The EM-34 – Ground Conductivity Mapping with a Two-coil Inductor

A Thesis presented

by

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DECLARATION

I, Harry Ashenden, confirm that the work submitted in this dissertation is my own and that appropriate credit has been given where reference is made to the work of others.

Signature: HAshenden

Date: 04/05/2020

Abstract

The Geonics EM-34 is an inductive survey technique deployed for gaining measurements of ground conductivity. The survey has been designed to combat the disadvantages of conventional resistivity techniques, which has led to these techniques being widely not accepted for engineering purposes. Literature based on background knowledge and survey output information of the EM-34 is sparse, questioning the validity of the dual coil inductive field method. By examining the principles of the Electromagnetic Induction method, we examine how the output of ground conductivity is produced from the slingram-type instrument and the factors that affect ground conductivity based on the low induction number theory. Two case studies have been performed to analyse various concepts of an EM-34 survey, including the effect of varying the intercoil spacing on conductivity readings as well as exploring the effect of using a mixed coil orientation, which is not recommended for an EM-34 survey. Also, we uncover the parabolic shape of EM-34 conductivity profiles which include negative conductive values produced by underlying anomalous conductive bodies. We conclude that an EM-34 survey is proven to be a suitable complement to other methods of conductivity determination This is because measurements of terrain conductivity are given with a larger resolution than EM-31 and ERT surveys thanks to a station by station approach along traverses, yet we discover how sensitive an EM-34 survey is, with errors outlined on conductivity readings.

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Acknowledgements

Firstly, I would like to thank my dissertation supervisor Professor Richard Holme for his continued support in the classroom and the field throughout the completion of my dissertation and for making this project possible. Kind regards should also be given to all of the numerous individuals who provided fieldwork assistance with all EM-34 surveys. I would also like to thank RSK who provided me with support with regards to the background of the EM-34 and EM-34 survey operation. Finally, I would like to thank the many friends and my family who have supported me through my three years at the University of Liverpool.

Chapter 1

Introduction

Electrical resistivity techniques (ERT) field methods have been created and modified in the past to gain measurements of terrain conductivity to a significant level of resolution and accuracy. However, a large proportion of past techniques have several shortcomings that have prevented them from being accepted for an engineering purpose (McNeil, 1980). This is because a large workforce is required to conduct an electrical resistivity survey and the results of the survey lacks precision, as there was little certainty of how representative the results were of the geological environment surveyed, including the detection of lateral variations of resistivity with respect to depth. Furthermore, the errors in an ERT survey due to resistive inhomogeneities close to the electrodes are large, giving a low signal/noise ratio and overshadowing any deeper effects from resistive bodies, adding to the difficulty in calculating the true depth and geometry of underlying resistive bodies. The difficulty in acquiring accurate terrain conductivity values was recognized by Geonics Limited, which led to the development of the EM-34, which is an electromagnetic field method used to map terrain conductivity with a smaller amount of manpower. The survey technique is used for groundwater exploration purposes and is designed to survey up to an effective exploration depth of 60m.

1.1 Motivation

The inductive technique has been disregarded in comparison to other relevant resistive field methods as there has been a large uncertainty over the inductive principles and the instrumentation of the EM-34, including a lack of understanding of the conversion to terrain conductivity. An attempt has been made to give clarity of the principles of the inductive technique, including an analysis of the dual loop system with the low induction number theory. A breakdown of the instrumentation and the procedures of an EM-34 survey is given before an investigation into the EM-34 survey output in the form of 2 case studies. A discussion of the results of these case studies will clarify the conclusions that can be made of an EM-34 survey, including the resolution on conductivity readings and the physical factors that affect a survey. We are also able to identify the geological setting based on ground conductivity values. A discussion of the results will enable us to compare and contrast this survey technique to other well-known relevant survey techniques, including the ERT and EM-31, gaining an insight into the level of accuracy of an EM-34 survey and discovering if the EM-34 is the key to obtaining accurate terrain conductivity measurements.

1.2 Historical Background of the EM-34

The life of the machine began in the 1960s, as Geonics developed their third EM device after the EM-15 and EM-16. Geonics originally developed the EM-17 in 1969 after a similar device called the Ronka horizontal loop EM-MK5, which gave Geonics the idea to develop the EM-17. The purpose of the EM-17 was for mineral exploration. This was in accordance with the main aim of Geonics at the time. This was created when Vaino Ronka was the founder of Geonics. The EM-17 involves the use of two coils, a transmitter coil and a receiver coil. A magnetic field was generated at the transmitter coil, known as a primary field, with the receiver coil detecting any changes in the phase of the primary field to the modified primary magnetic field due to underlying conductors, known as the secondary field. The EM-17 measured certain phase components between these 2 fields as these phase components would vary in size due to effects from the ground. The ratio of the magnitude of these phase components to one another would indicate metallic conductivity, as the shape of the data profile over a mass of conductive mineralization could be related to the depth and geometry of the mass. The EM-17 displayed values of these phase relationships since an anomalous response over highly conductive mineralization would include both components of the secondary field. Duncan McNeill purchased Geonics in the early 1970s, moving the focus from minerals to environment and groundwater. The EM-17 was redesigned as the EM-34, to be used to measure ground apparent conductivity.

Features of the EM-17 were maintained, but 2 main changes were identified to the device during this transition to the EM-34. Firstly, The EM-34 is designed to map normal soil and rock electrolytic conductivity rather than the electronic conductivity of metallic minerals. Electrolytic conductivity arises from currents that are due to the movement of ions in solution rather than electrons on metallic interfaces. Electrolytic conductivity is of a smaller magnitude than metallic conductivity. Instead of displaying values of phase relationships between the primary and secondary magnetic field, the EM-34 displays the calculated conductivity in mS/m and a separation meter. Secondly, a buck-out voltage was introduced to the system to remove the effect from the primary magnetic field at the receiver during a survey. With the EM-34, the primary magnetic field is recorded at the receiver during machine calibration, before any survey, allowing only the secondary magnetic field to be recorded during a survey to gain an output of conductivity. Yet, during a survey, the primary magnetic field can still be detected and so to measure the small secondary field, the primary had to be removed from the total measured response from the receiver. This was done by a buck-out voltage equal and opposite to the voltage due to the primary field in the receiver coil, filtering out any effects of the primary magnetic field at the receiver coil. The device was designed so that as long as the coils are at the correct separation, the primary field voltage will be removed well enough to accurately measure the secondary magnetic field. A separation meter was introduced for the EM-34 to gauge the accuracy of the conductivity value produced and how well the primary field has been filtered, as the buck-out voltage would have a maximum effect when the coils are co-planar and at the correct separation.

Chapter 2

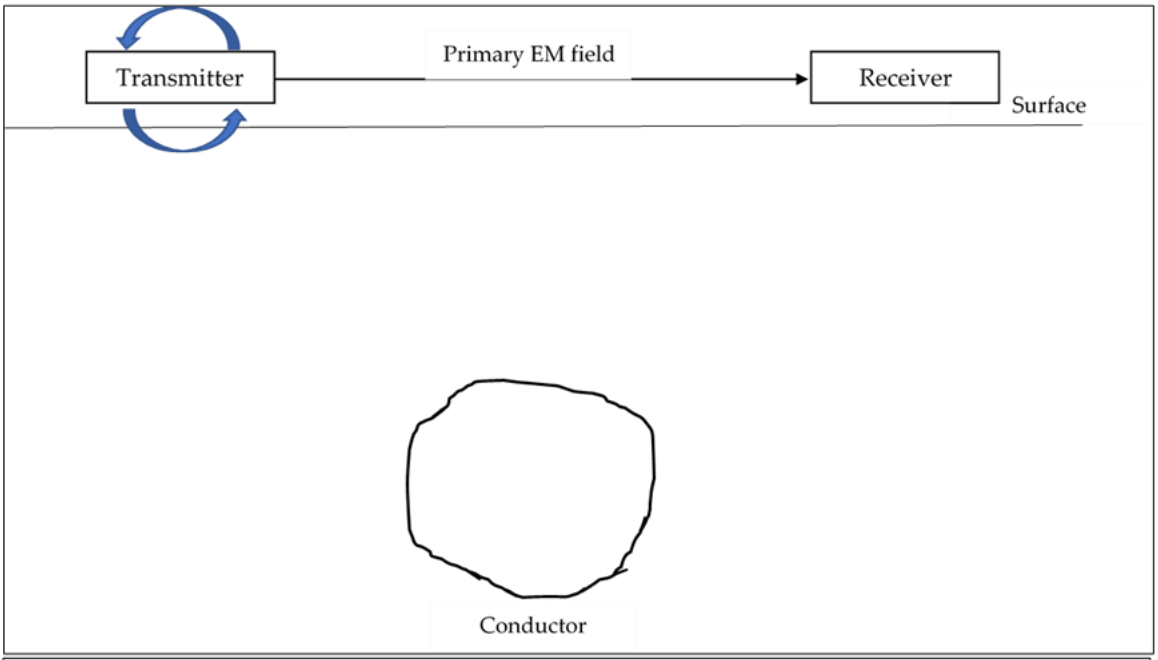
EM Theory

2.1 The Theory of EM Generation and Propagation

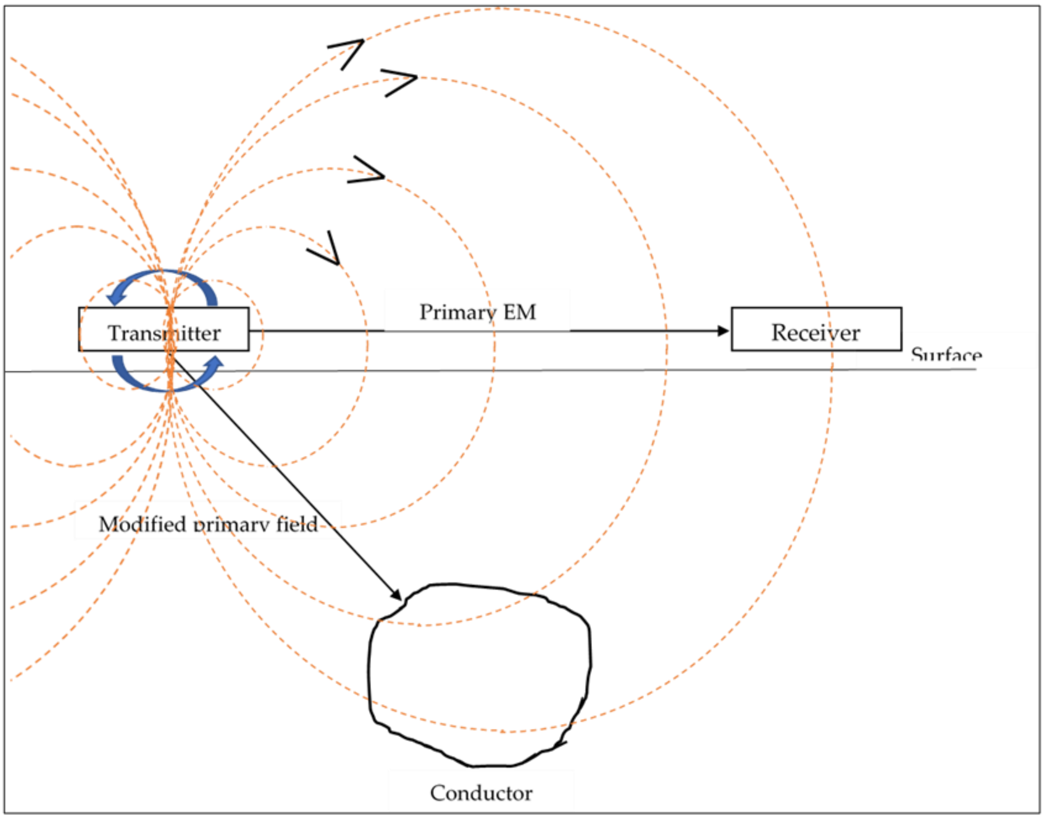
The electromagnetic principles of an EM-34 survey has never been understood concerning the terrain conductivity output of the EM-34. The inductive method is based on elements of electromagnetic theory, involving the production of electromagnetic waves from a transmitting coil in the form of a primary field and the detection of modified secondary fields at the receiver coil. EM waves have an electric and a magnetic vector at right angles to each other in which are both perpendicular to the direction of propagation. The theory is built on Maxwell's equations, including the effects of Faraday's and Ampere's laws**.** The production of EM waves from the EM-34 is due to an electric current oscillating backwards and forwards in a conducting body, which is known as an alternating current (AC). A voltage also runs with the AC. This AC generates a magnetic field from the transmitter as the induced electromotive force is proportional to the negative rate of change of the magnetic flux (Everett, 2013). The generation of a magnetic field is the main principles of Ampere's Law, as a time-varying magnetic field generates a circulating electric field. This is the first field to be generated, hence called a primary magnetic field, which will begin to propagate through the Earth. This is the basic principles of the generation of EM waves, yet we will concentrate on the time-varying magnetic field component of the EM wave when discussing the induction method. The magnetic field will travel into the Earth, with the electric field travelling perpendicular to the time-varying magnetic field.

The primary magnetic field will encounter conductive bodies inside the Earth. The interaction of the time-varying primary magnetic field component of the EM wave and the conductive body will induce Eddy currents, which are low amplitude currents which circulate in conductors in a swirling pattern. These currents will flow perpendicular to the plane of the magnetic field. The time variance of the primary magnetic field around stationary bodies will induce time-varying Eddy currents. Under Faraday's law, the eddy current will generate a secondary time-varying magnetic field, which will travel outwards from the body. The secondary time-varying magnetic field will also generate a circulating electric field, creating a new EM wave.

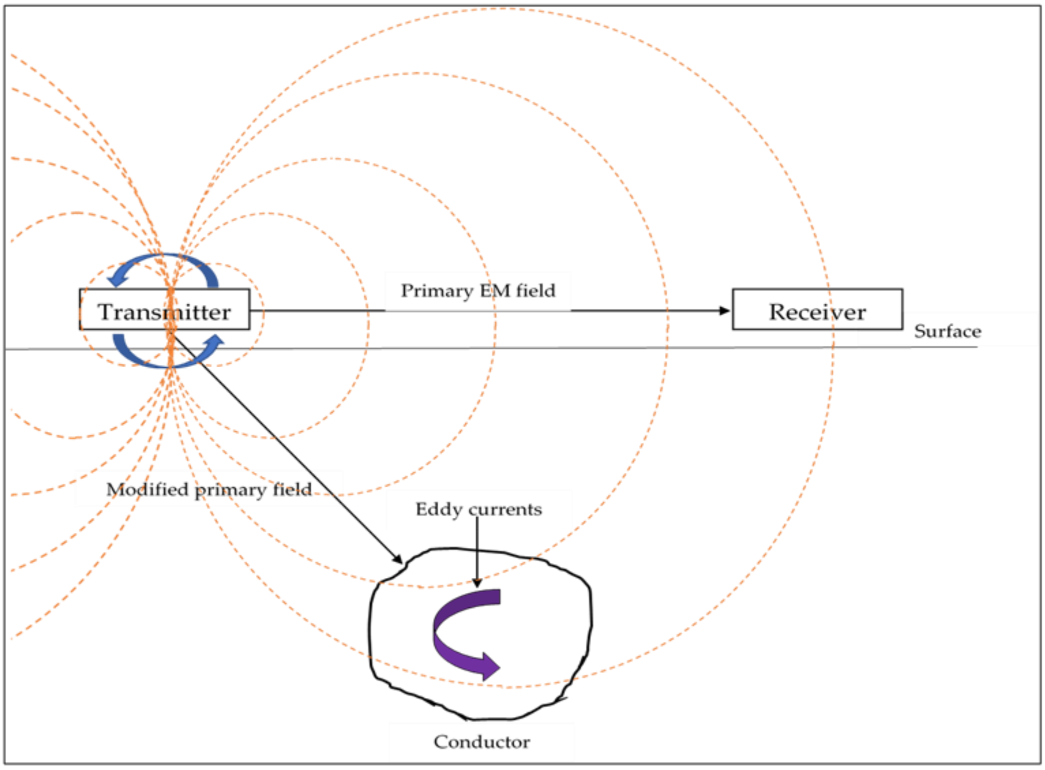
The production of this secondary magnetic field is generated by conductive objects or liquids and a resultant field will be detected at the receiver, which is comprised of both the primary and secondary magnetic fields. The interaction of the resultant field will induce currents in the receiver coil, in which a voltage can be measured. This measurement may be split into contributions from the primary and secondary magnetic field to the resultant field. The primary and secondary fields will have the same frequency, yet phase changes will be present. Figure 1 summarizes the generation of the primary and secondary magnetic field in 4 simple steps. This EM method depends on the fact that a primary magnetic field will produce no eddy currents beneath the surface unless the ground is saturated or underlying conductors are present, as this will produce significant eddy currents. The inductive method is based on the phase relationships between the primary and secondary field. When conducting material is present beneath the surface, the eddy currents generated are at an angle to the transmitter and receiver that is not 90° to the primary magnetic field. We can use this phase difference between the primary magnetic field and the resultant magnetic field to give information of the underlying conductors and is used to calculate terrain conductivity (Beck, 1981)



