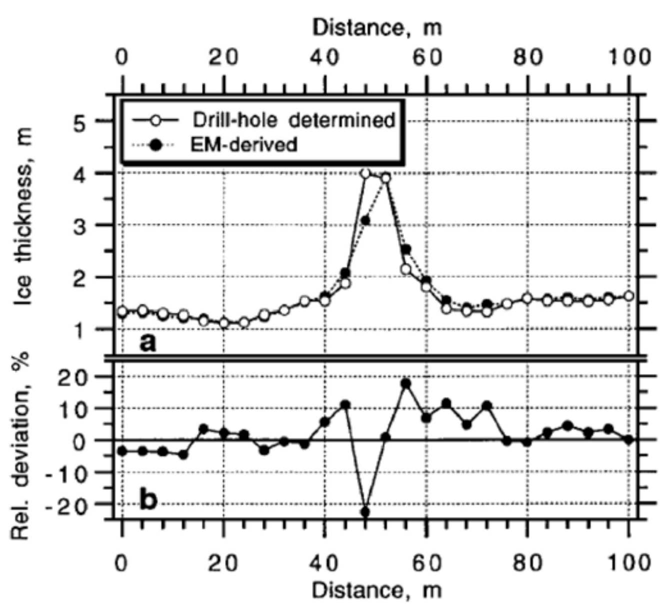
- Horizontal dipoles used to give maximum sensitivity to near surface structure.

- Figure 3 from Haas et al., (1997) is shown below and confirms the empirical relationship between the apparent conductivity measured by the EM31 and ice thickness.

- Ice resistivity changes from summer to winter but does not have a significant effect.

- Figure 4 from the same paper shows ground truth obtained by comparing geophysical estimate of ice thickness with direct measurement from coring.

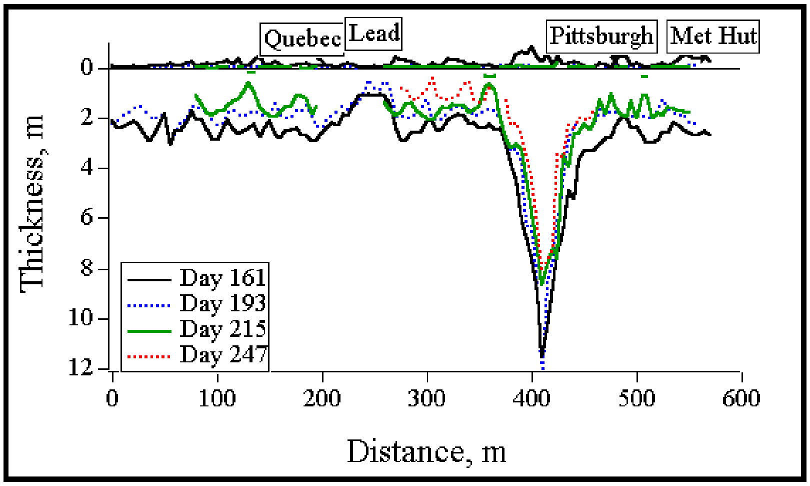




- See later that helicopter measurements can use a similar technique to measure sea ice thickness. Helicopter and ground level estimates give consistent results.

- The airborne measurements allow large areas to be surveyed. Monitoring sea ice extent and thickness has become an important method for monitoring climate change in the Arctic

- For more information see webpage of Dr. Christian Haas in EAS http://eosl.eas.ualberta.ca/2_people_haas.html



- Other studies have monitored changes in thickness over a field season

- http://www.crrel.usace.army.mil/sid/perovich/SHEBAice/em31thk.htm
- In this case the EM31 was mounted inside a kayak
- Accuracy of EM31 instrument is ~0.001 S/m, so if Sea ice is 3 m thick, this gives 0.015 m precision. If sea ice is 5 m thick, this gives 0.09 m

- This approach has also been used by deploying an EM31 from the bow of an icebreaker! See movie courtesy of Christian Haas.

D2.6.4 Agriculture

- Ground based surveys that generally need to be calibrated with some ground truth to work in each location.