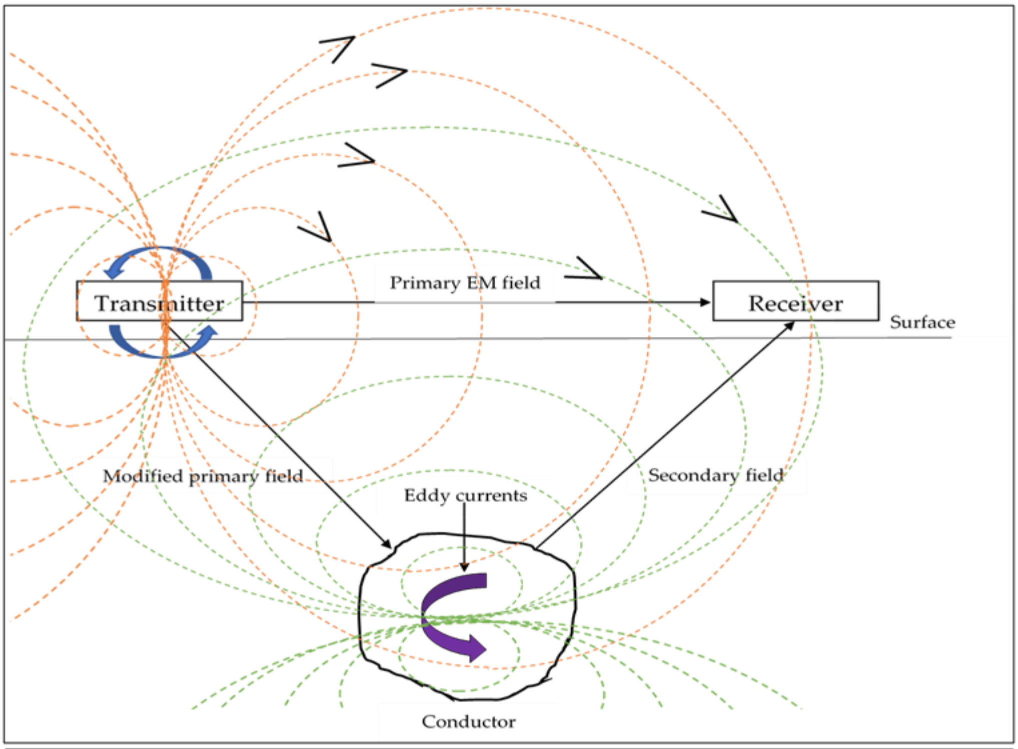
Step 1 – A time varying current is produced in the transmitter, as shown by the blue lines.



Step 2 – The time varying current produces a primary magnetic field as a result of Ampere's Law, as shown by the orange lines.



Step 3 – Voltage is induced in the conductor due to a changing magnetic field incident on the conductor, inducing Eddy currents in the underlying conductor as a result of Faraday's Law, as shown by the purple arrow.



Step 4 – A secondary magnetic field is produced, as shown by the green lines.

Figure 1 – A 4 step schematic showing the generation of Primary and Secondary magnetic fields.

2.2 Phase Shift of Magnetic Fields

The transmitter will generate a primary magnetic field. The voltage induced in underlying conductors will lag behind the primary magnetic field by an angle of $\pi/2$. The induced voltage is the time rate of change of magnetic flux, and so at maximum and minimum points of the primary magnetic field, the induced voltage in the underlying conductor will be zero. An underlying conductor will have a resistance (R) and also an inductance (L). The inductance acts as the feature of the conductor to oppose a change in the magnetic field linked with it (Beck, 1981). Eddy currents generated from the conductor when induced by a primary magnetic field will show no lag to the secondary magnetic field. Yet, the secondary magnetic field will lag behind the induced voltage in the conductor by a given angle (α). This lag will affect the resultant magnetic field, which will, therefore, show a lag to the primary magnetic field by another given angle (φ). This angle (φ) encompasses the induced voltage lagging behind the primary magnetic field by an angle of $\pi/2$ and an additional lag in secondary magnetic field from the induced voltage (α). This additional phase lag will give us the electrical properties of the conductor. For a good conductor, $\alpha = 90°$ and ($\varphi = 0°$). For a bad conductor, the angles α and φ will be 0°. This process of phase interrogation acts as a rough indicator of a good conductor and a bad conductor. Figure 2 summarizes the phase shifts discussed above.

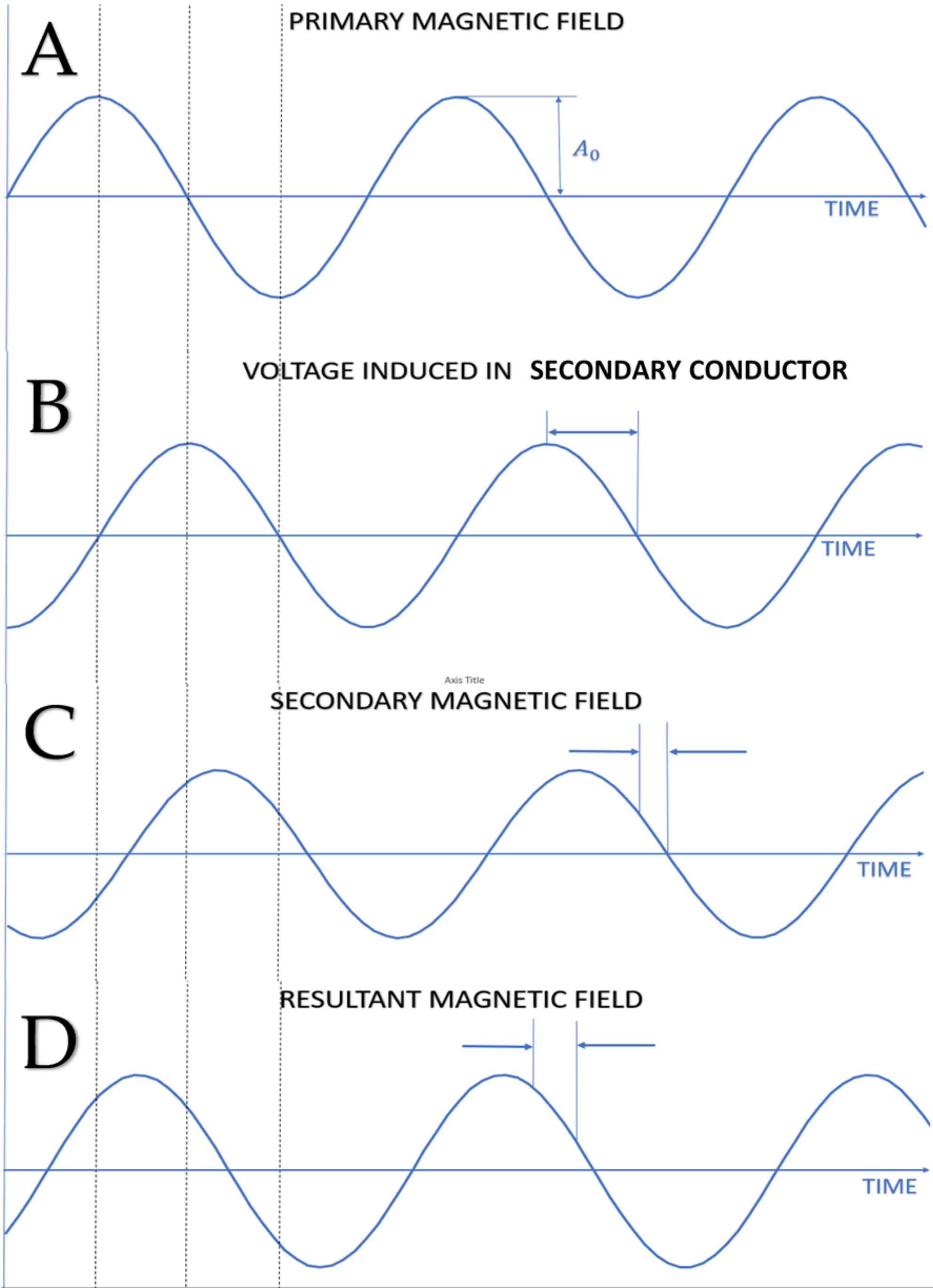


Figure 2 – A schematic of how the resultant magnetic field (D) lags behind the primary magnetic field (A) of angle φ due to a lag of angle π/2 between the primary magnetic field and the voltage induced in the underlying secondary conductor (B) and a lag of an angle α of the secondary magnetic field to the voltage induced in the secondary conductor.

2.3 Introduction to the Terms In and Out of Phase

As the EM-34 is a frequency domain instrument, there are 2 main components of the secondary magnetic field that is recorded and obtained by performing a Fourier transformation of the signal,

- An in-phase response (the real component of the secondary magnetic field) – this is the amplitude of the secondary magnetic field where the primary field is at a maximum.
- An out of phase response (the imaginary component of the secondary magnetic field) – this is the amplitude of the secondary magnetic field when the primary magnetic field is zero.

This response can be illustrated in Figure 3. If we want to measure the relative contributions of the imaginary and real components, we would need 2 reference signals, which are an in-phase signal with the transmitted signal and one which is 90 degrees out of phase with the transmitted signal. These signals are sent straight to the receiver via a cable that connects the transmitter and the receiver so that these signals would not undergo any interference from any underlying conductors. The phase of the reference signals would not be altered. These signals are used as reference points to measure the magnitude of phase shifts.

if you were to take the ratio of the amplitude of the real and imaginary components of the secondary magnetic field, you would end up with a ratio would give us information of the amplitude and phase of the ground response. These components are used in the processing of giving an output of terrain conductivity. This process of obtaining this ratio is based on the extend of the delay of the secondary magnetic field to the primary magnetic field.

We need to mathematically show this delay of the secondary magnetic field to the primary magnetic field. Firstly, we need to mathematically represent the primary and secondary magnetic field. The fields arise from a time (t) varying harmonic current (I)

$$I(t) = I \sin(\omega t)$$

with ω = 2πf (f = operating frequency). The primary and secondary magnetic fields that would arise from the transmitter and the conducting body respectively would be in the form,

$$H_p(\rho, t) = H_0(\rho) \sin(\omega t)$$

$$H_s(\rho, t) = H_1(\rho) \sin(\omega t + \theta)$$

where ρ is the radius of the transmitter coil. H_0 and H_1 represent the amplitude of the magnetic fields. The primary field will be significantly greater than the secondary field in amplitude. θ represents the lag of the secondary magnetic field from the primary magnetic field due to the eddy currents generated from conductive bodies. If the underlying surface is resistive, the secondary field is completely in phase from the primary magnetic field. Yet, if the underlying surface is conducting, the secondary field is out of phase from the primary magnetic field. The receiver coil will measure the resultant field which is a combination of the primary and secondary magnetic fields. We can break down the resultant field as a function of the primary and secondary magnetic field,

$$H_R(\rho,t) = H_p(\rho,t) + H_s(\rho,t)$$

$$H_R(\rho,t) = H_0(\rho)\sin(\omega t) + H_1(\rho)\sin(\omega t + \theta)$$

into two components to represent the real and imaginary responses,

$$H_R(\rho,t) = (H_0 + H_1\cos(\theta))\sin(\omega t) + (H_1\sin(\theta)\cos(\omega t)$$

with the real response (Re) is such that Re = $[H_0 + H_1\cos(\theta)]$ and the imaginary response (Im) is such as Im = $[H_1\sin(\theta)]$. When the primary signal is known, the H_0 can be subtracted to make Re = $[H_1\cos(\theta)]$. The larger the Re/Im ratio, the larger the conductivity of an underlying conductor. (Reynolds, 2011)). With knowledge of the primary magnetic field recorded during calibration, we can retrieve information of the amplitude of the secondary magnetic field mathematically by using the real and imaginary components,

$$A = \sqrt{(Re)^2 + (Im)^2} = \sqrt{[H_1\cos(\theta)]^2 + [H_1\sin(\theta)]^2} = |H_1|$$

The measured imaginary response will be used to interpret the ground conductivity as the response will give us information on the presence of any conducting bodies. If the imaginary response goes to zero, conductive bodies will not be present.

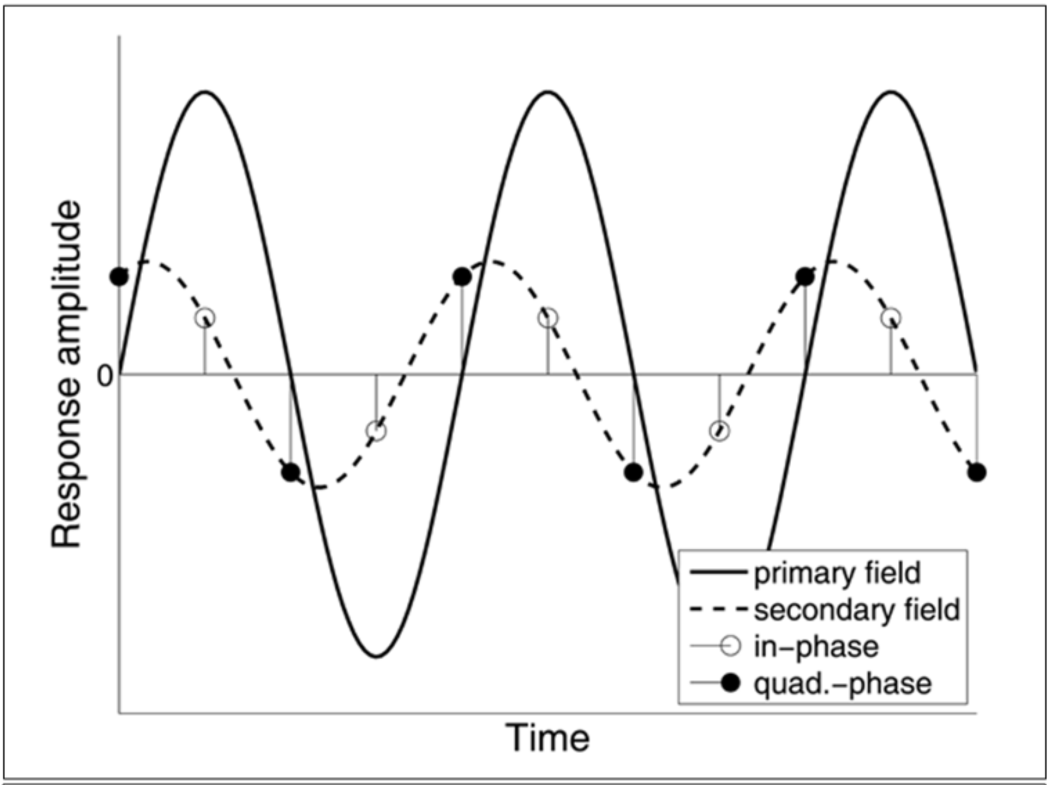


Figure 3 – A graphical representation of the terms in-phase and out of phase (after Simpson, 2009)

2.4 Using the Low Induction Number Theory to gain an Output of Terrain Conductivity

The device is created to give a direct output of apparent conductivity with an approximation applied to simple calculations which are built into the EM-34. This approximation is referred to as a “low induction number (LIN)” (Selepang, 2016).

The approximation is based on a few assumptions, such as,

1. Instruments operate at low frequencies of less than 15 kHz.

2. The instrument is operated at zero elevation.

3. The magnetic permeability of free space is $\mu_0 = 4\pi \times\ 10^{-7}\mathrm{Hm}^{-1}$ SI units). This states that a survey is conducted in a non-magnetic geological environment.

The basis of the LIN theory is that the EM-34, which operates on the fundamentals of EM induction as previously discussed, can measure field intensities that can be converted into the apparent conductivity of the subsurface. The induction number (B) is defined as the ratio of the intercoil spacing (s) divided by the skin depth. The skin depth is defined as the distance at which the amplitude of the field has fallen to 1/e of its magnitude at the surface of the earth or from a reference point (Telford et al., 1990). One of the main LIN approximations is that B $\ll$ 1. With this approximation, we can say that the imaginary component of the secondary magnetic field is now analogous to the apparent conductivity measurements. The approximation has implied that apparent conductivity measurements are directly proportional to the magnitude of the secondary magnetic field. With the LIN constraint incorporated into the EM-34, the imaginary component of the secondary magnetic field can be written as,

$$\left(\frac{H_s}{H_p}\right) \cong \frac{i\omega\mu_0\sigma s^2}{4}$$

with the ratio of the secondary to primary field proportional to apparent conductivity. H_p represents the primary magnetic field and H_s represents the secondary magnetic field. s represents the intercoil spacing (m) and μ_0 representing the permeability of free space. With all of these quantities known before or during a survey, we can re-arrange so that the apparent conductivity (σ_a) is a direct output of the device,

$$\sigma_a = \frac{4}{\omega\mu_0 s^2}\left(\frac{H_s}{H_p}\right)$$

Ground conductivity readings can now be obtained, with ground conductivity measured in milli-Siemens per meter (mS/m).

Chapter 3

Methodology

3.1 EM-34 Instrumentation

The Canadian-based company called Geonics-Limited designed and manufactured the EM-34 as they specialize in manufacturing electromagnetic geophysical instrumentation. The device is an example of a frequency domain instrument in which there is no electrical contact made with the ground. This device is classified as a slingram system described by Mcneil (1990), as it is a moving-source dual-coil method.

Figure 4 gives a representation of the instrumentation set up of the EM-34 system, which is based on two coils which are connected to two consoles respectively. These coils act as a transmitter and receiver. This is because the consoles provide a current to the coils as the console is connected to the coil with a cable and the two coils magnetically link together during a survey, as well as any conductive bodies present within the Earth. The two coils are physically connected by a reference cable. The length of the cable will govern the intercoil spacing. This distance can be either be 10m, 20m or 40m. Each intercoil spacing is linked with a known operating frequency, which is 6.4kHz, 1.6kHz and 0.4kHz respectively. During an EM-34 survey, it is essential to maintain a fixed single frequency for a fixed intercoil spacing. All of the cables used in the instrumentation will be shielded to prevent electromagnetic interference. The EM-34 can also operate with a choice of coil orientation, which affects the direction of the magnetic dipole propagation. These orientations or modes are called horizontal or vertical magnetic dipole modes. Horizontal dipole mode is when the coils are perpendicular to the ground and are upright. Vertical dipole mode is when the coils are laid flat on the ground. These modes are shown in Figure 5. The coils should remain in contact with the surface throughout the survey.

The output of the system is given on the console that is connected to the receiver coil. There are 2 outputs which are recorded during a survey. The value displayed on the right is a reading for ground conductivity. This displays the calculated conductivity value using the ratio of the primary and secondary magnetic field, as already discussed. The value displayed on the left is the separation meter. This is showing the in-phase component of the secondary magnetic field, which should be zero. Assuming the coils are coplanar, the value should display zero. This shows you're at the correct separation and so is used to determine correct coil separation, so the conductivity measurement will be accurate. This value should be within ± 300 for the conductivity value to be deemed as accurate. On the receiver console, there are different options for conductivity sensitivity. These are 10mS/m, 100mS/m and 1000mS/m. These options define the resolution of the output of conductivity, allowing for a greater detail to readings. The sensitivity scale should be chosen before a survey and should be chosen based on rough estimates of the subsurface geology, as anomalous conductive bodies will give a larger range of conductivity values. Figure 6 shows the system in use during the field. The survey is operated with 2 people. One person is in control of the transmitter console and coil, with the other person in control of the receiver coil and console. There is the option of using a data logger within the system which electronically records and stores values for conductivity. For surveys presented in this dissertation, values of conductivity and separation were manually recorded and computed into Microsoft Excel.

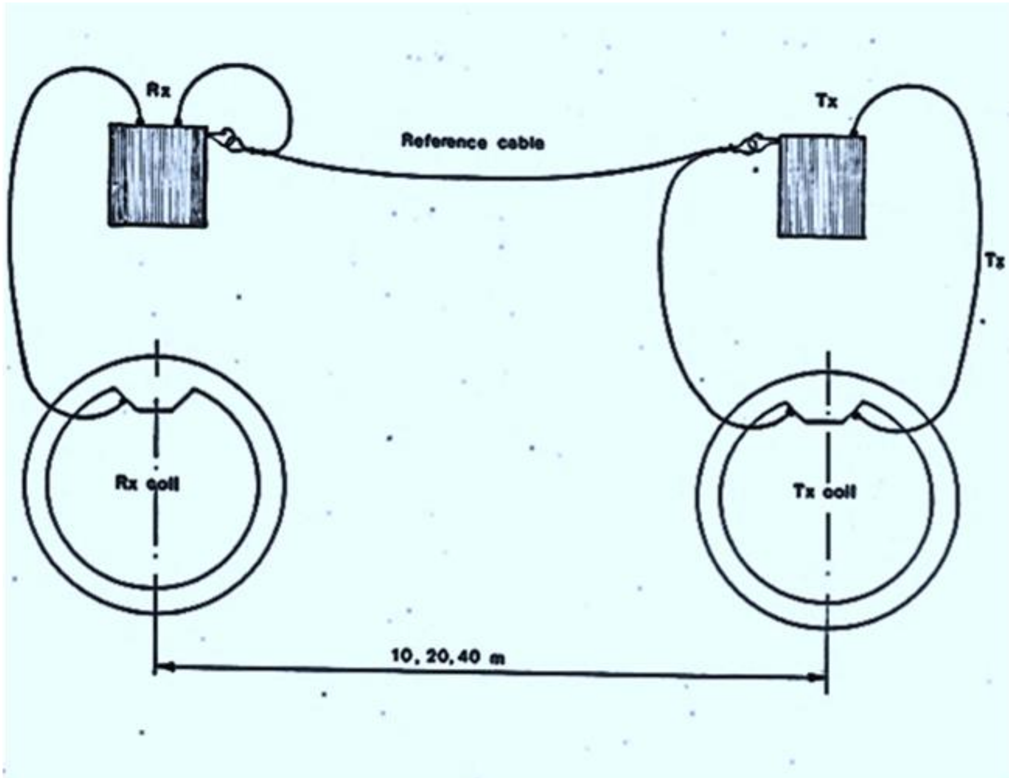


Figure 4 – A diagram displaying the instrumentation set up of an EM-34 survey.

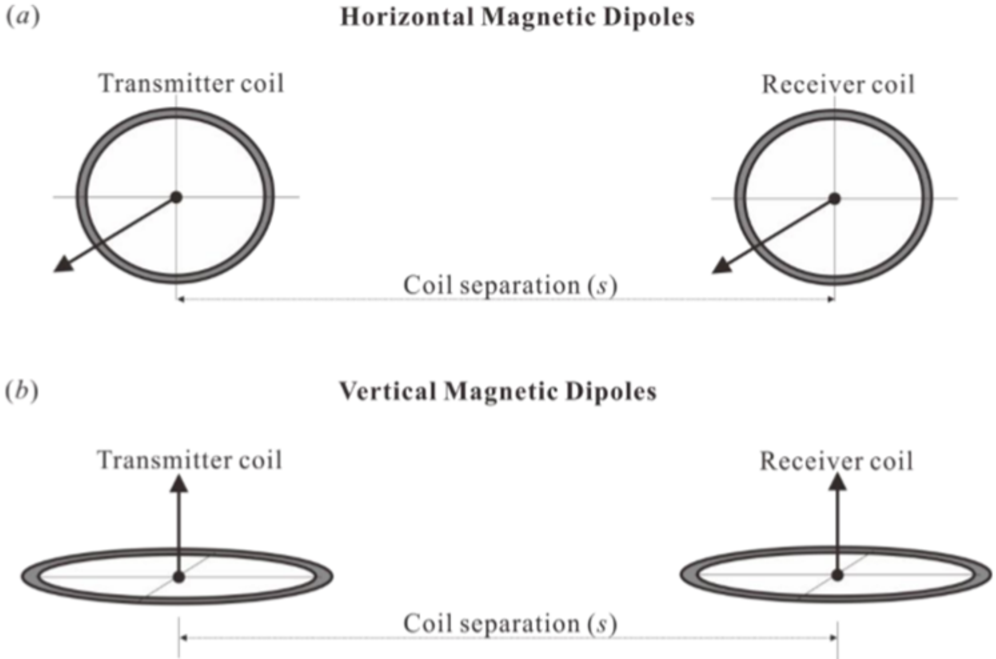


Figure 5 – A diagram representing the orientation of the coils in the horizontal or vertical magnetic dipole mode (after Selepeng, 2016)

Figure 6 – A collection of pictures showing how an EM-34 survey is conducted.
Left) The use of the instrumentation of the receiver coil with an operator.
Right) 2 operators conducting an EM-34 survey, with the coils co-planar.

3.2 Physical Survey Set up Procedures

When performing an EM-34 survey, there are a series of procedures that must be carried out to ensure that the system is fully operational and the devices are calibrated. In the appendix, there is an operation manual which is designed to give a series of instructions on how to set up the EM-34 system and how to take a reading. There are also several periodic checks stated in the operational manual to configure the device before conducting a survey. There are 2 main procedures done to calibrate the device. The first one is electronic nulling. This process involves producing a zero output on both readings. This is done so that the primary field is recorded and compensated so that the receiver only responds to changes in the secondary field (Kearey et al., 2002). The second one is a gain check, which is performed to ensure that the electronic nulling process is accurate. When performing an EM-34 survey, it is essential to maintain a certain dipole orientation throughout a traverse and to keep the transmitter and receiver the same way around when going from one traverse to another. Keeping the coil orientation constant throughout a traverse allows the secondary magnetic field to be transient. It is also important to keep the coils planar during an EM-34 survey

3.3 Physical Applications of the LIN Condition

As already discussed, a condition which is maintained throughout calculations of conductivity, which are integrated inside the EM-34 system, is the low induction number (LIN) condition. The induction number is a ratio of the intercoil spacing to skin depth. The LIN condition affects the accuracy of the output of subsurface conductivity as it has been observed that with an increased intercoil separation, there is a greater deviation from the LIN condition as the values returned from an EM-34 survey may not be an accurate representation of conductivity for a larger intercoil survey (Reynolds, 2011). This is because for a larger intercoil spacing, the larger the induction number (B) as the induction number is defined as the ratio between the intercoil spacing and the skin depth. To keep the LIN condition valid, $B \ll 1$. We can say that for a smaller intercoil spacing, the smaller B will be. This also means that for a smaller value of B, the output of conductivity will be closer to the true subsurface conductivity. This observation may be noted as a consequence of a geometrical effect of the magnetic waves detected by the system (Beamish, 2011). It has also been observed that the smaller induction number, the larger the skin depth for a given intercoil spacing. Since the skin depth will be large when the LIN condition is obeyed, we can say that the depth of exploration is controlled by the intercoil spacing and not governed by the skin depth. With the LIN condition obeyed, we can also say that the larger the intercoil spacing, the larger the skin depth.

As the exploration depth of an EM-34 survey is controlled by the intercoil spacing, we can introduce values of exploration depths with changing intercoil separations and coil orientations. These values are after McNeil (1980) and these values are true assuming that the instrument is operated at zero elevation. Table 1 shows these values for the EM-34 system. The main pattern is that for the horizontal coil orientation, the exploration depth is 75% of the intercoil separation and for the vertical coil orientation, the exploration depth is 150% of the intercoil spacing.

Intercoil Spacing (m)	Exploration Depth (m)	
	Horizontal Coil Orientation	Vertical Coil Orientation
10	7.5	15
20	15	30
40	30	60

Table 1 – The effective exploration depths for each intercoil spacing for an EM-34 survey.

3.4 Resolution

The resolution of the EM-34 needs to be considered if a survey can be completed successfully and target bodies can be detected. The larger the intercoil spacing, the larger the volume of ground surveyed for a given traverse. This means that if a small and shallow body may not be detected for a 40m intercoil survey. Furthermore, a smaller distance between station readings would imply a smaller sampling interval. This gives a larger spatial sampling since more readings can be made along a traverse, yet the sampling interval would be governed by the versatility of the EM-34 operation. Suitable sampling intervals for an EM-34 survey should be 1m spacing between station readings along a traverse.

3.5 Factors Affecting Terrain Conductivity

Terrain conductivity is defined as the cumulative subsurface conductivity from the surface to the depth of exploration of the instrument. Electromagnetic methods will give an output of apparent conductivity, which is influenced by measurements of the terrain conductivity of the Earth. The conductivity values produced by the EM-34 is a measure of electrolytic conductivity, as any underling currents due to movement of ions in solution directly links to terrain conductivity. Electrolytic conductivity readings can be influenced by the rare appearance of any minerals within rocks or soils that have a high conductivity, such as Graphite or Magnetite. However, most soil and rock minerals are electrical insulators of high resistivity (McNeil, 1980). This is why electrolytic conductivity can be generalized so that terrain conductivity is mainly associated with solutions passing through insulating soil and moisture-filled pore spaces within the soil and rock matrix. With this generalization, we can list the main factors affecting terrain conductivity,

- **Size of soil particles** – The general pattern is that conductivity increases with decreasing soil particle size. This makes the most conductive particle to be of true clay particle size. This is due to a more direct current path present in finer-grained soils and is also influenced by a large number of exchangeable ions that are held on the surface of clay particles. This is the reason that silty soils tend to be more conductive than clean sands and gravels.
- **Porosity of the subsurface material** – This underlines the shape, size and number of pores, as well as the interconnecting passages. T0he larger the pore space within the subsurface, the larger the amount of pore fluids.
- **The amount of pore fluids inside and within pores** – A larger amount of pore fluids links to a larger quantity of electrolytes, which would give a larger terrain conductivity. A particular example of this would be old unlined landfills that add electrolytes soils by leachates emanating from the landfill materials, linking to the environmental purpose of the EM-34.

The conductivity output of an EM-34 will allow us to gain a geological interpretation of the subsurface as a combination of these main actors will directly affect the ground conductivity output.

Chapter 4

Case Study 1 – Abercromby Square

4.1 Background

Abercromby Square is a local park on the southern side of the University of Liverpool campus. The park was designed at the beginning of the Nineteenth Century. Before development, the area was composed of fields, marsh and a large lake called Moss Lake that extended for about 280 acres. The lake had become a peat bog in the 1660s before the peat bog was eventually drained and the land used for building. Figure 7 shows the location of Abercromby Square. The park is now situated on the campus of the University of Liverpool.

Figure 7 – A Google Earth image showing Abercromby Square situated on the University of Liverpool campus.

4.2 Survey Aims and Information

The aims of the EM-34 surveys that were conducted in Abercromby Square are to get a better understanding of the survey's set up, calibration methods and physical implications of the survey. Performing an EM-34 survey to this level enabled us to check that the surveys were done correctly and efficiently, allowing us to go to a more advanced level in any future surveys. We also wanted to assess the output of the EM-34, and so conductivity values and separation values were recorded with different coil orientations and different intercoil spacing along traverses, inspecting the variation if any, of conductivity with respect to depth and position. This assessment could provide us with an insight into the near-surface terrain conductivity of Abercromby square. The University provided with access to Borehole information of Abercromby Square in the form of a core sample. This information, as shown in Figure 8, would allow us to compare our analysis of terrain conductivity with the materials that make up the borehole. The level of resemblance would be an indicator of the accuracy of our surveys. By recording the separation values, we can get a sense of the accuracy of our conductivity profiles.