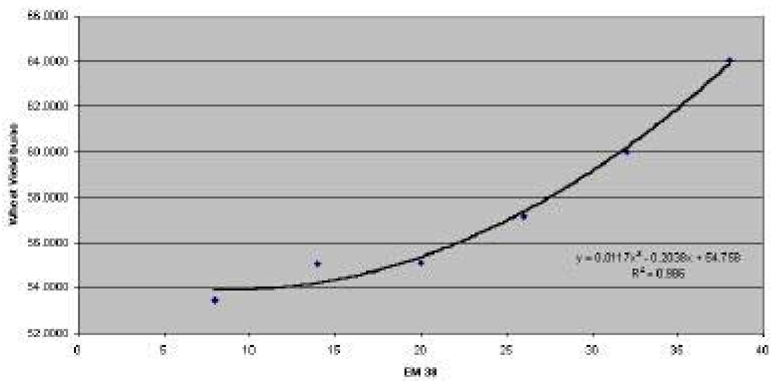
- Commonly used system is the Geonics EM38 Ground Conductivity Meter.

- For agriculture they work well since they are non-invasive and the instrument can be mounted on a tractor.

Applications include
- mapping salinity variations in a field
- mapping moisture variations in a field
- mapping depth of soil
- mapping depth of flood deposits
- Mapping sand content of soil

Study of EM38 conductivity and crop yield in Australia
Rampant, P., and M. Abuzar, (2004)
http://www.regional.org.au/au/asssi/supersoil2004/s5/oral/1513_rampantp.htm

Professional Agricultural Consulting Education and Research
http://pacer-corp.com/ElectCond.htm



- This plots shows the correlation between wheat yield and EM38 conductivity (a proxy for water content)

- Monitoring salinization at Stettler, Alberta, (McKenzie et al., 1997)

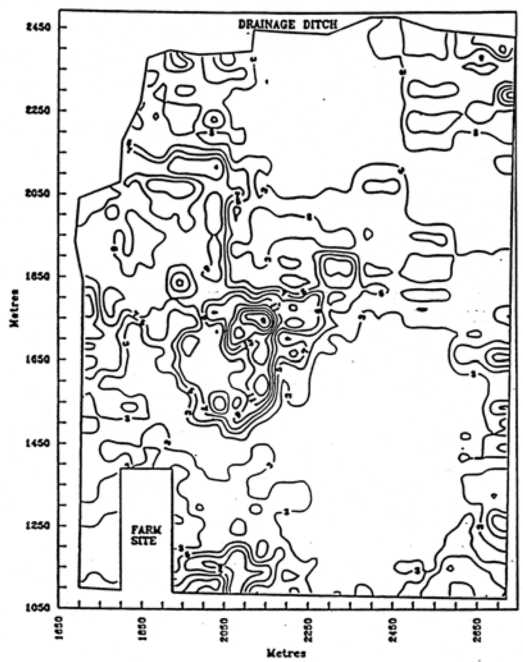


Figure 7. Soil conductivity (dS/m), Stettler, Alberta.

References

Haas, C., S. Gerland, H. Eicken, H. Miller, Comparison of sea-ice thickness measurements under summer and winter conditions in the Arctic using a small electromagnetic induction device, *Geophysics*, 62, 749-757, 1997.

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Kovacs, A., and Morey, R. M., 1991, Sounding sea-ice thickness using a portable electromagnetic induction instrument: *Geophysics*, **56**, 1992–1998.

McKenzie, R.C., R.J. George, S.A. Woods, M.E. Cannon, D.L. Bennett, Use of the Electromagnetic-Induction Meter (EM38) as a tool in managing salinisation, *Hydrogeology Journal*, 5 (1), 1997.

Palacky and West (1991), chapter 10 in "*Electromagnetic methods in Applied Geophysics – Volume 2 - Applications –Part B*", edited by Misac Nabighian, and published by the SEG.

Appendix : non essential material

- When the TX and RX dipoles have their axes horizontal, can show that

$$\frac{H_z}{H_z^P} = 2\{1 + \frac{3}{k^2 s^2} + [3 + 3iks - k^2 s^2]\frac{e^{-iks}}{k^2 s^2}\}$$