A total of 3 traverses were created in Abercromby Square as shown in Figure 9. A survey was conducted on the 28th October 2019, between 12:00 – 13:30 along Traverse 1, with surveys conducted on 08/11/2019 between 14:30 and 16:00 along Traverse 2 and Traverse 3. The weather conditions for both days were mild and dry. The 100mS/m sensitivity range was used in this area for all traverses as no metallic body was expected to be detected. The traverses were running completely on grass, with no nearby conductors in the vicinity of the park.

A singular survey was carried out along Traverse 1 which ran from west to east. The traverse was 20m long. Readings were taken at every 1m along Traverse 1 for both coil orientations, with a 10m intercoil separation was used and maintained for this survey. Results for Survey 1 will be presented in the form of a conductivity profile, with the profile running from west to east in the direction of the survey.

Surveys along Traverse 2 and Traverse 3 ran from south to north. The overlapping of Traverse 2 and Traverse 3 was done to test the vertical changes in conductivity, as between the 2 surveys, the intercoil separation was varied, with a 10m intercoil spacing used on Survey 2, followed by a 20m intercoil spacing for Survey 3. Both surveys were carried out with the coils in the vertical dipole orientation. The larger intercoil spacing will allow for a larger exploration depth. Readings were taken every 2m for the Survey 2, and every 1m for Survey 3. Results will be presented for Survey 2 and 3 with the conductivity profiles running from south to north.

Figure 8 – Borehole information of Abercromby Square, displaying the type of soil present inside the borehole (right). The borehole (left) reaches a depth of 7.5m

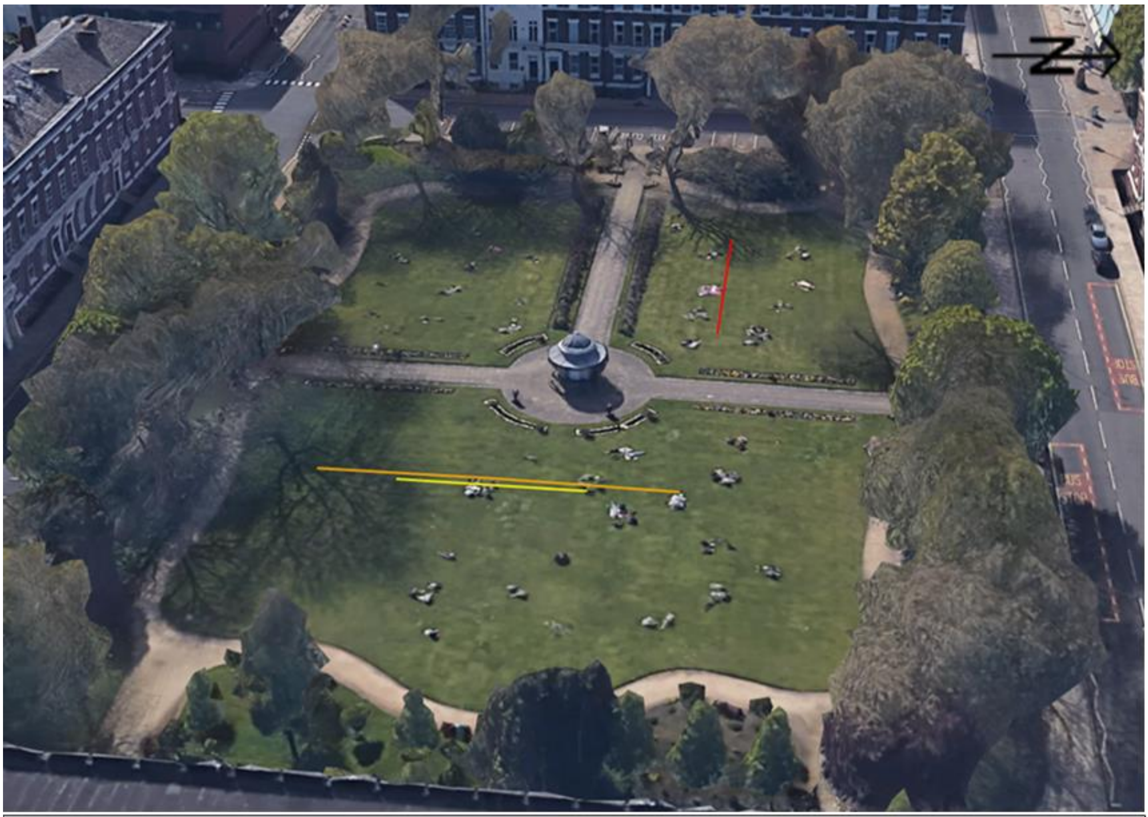


Figure 9 – The locations of the traverses for all 3 surveys performed in Abercromby Square.
Survey 1 – Red
Survey 2 – Orange
Survey 3 - Yellow

4.3 Survey Results

The conductivity values recorded for both coil orientations along Traverse 1 shows no major anomalies, as shown in Figure 10a. The conductivity ranges for each coil orientation are between 3mS/m and 4.5mS/m for the horizontal coil orientation and 6.5mS/m to 9mS/m for the vertical coil orientation. This shows that profiles are relatively flat, indicating that there was no substantial lateral change in geology. The small difference in conductivity values between the horizontal and vertical dipoles indicates a pattern of a steady increase of terrain conductivity between exploration depths of 7.5m and 15m. The magnitude of conductivity values recorded indicates that silt has been detected at these depths, with the increase in conductivity with depth potentially due to an increase in grain saturation. We can compare our observations to the core sample, which show a silt like soil observed at the bottom of the borehole at 7.5m. This correlates with the interpretation of geology that was made from the conductivity values recorded, giving our survey a significant level of accuracy. The values for separation recorded were all within the $\pm$300 range as shown in Figure 10b, indicating that coils were coplanar throughout the survey and that the conductivity values obtained are accurate.

When the intercoil separation was changed, we observed the change in the magnitude of conductivities across Survey 2 and Survey 3 as shown in Figure 11 as there is a large increase in conductivity observed when the intercoil spacing is increased. For Survey 2, the values in conductivity range from 7mS/m to 9mS/m for both coil orientations, yet for the 20m intercoil separation, the values range from 160mS/m to 166mS/m for both coil orientations. No substantial lateral variation in geology was observed, as the conductivity profiles were flat. However, the range of values of conductivity obtained for Survey 2 matches with the results from Survey 1, indicating that the layer of silt detected in Survey 1 is consistent throughout the park. The increase in values for a larger intercoil spacing suggests a vertical change in geology between depths of 15m and 30m, with a different type of soil detected. The magnitude of conductivities obtained would suggest that soil of clay-sized particles is present between 15m and 30m. The large increase in values could also suggest that the water table has been detected between depths of 15m and 30m. These results follow the general rule for terrain conductivity that conductivity increases with depth because of a reduction in grain size or increase in moisture content.

This case study enabled us to detect vertical variations of soil properties within the subsurface by varying the coil orientation and the intercoil separation this allowed us to gain a bigger understanding of the geological setting, The variation in intercoil septation along the same traverse allowed for a larger exploration depth, giving a larger portrayal of the geological setting of Abercromby Square. Values for separation recorded were all within the ±300 range, indicating that the coils were maintained in a co-planar fashion

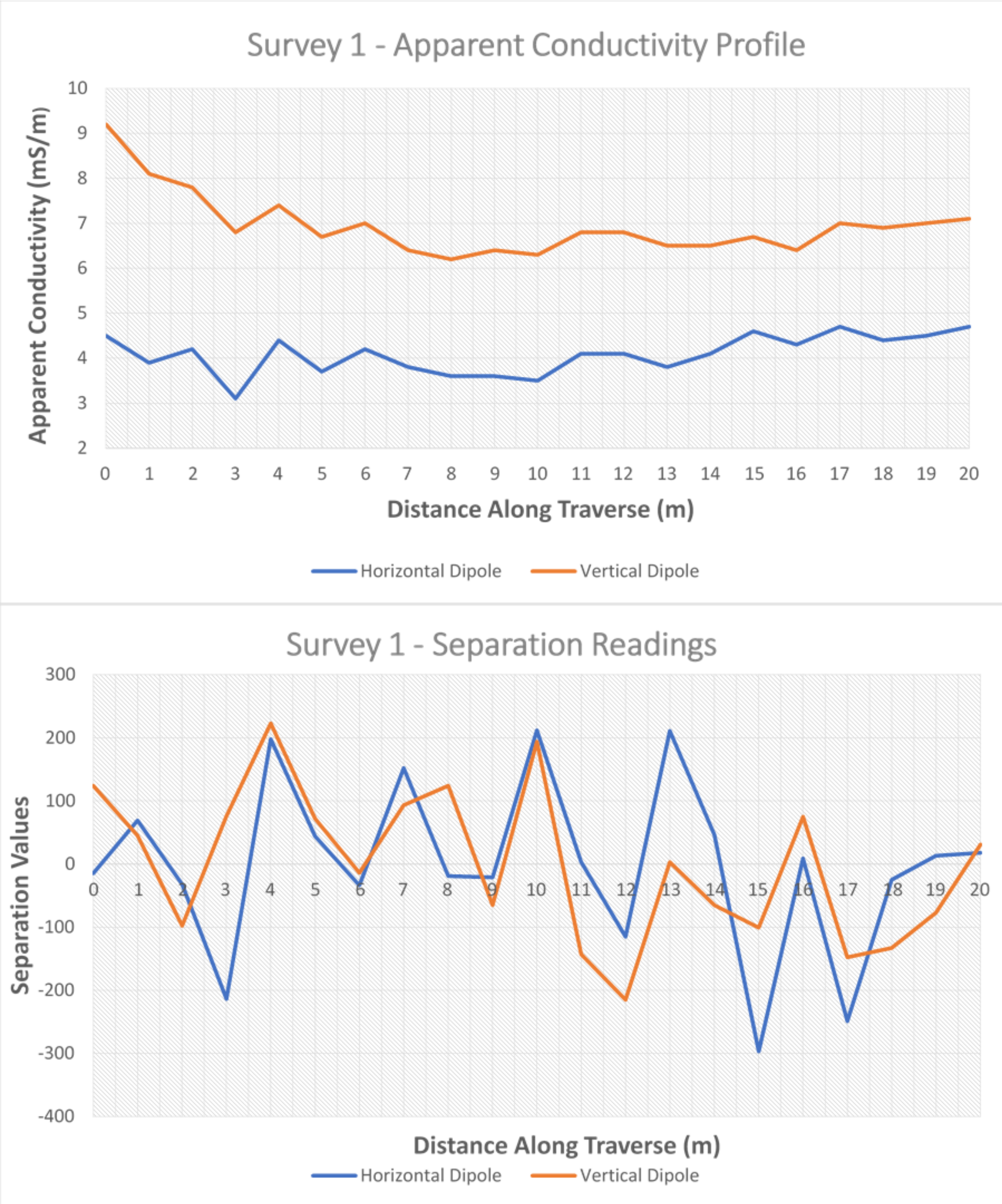


Figure 10 – a) Conductivity profiles for both coil orientations for Survey 1. b) Separation values for Survey 1.

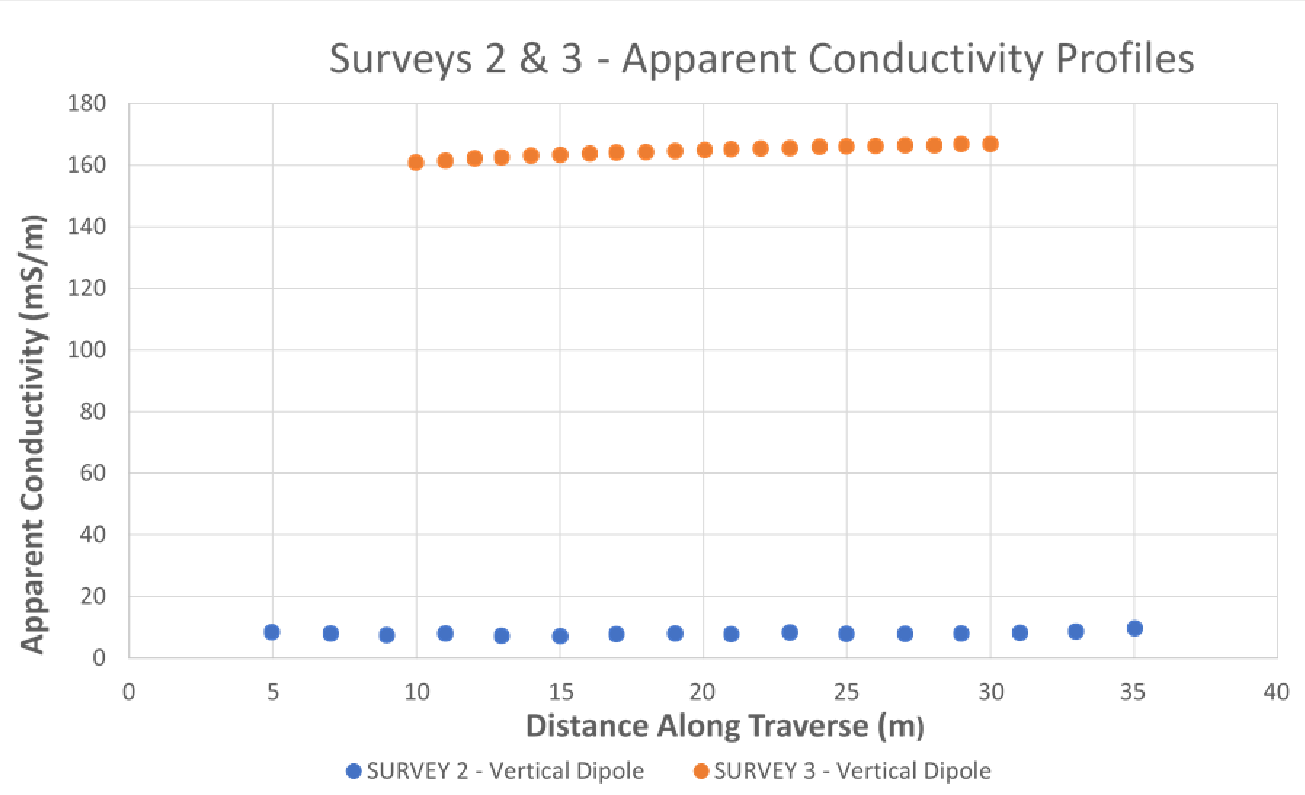


Figure 11 - Conductivity profiles for the vertical coil orientation of Surveys 2 and 3.

Chapter 5

Case Study 2 – Everton Park

5.1 Background

Everton Park is located on the outskirts of Liverpool and was created in the early 1980s. The park itself has a rough topography but surveys were conducted on land with a slight topographic elevation of approximately 3m, as shown by the yellow box in Figure 12. Historical maps of Everton Park from up to 40 years ago reveal the presence of infrastructure present in the area. However, it is difficult to identify the building type that is present. There are also several roads than ran through the area next to any buildings.

Figure 12 – A Google Earth Image of Everton Park. The red boxes indicate the areas of interest for all surveys. The yellow box highlights a slope within the areas of interest. The orange area highlights an area of anomalous conductivity.

5.2 Survey Aims and Information

Varying the intercoil spacing would indicate the change in terrain conductivity with respect to depth, as discovered in Abercromby Square. Yet, in Everton Park, we can begin to give an in-depth analysis of the EM-34 by investigating the reproducibility of an EM-34 survey on a variety of timescales ranging from a week to a year. We also investigated the change in conductivity outputs, if any, by varying the sensitivity of the device between surveys.

Furthermore, we investigated the effect of the conductivity output when the coils were not at the correct separation, giving a sense of error on any results. Moreover, there was an investigation into the survey output when a mixed intercoil separation was used. We also investigated the output of the EM-34 when there was a change in the topography of an EM-34 survey. There was also an investigation into the response of the EM-34 when a buried conductor was detected in the subsurface geology. These survey aims will be discussed individually.

Using several geophysical survey methods in Everton Park, including EM-34, EM-31 and ERT surveys would allow for direct comparisons to be made between these survey techniques and their outputs, including the different survey outputs to a buried conductor to test if the EM-34 is an accurate and reliable survey technique.

Figure 13 shows all a range of traverses that were created as surveys were completed across 3 separate days. We have also acquired data from a survey that was conducted in 2019 also shown in Figure. All surveys ran from north-east to south-west, with both coil orientations used in each survey. A distance of 0m along the traverse in the profiles will be equivalent to the most north-eastern point of the traverse. Therefore, all profiles presented will show the variation in conductivity along traverses in a direction from north-east to south-west. Values of conductivity and separation were recorded for each survey. Table 2 provides survey information for all individual surveys. The name of the surveys correspond to the day in which surveys were carried out across the 3 separate days, as well as the additional survey information from 2019. A discussion of the various conductivity profiles produced will be made to investigate different aspects of the EM-34, before making a comparison between the EM-34 and other relevant survey methods.

SURVEY NAME	DATE OF SURVEY	TRAVERSE LENGTH (m)	INTERCOIL SEPARATION (m)	SENSETIVITY RANGE (mS/m)	WEATHER CONDITIONS
Survey 1.1	24/02/20	30	10	1000	Dry
Survey 1.2	24/02/20	30	10	100	Dry
Survey 1.3	24/02/20	15	10	100	Dry
Survey 1.4	24/02/20	15	10	100	Dry
Survey 2.1	02/03/20	90	10	100	Dry
Survey 2.2	02/03/20	30	10	100	Dry
Survey 3.1	09/03/20	40	20	100	Wet
Survey 3.2	09/03/20	40	20	100	Wet
Survey 4.1	25/03/19	60	10	100	Dry

Table 2 – Survey Information of all surveys conducted in Everton Park

Figure 13 – The locations of traverses of all surveys performed in Everton Park. All surveys run from north-east to south-west.

Survey 1.1/ 1.2 – Red
Survey 1.3/1.4 – Black
Survey 2.1 – Dark Blue
Survey 3.1 – Yellow
Survey 3.2 – Green
Survey 4.1 – Orange

5.3 Varying the Intercoil Spacing

Similar to the case study in Abercrombie Square, we can vary the intercoil spacing across overlapping traverses to gain an insight into the geological setting of Everton Park and obtaining terrain conductivity information. The traverses for Surveys 1.2 and 3.1 show a 20m overlap and the intercoil separation between the 2 surveys vary, so by viewing conductivity values from the vertical dipole configuration, we can view any vertical variations in terrain conductivity. We can observe from Figure 14 that at an exploration depth of 15m, the terrain conductivity is fixed across the profile at approximately 8mS/m, showing no major horizontal variations in conductivity. Yet, at an exploration depth of 30m, a small increase in values across the profile is observed from 162mS/m to 175mS/m. We can observe a similar pattern to the previous case study with the magnitude of conductivities recorded for each survey increasing with depth, as a large change of terrain conductivity has been observed between 15m and 30m depth. This could be explained by the EM-34 detecting the change in soil type from a silt to a very fined clay in this duration, or the detection of more saturated materials at a larger depth, with the water table possibly detected in Survey 3.1. The variation of the intercoil spacing of the EM-34 allowed to view a larger geological setting, with the increase in terrain conductivity with depth observed up to a depth of 30m.

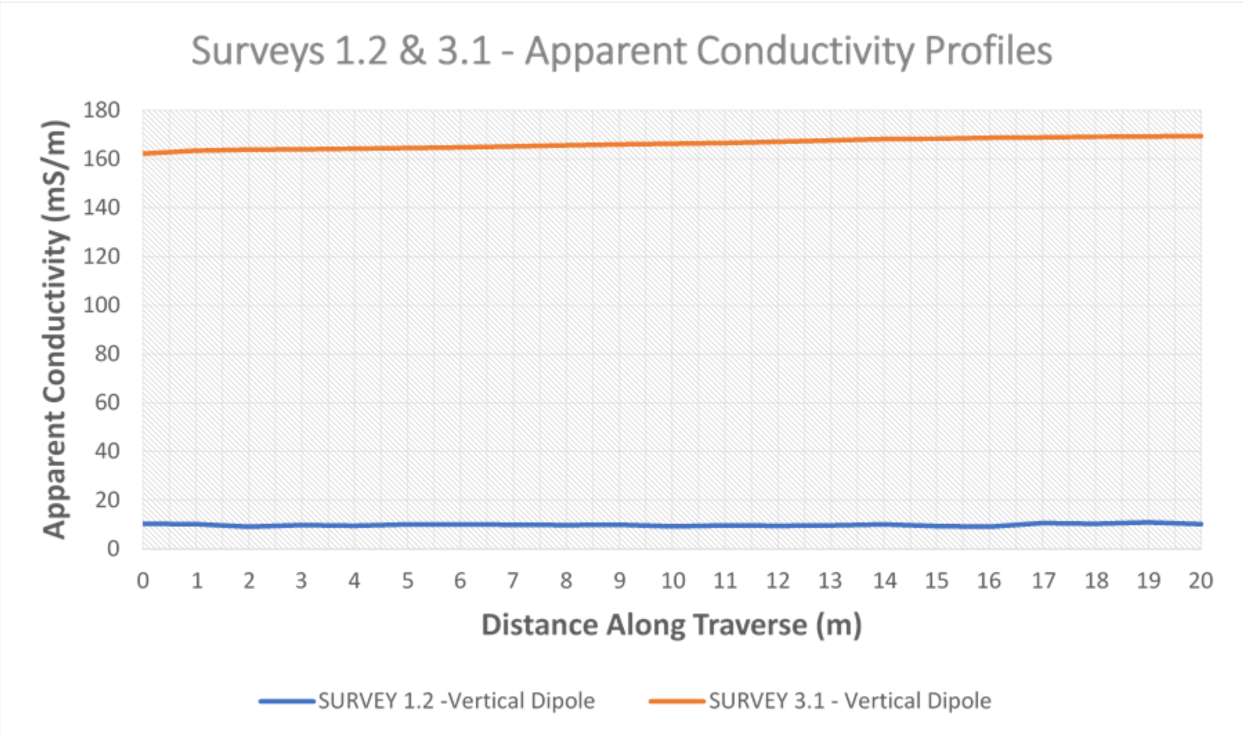


Figure 14 – Conductivity profiles for the vertical coil orientation of Surveys 1.2 and 3.1.

5.4 Varying the Sensitivity Range of the EM-34

The effect of changing the sensitivity range between surveys was performed to analyse if there was any variation in the conductivity readings produced by an EM-34 survey. Surveys 1.1 and 1.2 were conducted with a variation in the sensitivity range, with Surveys 1.3 and 1.4 conducted with a fixed sensitivity range. We can observe in Figure 15 that both of the coil orientations for Survey 1.1 follow the same trend in profile shape between 0-10m, with a difference in readings of 2mS/m on average between coil orientations. Between 10-30m, the conductivity values are observed to fluctuate less, with values for both coil orientations matching in conductivity magnitude. These conductivity values recorded were fluctuating from 7-8mS/m. For Survey 1.2, we can observe a general decrease in values for the horizontal orientation from 13mS/m to 8mS/m along the traverse. Values recorded for the vertical orientation consistently ranged from 9-11mS/m. The main observation from Figure – is the low correlation between conductivity profiles for both coil orientations between surveys, underlying the importance of maintaining the sensitivity range for a given traverse to allow for accuracy when attempting to reproduce an EM-34 survey. Figure 16 shows the high correlation in conductivity values between separate surveys for both coil orientations. For both Surveys 1.3 and 1.4, the horizontal orientation showed a gradual decrease in conductivity along the traverse from 12mS/m to 10mS/m, with the values of conductivity for the vertical orientation broadly increasing along the traverse from 8mS/m to 10mS/m. This observation outlines that maintaining the sensitivity range for a given traverse allows for a greater accuracy when reproducing an EM-34 survey, as values between surveys where the sensitivity range was maintained showed a larger correlation in comparison to surveys with a changing sensitivity range.

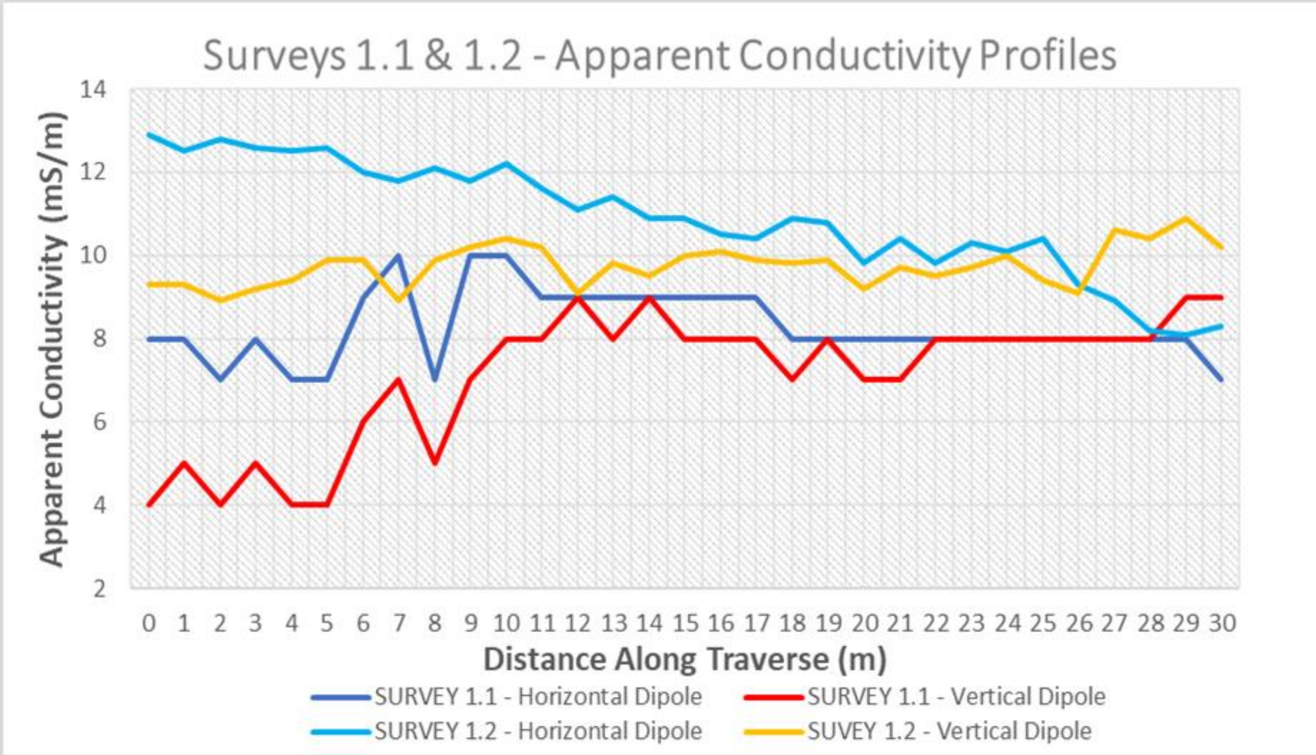


Figure 15 – Conductivity profiles for both coil orientations for Surveys 1.1 and 1.2

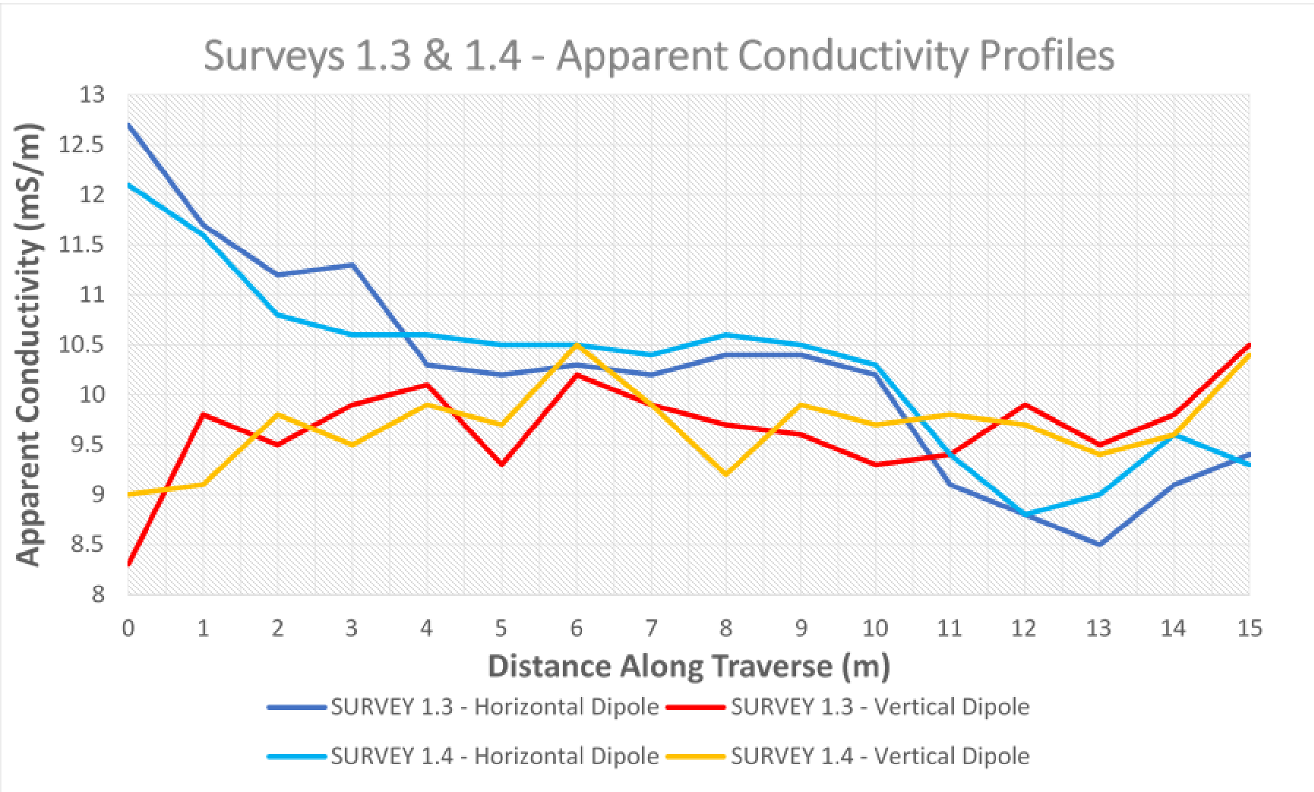


Figure 16 – Conductivity profiles for both coil orientations for Surveys 1.3 and 1.4

5.5 Varying from the True Intercoil Separation

An investigation was carried out at the most south-western point of Survey 1.4 into the variation in conductivity readings if the coils were in the same orientation but the coils were not at the correct separation. The investigation was done by marginally varying the intercoil spacing around 10m by moving just the receiver coil 1m closer to the transmitter coil from an intercoil spacing of 10m, with the transmitter coil remaining stationary, then moving the coil 1m further away from the receiver from an intercoil spacing of 10m. Values of conductivity were therefore recorded at intercoil separations between 9m and 11m, with the EM-34 on 10m intercoil spacing mode. Values were recorded every 0.2m. This was completed with the coils in the horizontal dipole orientation We can observe in Figure 17 that as you go closer to the receiver coil (negative separation values), the value for conductivity drops at a steady rate. As you go further away from the receiver coil (positive separation values), the value for conductivity increases at a faster rate than the rate observed when the coil was moved closer to the receiver. We can conclude such as there is a high variation of conductivity readings with an intercoil spacing that is different from the true intercoil spacing, which stresses the importance of accuracy for coil alignment. The conductivity readings range from the true value of conductivity by a maximum of ±6ms/m when the intercoil spacing varies by 1m from the true intercoil spacing. With a variation of 0.2m from the true intercoil spacing, we observe a variation from the true conductivity reading of ±1.6ms/m, giving a sense of error on each conductivity values recorded. Any major inaccurate conductivity readings can lead to a different interpretation of the soil constituents or potentially deciding if there is a major signal present in the profile.

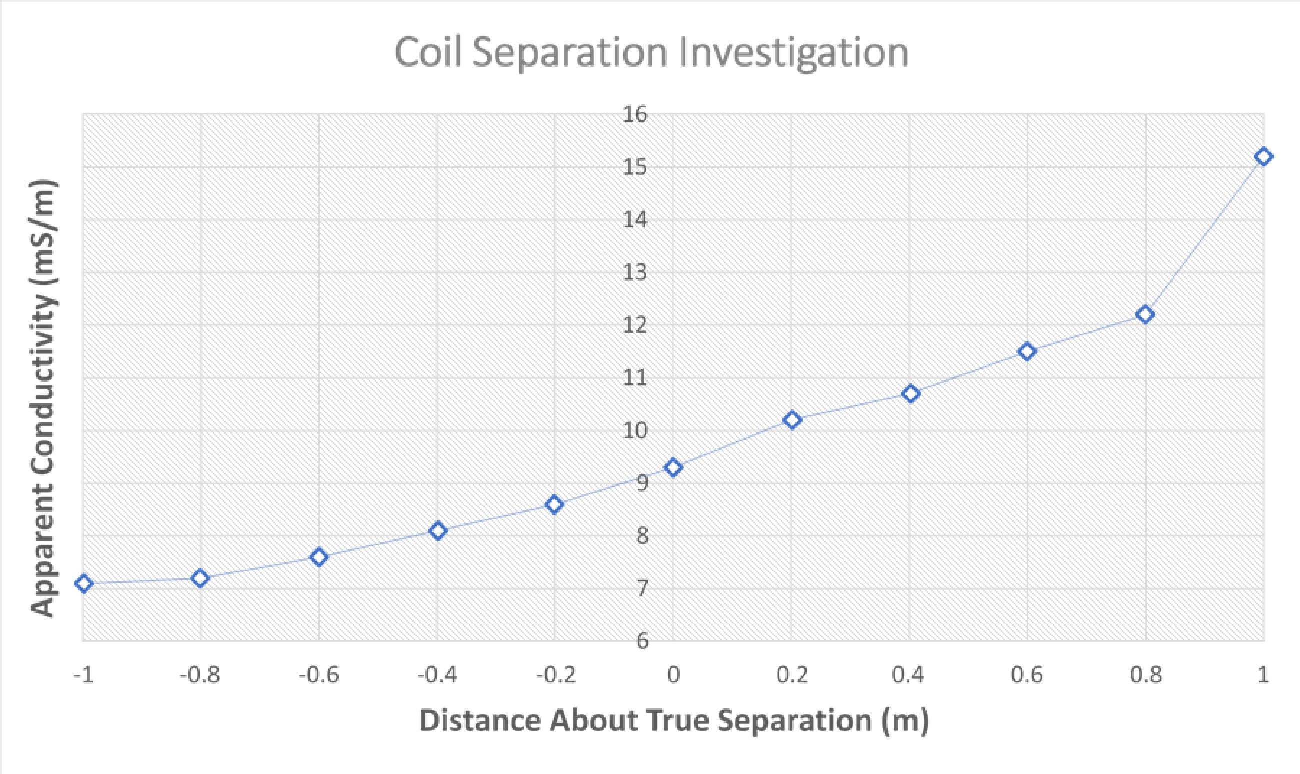


Figure 17 – A conductivity profile showing the variation in conductivity about the true separation. A positive distance indicates an increase in intercoil separation from the true separation (1m corresponds to 11m intercoil spacing), with a negative distance indicating a decrease in intercoil separation from the true separation (-1m corresponds to 9m intercoil spacing).

5.6 Testing the Reproducibility of an EM-34 Survey

To gain an insight into the level of reproducibility of an EM-34 survey, conductivity profiles can be compared on a series of different time scales with the traverses overlapping and coil separation maintained to view the ability of an EM-34 survey to reproduce with respect to time. Figure 13 shows that there is a 15m overlap between Survey 1.3 and 2.1, allowing us to inspect if the terrain conductivity has varied over one week. Figure 18 shows that in the horizontal coil orientation, both surveys show a decrease in values from approximately 12mS/m-9mS/m. In the vertical coil orientation, there is a general agreement in conductivity profiles from 2-13m both surveys display a constant conductivity output of roughly 9mS/m. On the whole, for both coil orientations, the conductivity values recorded does not vary, giving evidence that an EM-34 survey can be reproducible for up to one week. Figure 13 displays a 30m overlap in Surveys 1.2 and 4.1 with the intercoil separation maintained for both surveys. By comparing conductivity profiles created in different years, we can gain insight into the extend of the timescale that the EM-34 is reproducible. The conductivity profiles displayed in Figure 19 for both coil orientations show a stronger correlation between different surveys towards the south-western side of the traverse, yet there is a weaker correlation between Surveys 1.2 and 4.1 in conductivity profiles for both coil orientations towards the north-eastern side of the traverse. This outlines that the terrain conductivity may vary across the timescale of a year, questioning the reproducibility of an EM-34 survey across the duration of one year.

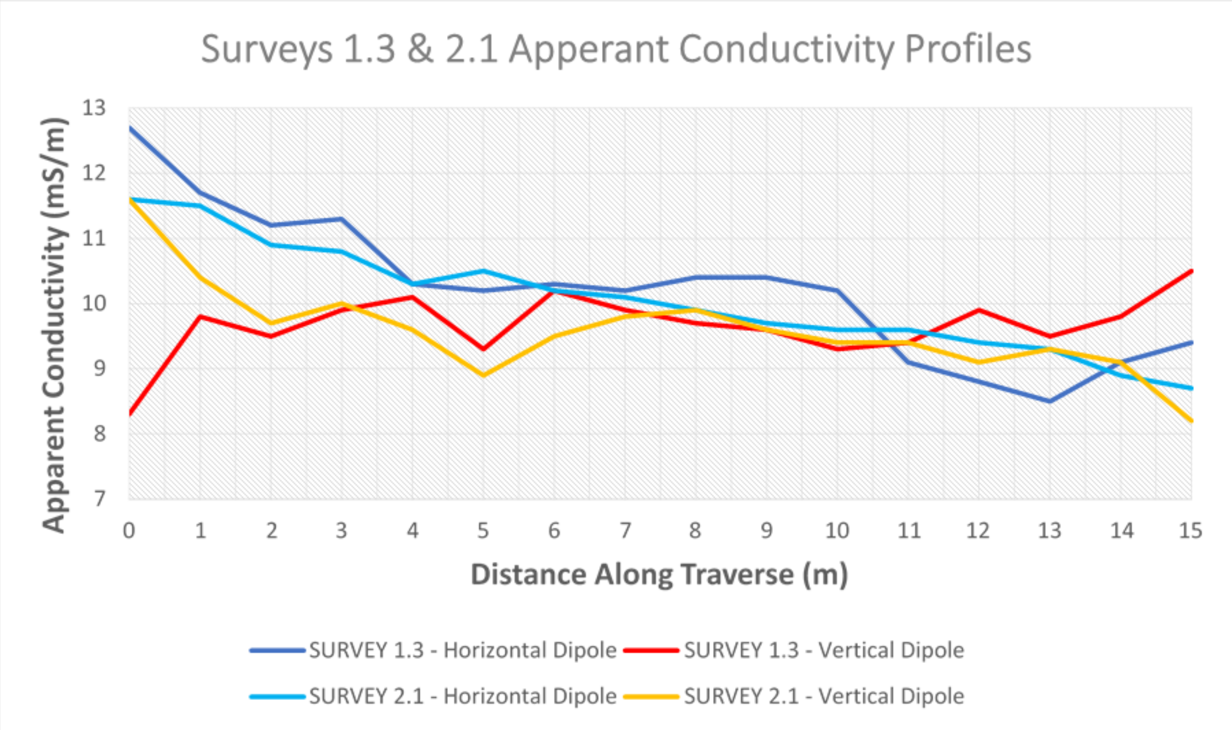


Figure 18 – Conductivity profiles for both coil orientations for Surveys 1.3 and 2.1.

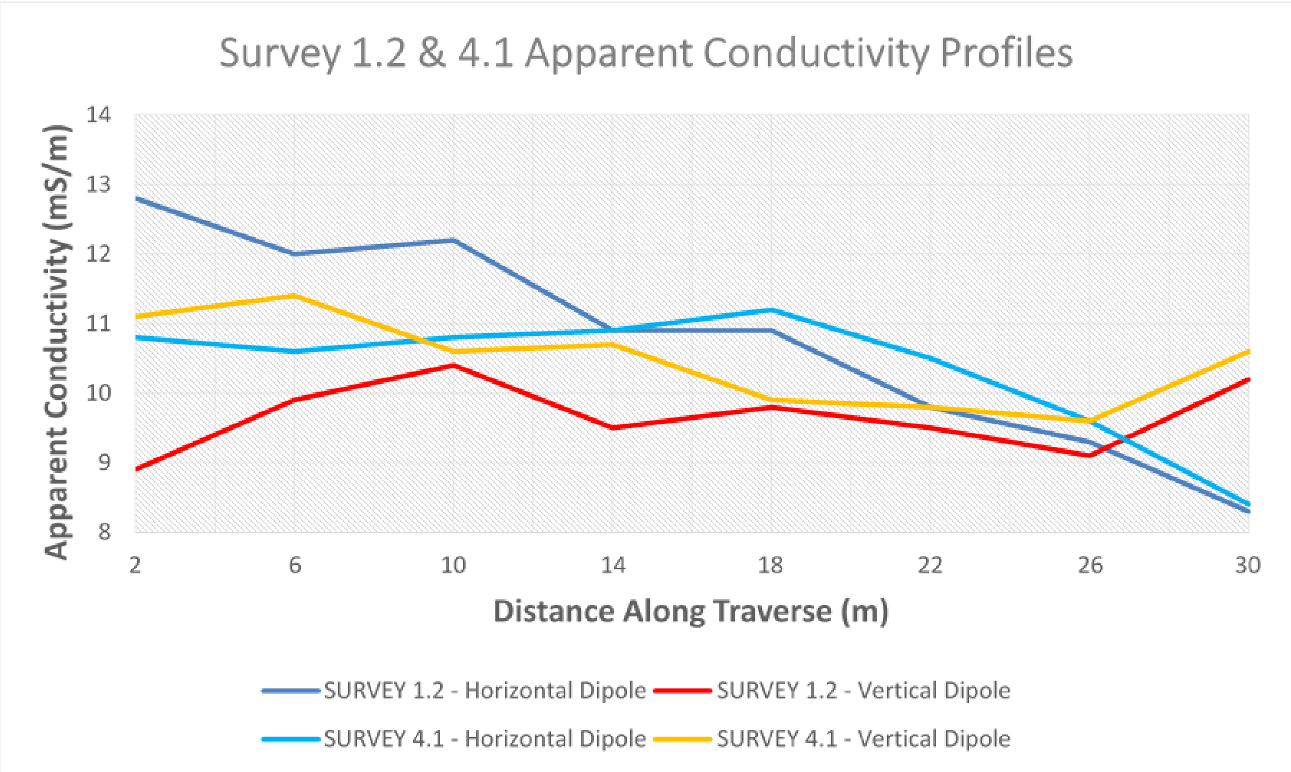
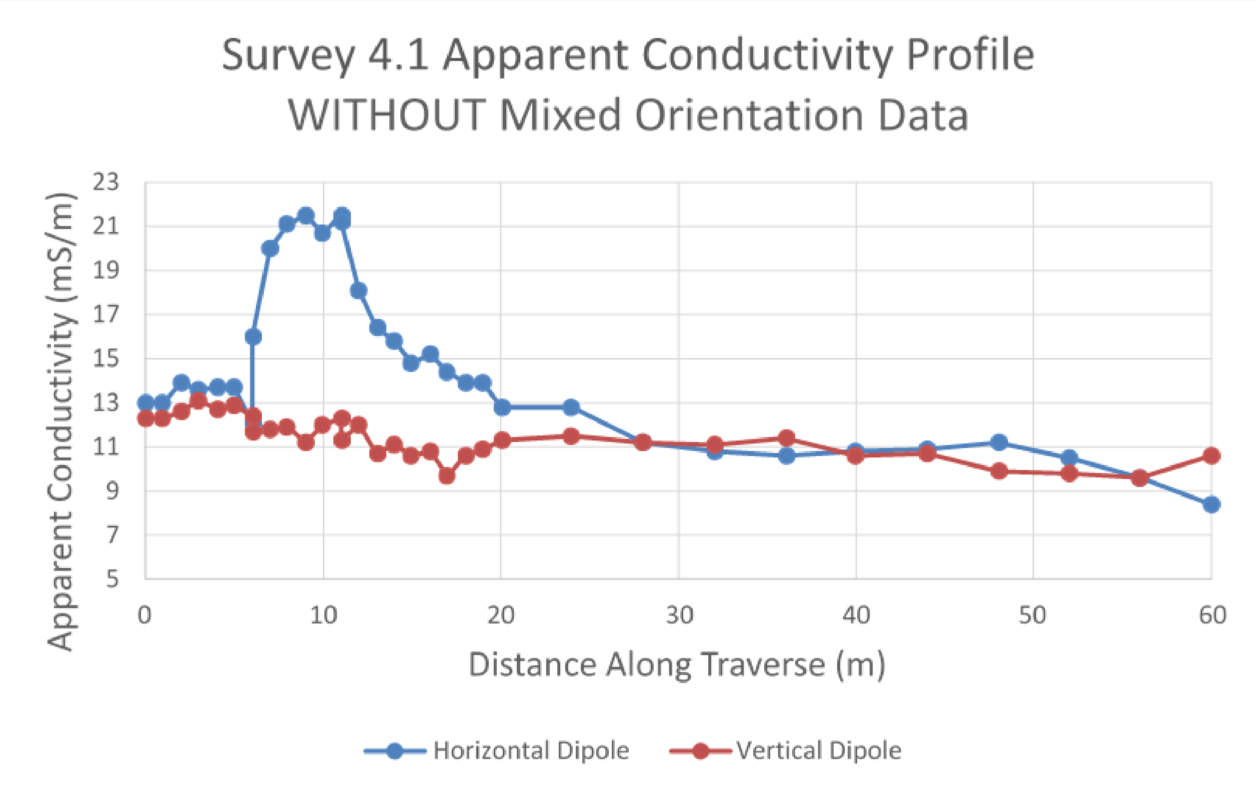


Figure 19 - Conductivity profiles for both coil orientations for Surveys 1.2 and 4.1.

5.7 Varying the Coil Orientation from Co-Planar

For Survey 4.1, the effect of varying the coil orientation on conductivity values was investigated to see if we can gain more information of the subsurface with a mixed coil orientation. Values of conductivity were recorded for both coil orientations, as well as a third coil orientation with the transmitter coil in a horizontal orientation and the receiver coil in a vertical orientation. Figure 20a displays the conductivity profiles for both coil orientations without the mixed coil orientation. We can observe that in the vertical dipole orientation, there was a small decrease in values across the entire traverse from 13mS/m to 10mS/m. The horizontal coil orientation displayed an anomalous increase of conductivity values from 13mS/m to 23mS/m at 10m along the traverse. Following this increase, the values began to decrease across the traverse to approximately 9mS/m. With the mixed coil information as shown in Figure 20b, we can see that a contrast in conductivity values recorded from the other coil orientations highlighted in Figure 20a. The mixed coil orientation recorded values are in the order of 150mS/m – 200mS/m, which does not correlate with other coil orientation results along the traverse. The EM-34 device is nulled before a survey is performed, so that receiver only responds to changes in the secondary field. The design of the EM-34 meant that the coils were null coupled in the same orientation so the primary field detected by the receiver coil can be bucked-out and the receiver coil will record the vertical component of the secondary field. Therefore, a mixed coil orientation would not display an accurate true value of conductivity. This is because if the coil orientation is mixed, the receiver coil will not record the vertical component of the secondary field, but that of an angle to the secondary field. The EM-25 is an example of a survey that used a mixed coil geometry, yet the device was designed to measure tilt angle instead of conductivity to give information of the location of conductive ore bodies. The receiver coil was rotated so that a null reading was obtained, as the coil is aligned with the major axis of the polarisation ellipse, giving a tilt angle. This technique was designed to locate deep conductors, with the EM-34 designed differently to obtain terrain conductivity. Therefore, the mixed coil orientation should not be used in any EM-34 surveys.



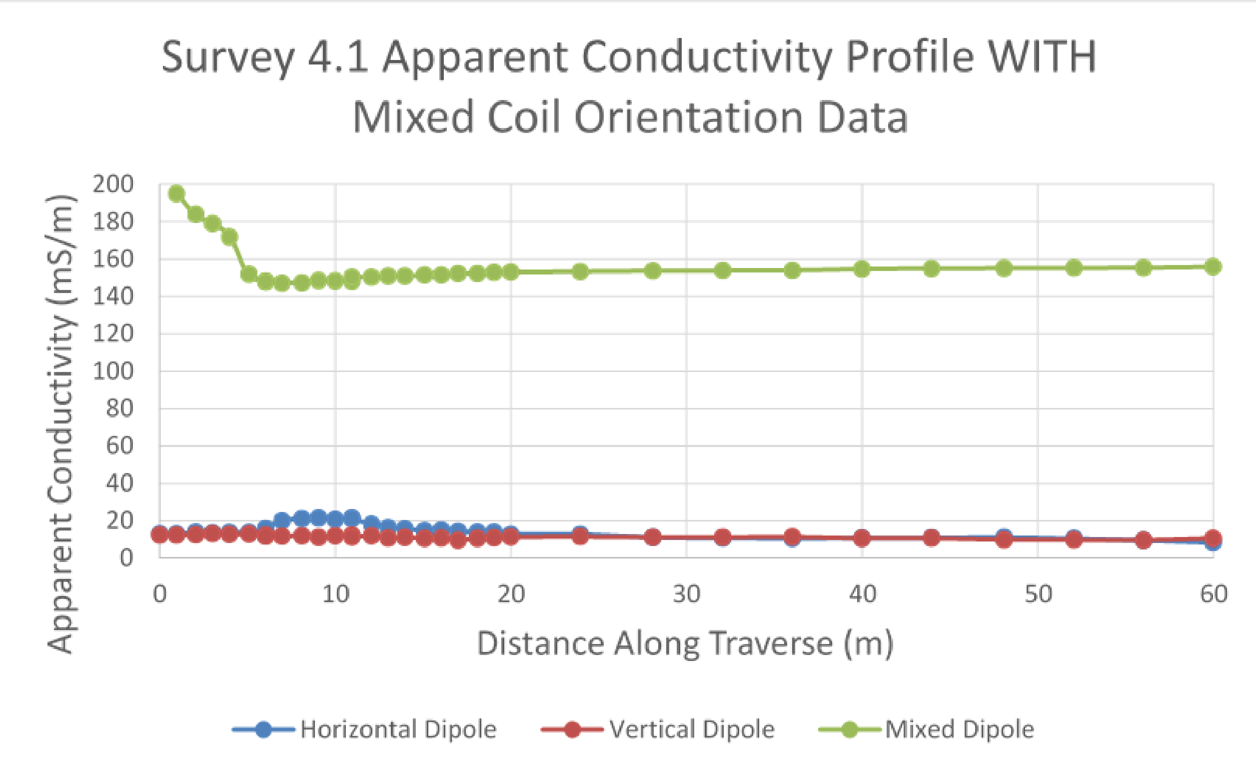
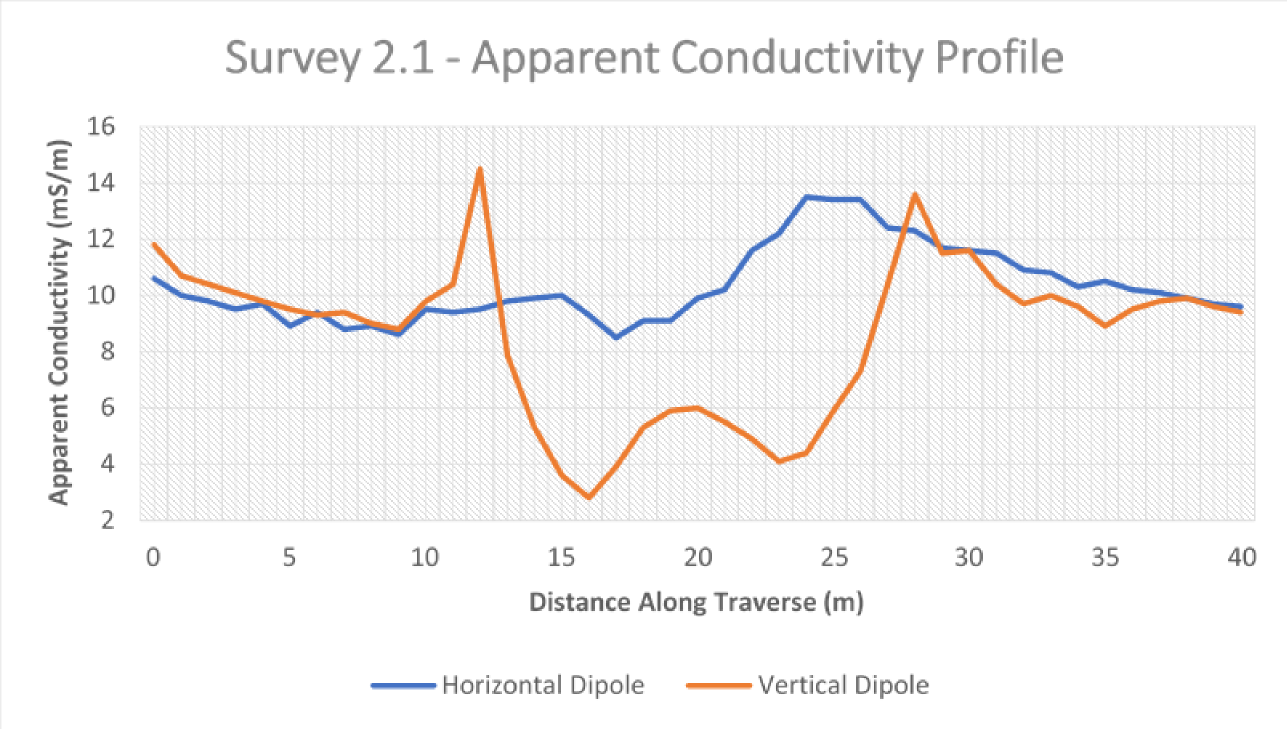


Figure 20 a) Conductivity profiles for both coil orientations for Survey 4.1. b) Conductivity profiles for Survey 4.1, including mixed coil orientation data.

5.8 Varying the Topography of a Traverse

As highlighted in Figure 13, the working area experienced a showed topographic variation in the form of a 3m slope, with a slope identified in Figure 13. We launched an investigation into the output of the EM-34, in particular the separation readings, when an EM-34 survey was conducted on land that is not flat. The traverse for Survey 2.1 experiences a change in topography with the traverse sloping downwards from north-east to south-west at a section from 10m to 25m along the traverse, and so we can analyse a 40m section of the north-eastern side of the traverse for Survey 2.1 to analyse if there is any major variation in conductivity or separation values. Figure 21a shows that between 0m - 10m, both coil orientations show a decrease in conductivity from 12mS/m to 9mS/m. Yet, between 10m and 28m, the conductivity profile for the vertical coil orientation displays a parabolic shape, ranging in conductivity values of 3mS/m to 14mS/m. The horizontal coil orientation displays a general increase in conductivity in this duration from 10mS/m to 14mS/m. Between 28m and 40m, the conductivity profiles for both coil orientations show a strong correlation, with both profiles showing a decrease in conductivity values from 14mSm down to 9mS/m. It is clear to see the deviation in conductivity profiles exists when the traverse is not flat. Figure 21b shows that at points of 10m and 25m along the traverse, the separation values for the vertical dipole orientation display readings that are beyond ±300. These points of deviation roughly correspond to the edges of the slope highlighted in the traverse and the points in the conductivity profiles where the values for both coil orientations displayed a low correlation. Therefore, the conductivity profile for the vertical coil orientation between 10m – 25m is not representative of the true terrain conductivity, with the change in topography directly affecting the accuracy of conductivity profiles in the vertical coil orientation. However, the horizontal coil orientation remains unaffected to changes of traverse topography.



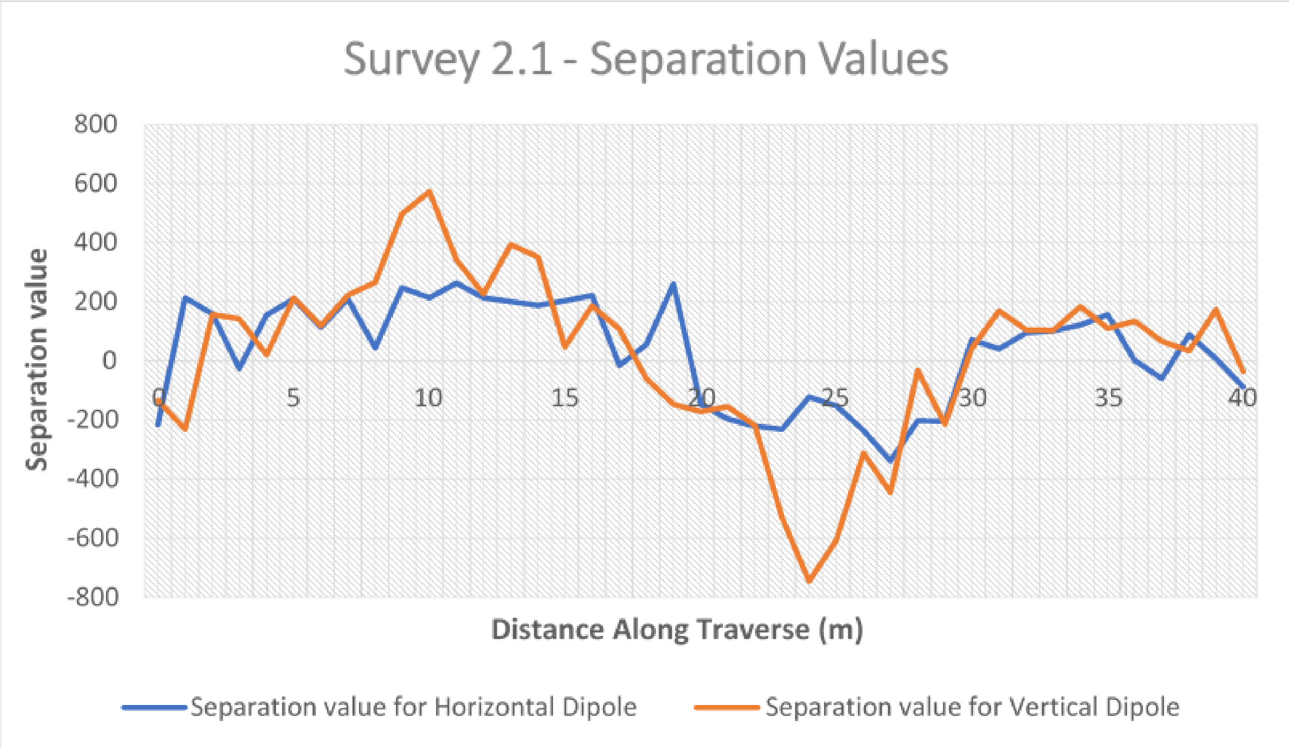


Figure 21 - a) Conductivity profiles for both coil orientations for a 40m section of Survey 2.1. b) Separation values for both coil orientations for a 40m section of Survey 2.1

5.9 Response of an EM-34 Survey in a Region of Anomalous Conductivity

Figure 13 highlights a region where surveys before our EM-34 surveys have identified a buried conductor beneath the surface. The analysis of Surveys 2.1, 2.2 and 3.2 will allow us to view the response of an EM-34 survey when a buried conductor, gaining information on the geometry of the conducting body. By varying the intercoil spacing, we can inspect the extent of the depth of the conducting body. In Survey 2.1, between 0m and 50m, values of conductivity for both orientations varied from 4mS/m to 14mS/m for this duration along the traverse, as shown by the conductivity profile in Figure 22, with the parabolic shape identified in the vertical dipole orientation. From 50m – 80m, the conductivity increased in the horizontal coil orientation, from approximately 10mS/m to 50mS/m over a 30m distance along the traverse, with conductivity readings decreasing to 30mS/m and then increasing to 40mS/m from 80m – 90m. In the vertical coil orientation, negative conductivity values were recorded from 64m to 70m, dropping to -24mS/m. From 70m – 80m, the conductivity rapidly rose to values in the range of 60mS/m – 70mS/m, before rapidly decreasing to negative conductivity values between -10mS/m and -30mS/m along the traverse between 80m and 90m.

Breaking down the trend in the vertical orientation, the original increase in conductivity values is due to the receiver coil moving closer to the conducting body. So too, is the transmitter coil. With greater primary field flux across the body, induced eddy current amplitude and resulting secondary magnetic field strength increases. This also contributes to a larger measured receiver response. As the receiver coil continues to move closer to the target, the vertical component of the secondary magnetic field becomes smaller, and eventually zero over the target. At this point, the secondary field vector is horizontal, and the measured conductivity will go to zero. As the system continues along the traverse over the body, eventually the receiver and transmitter coils will be on opposite sides of the body. Since the transmitter is still on the same side of the target as above, eddy current direction remains the same, as does the resulting secondary magnetic field. However, the receiver coil is detecting a negative secondary field, as its polarity is opposite to the primary magnetic field, hence the negative conductivity observation. When the transmitter coil is immediately above the target. the transmitter coil is null-coupled with the body, meaning magnetic flux is zero, so no eddy current is induced. With no eddy current, there will be no secondary field to measure, so conductivity values will now go to zero. When both transmitter and receiver coils have moved over the body, the secondary magnetic field direction is reversed, since the direction of induced eddy currents has reversed. and measured secondary field polarity is now back to positive, hence the observation of large positive values of conductivity measured.

Overall, the presence of a conducive body will create a parabolic shape in the conductivity profile, with negative conductivity values recorded. Figure 22 shows a repeated pattern of a parabolic shape in the conductivity profile between 60m – 74m and the most southwestern edge of the traverse, suggesting that 2 conductive bodies in close proximity have been observed. We can also observe the peak to peak distance of the parabolic shape, as the distance between the anomaly peaks between 60m – 74m is roughly the same as the intercoil spacing, indicating that a body is present at this point along the traverse between depths of 7.5m and 15m. However, since the EM-34 was designed to measure terrain conductivity and not metallic conductivity, we cannot trust the values of conductivity obtained to represent the true conductivity of the anomalous body, as the low induction number condition no longer applies. This is because the response from metallic conductors is more in-phase than out of phase with the primary field. This results in the receiver coil generating an in-phase response both to the primary field and to the in-phase component of the secondary field. This secondary field may either add or subtract from the primary field. This effect will disturb the calibration of the EM-34 because the bucking voltage is a fixed value and so the receiver coil will need to be moved until the total in-phase component (primary plus secondary) equals the bucking voltage.

We can view the results from Survey 2.2 in an attempt to gain the lateral extent of the underlying conductive body and view if the negative conductive response is observed along an adjacent traverse. The results from Survey 2.2 show a similar trend in conductivity profile shape from Survey 2.1, but the values of conductivity differ as seen in Figure 23. In the horizontal component, a general increase in conductivity values is recorded across the traverse from 10mS/m to 40mS/m. The vertical component shows she shape of the parabolic pattern observed in Survey 2.1, yet no conductive values were recorded. This is shown by a general increase from 20mS/m to 35mS/m between 0m and 10m, followed by a decrease in conductivity to approximately 12mS/m between 10m and 20m, then a swift increase in conductivity between 20m and 30m, with conductivity values reaching up to 58mS/m. This observation in the vertical col orientation can be interpreted as the system recording the effects of the edges of the metallic bodies that was located in Survey 2.1, with the vertical orientation showing a similar anomaly trend that was identified as a parabolic shape in Survey 2.1. However, negative values were not reached, leading us to believe that this traverse was not directly over the conductive body. This variation also backs up information that the metallic body is in the vicinity, yet the values of conductivity will not represent the true terrain conductivity of the subsurface geology.

With the explanation that Survey 2.1 detected the conductive body and Survey 2.2 detected effects from the edges of the body, we can suggest the geometry of the body to be a pair of isolated bodies and not a continuous linear feature. However, since the EM-34 measures terrain conductivity, we cannot fully say that the values of conductivity are representative of the true conductivity of the conducting bodies that have been observed.

To get an insight into the extend of the depth of the conductive bodies observed, we can evaluate and compare results from Surveys 2.1 and 3.2 that was recorded with a different intercoil separation in the vertical coil orientation. We can observe from Figure 24 that values of conductivity increase from 179mS/m to 186mS/m for a 20m intercoil separation across the traverse, with no negative conductivity values recorded. This observation gives us more information about the extent of the depth of the bodies, with the bodies likely to be confined at a likely depth above 30m.

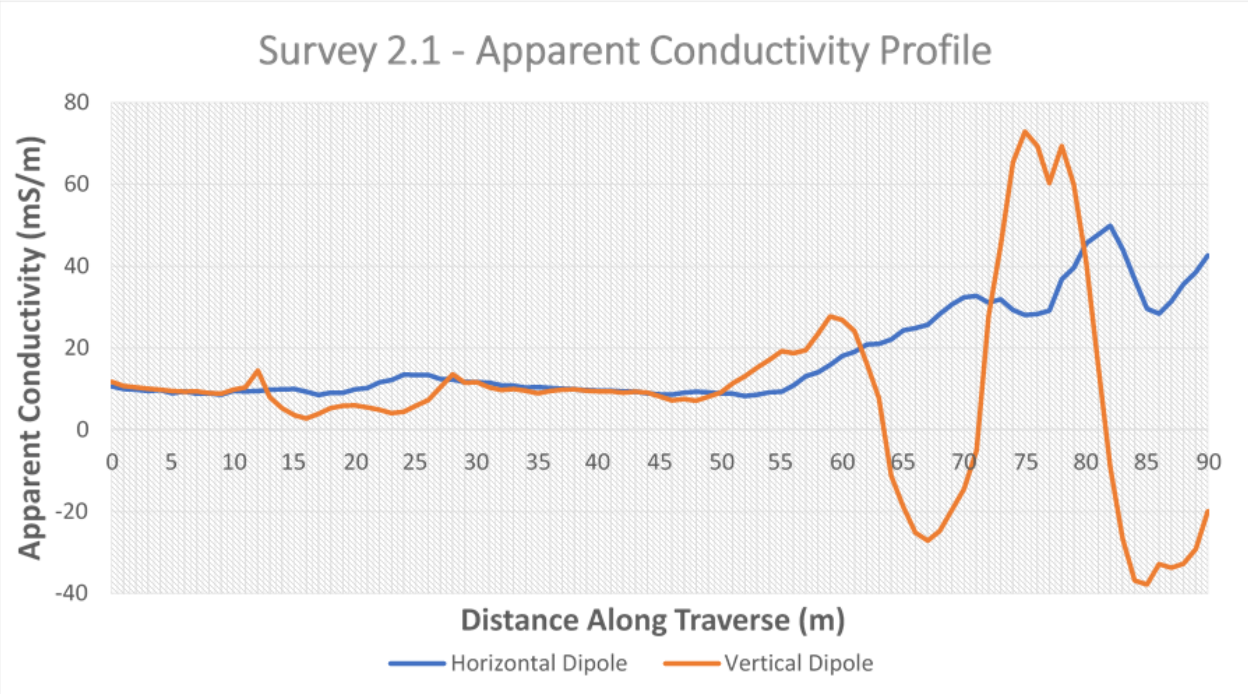


Figure 22 - Conductivity profiles for both coil orientations for Survey 2.1.

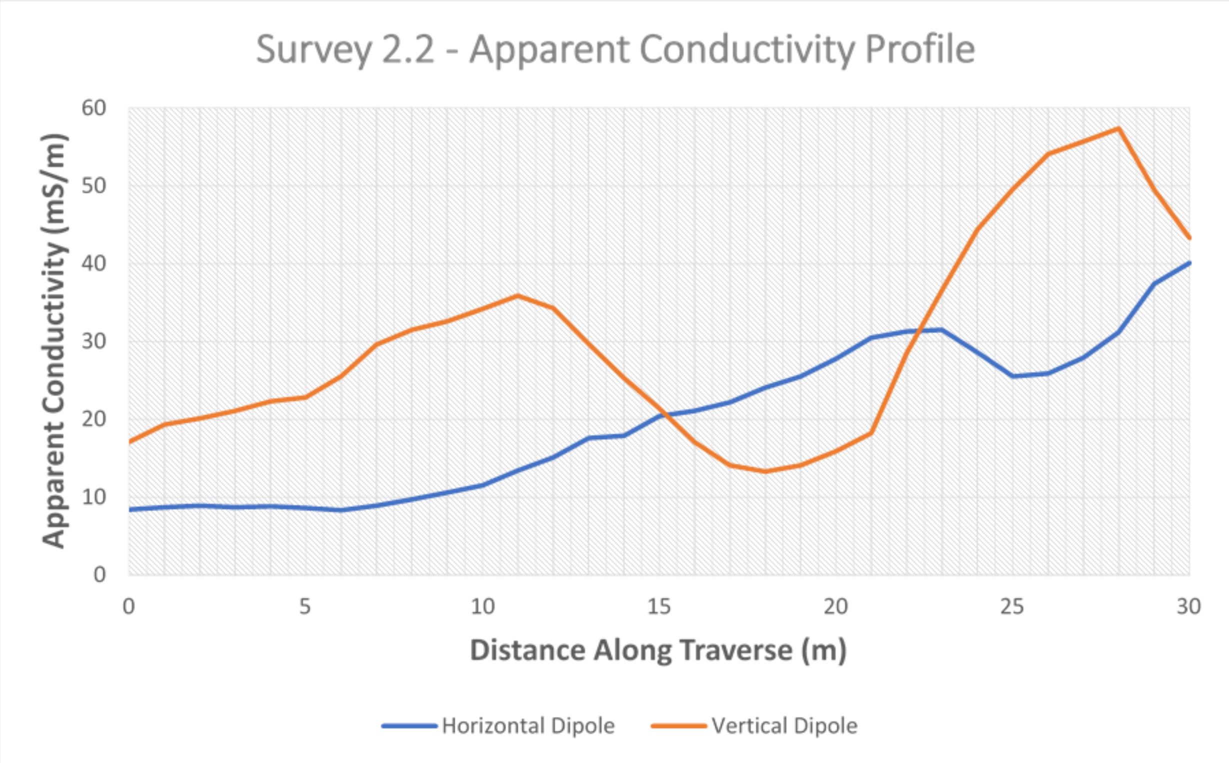


Figure 23 - Conductivity profiles for both coil orientations for Survey 2.2.

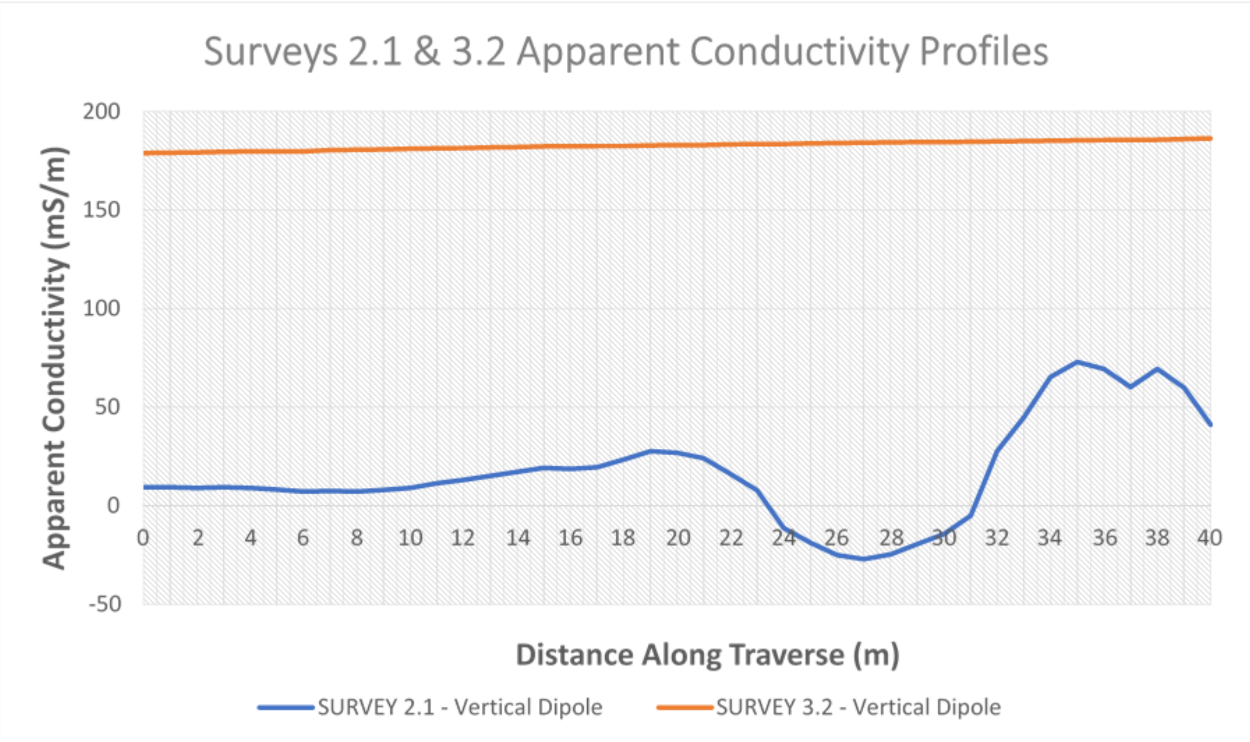


Figure 24 – Conductivity profiles for the vertical coil orientation for Surveys 2.1 and 3.2.

Chapter 6

In-depth Analysis Between EM-34 and Relevant Survey Methods

To directly compare the EM-34 with other relevant survey techniques, we can make comparisons between the EM-34 results and the conclusions reached with this survey technique with EM-31 and ERT survey results. This comparison will allow us to recognize if the interpretations made with the EM-34 of the subsurface geological setting are acceptable.

6.1 A Comparison of the EM-34 with the EM-31

The Geonics EM-31 maps groundwater contaminants or any subsurface features associated with changes in the ground conductivity. The electromagnetic inductive technique used for the EM-34 is also used for the EM-31, making measurements without electrodes or ground contact. Ground conductivity measurements are given in mS/m and are read directly from an integrated DL600 data logger, which allows for results to be displayed as a Real-Time (RT) graphical presentation. The coils are at a fixed intercoil separation of 3.66m, giving a total exploration depth of approximately 6m.

EM-31 surveys were conducted alongside EM-34 surveys within the same region as the surveys conducted in 2020, with Figure 25 showing the variation of ground conductivity in 3 30mx20m areas. The EM-31 survey displays the background terrain conductivity to be in the region of 8mS/m-12mS/m. If we compare this to values obtained from an EM-34 survey displaying an accurate output terrain conductivity for the horizontal coil orientation with a 10m intercoil separation, we can analyse Survey 1.3 in Figure 16 as this survey provided conductivity readings around the 10mS/m scale. This shows that the output of terrain conductivity from EM-34 and EM-31 surveys agree with one another, with the EM-34 giving values of terrain conductivity to a larger spatial resolution. A clear conductive anomaly with negative conductivity was detected by the EM-31, which spatially aligns with the negative conductivity readings observed with the results of Survey 2.1 in Figure 22. Both survey techniques can detect locations where ground conductivity varies, yet the EM-34 results show these changes to a higher level of spatial resolution due to a station by station approach along a traverse, allowing for more data to be acquired by the EM-34 along a given traverse. The EM-31 displays a broad area of negative values, meaning that interpretations cannot be made due to a lack of knowledge of the anomaly characteristics. Conductivity profiles generated from EM-34 surveys, in particular Survey 2.1, allowed to evaluate the number of bodies that were responsible for the negative conductive region detected by the EM-31, allowing us to gain more information about the conductive region to a higher level of resolution. This is because the shape of the anomaly on the conductivity profile produced by EM-34 surveys gave us the location of the conductive body along a traverse, allowing for a more precise detection of the anomaly, unlike the EM-31, which displayed a negative conductive region, giving a less precise detection in the location of the body. The ability to vary the intercoil spacing and assess profiles for different intercoil spacing allows us to give us information on the extent of the depth of the conductive. This is something that cannot be achieved by the EM-31 as the device is limited in exploration depth.

On the whole, The EM-31 survey is more time-efficient than the EM-34 and so a greater area can be surveyed, giving locations where the ground conductivity varies, yet the variation in intercoil separation allows for a greater exploration depth to be reached for any EM-34 survey and the apparent conductivity profiles generated to allow for a more detailed interpretation of the ground conductivity, so we can gain a higher level of knowledge of characteristic anomalies. The EM-31 acts as a reconnaissance electromagnetic survey, locating areas of anomalous conductivity, yet the EM-34 can gain characteristic interpretations of the geometry and extend of the anomaly, as well as giving a higher lateral resolution output of soil conductivity.

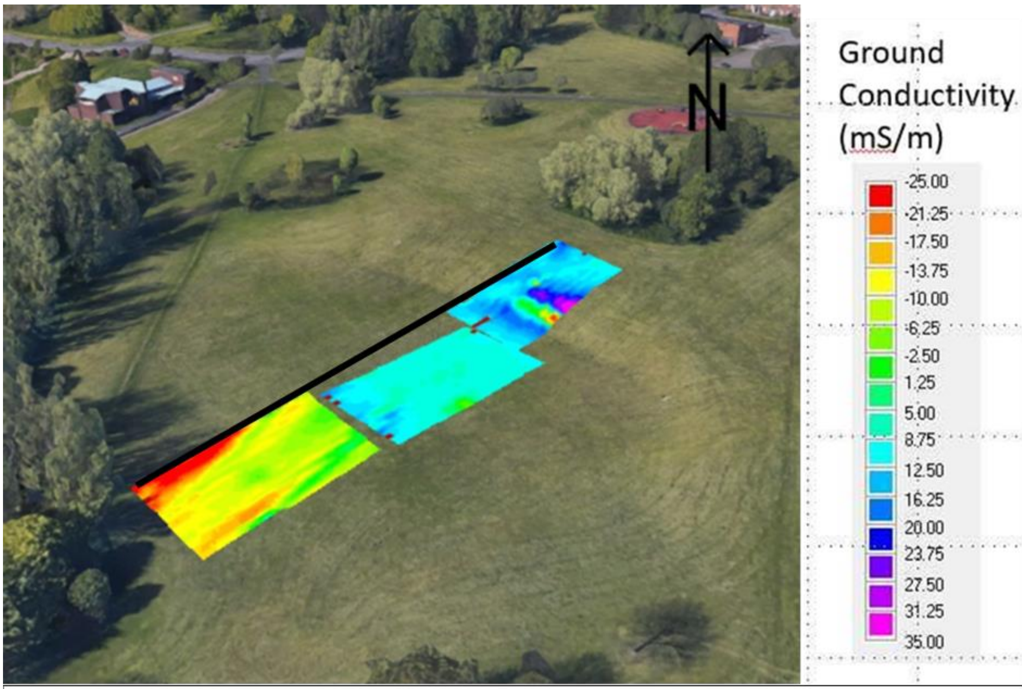


Figure 25 – EM-31 survey results displaying the ground conductivity of 3 30m x 20m areas inside the areas of interest. The black line represents the location of Survey 2.1.

6.2 A Comparison of the EM-34 with ERT

The Electrical Resistivity Tomography (ERT) technique is a technique used to classify the sub-surface materials in terms of their electrical properties. Variations in electrical resistivity typically correlate with variations in lithology and water saturation, which may be used to map groundwater. Acquiring resistivity data involves the injection of current into the ground by a set of electrodes and then the resulting field is measured by a corresponding set of potential electrodes. The electrodes are set up in a chosen array, which was a Wenner Array. Resistivity data is then obtained by the electrode pairing to build up a pseudo cross-section of apparent resistivity beneath the survey line by using a software called Res2D, giving an output of an image of ground resistivity, with the depth of investigation depends on the electrode separation and array geometry. The electrode spacing was 1m, and so the effective exploration depth reached to about 5m.

ERT surveys were conducted alongside the EM-34 surveys in the same region as the surveys conducted in 2020., Figure 26 shows a collection of ERT traverses that approximately match in location with the 90m traverse created in Survey 2.1, with each ERT traverse at a length of 32m, corresponding to 32 electrodes. We can observe from Figure 27 that no anomalous bodies have been located by the ERT towards the north-eastern side of the target area from Lines 2 and 3. This finding is in agreement with Survey 2.1 results, with an approximation of the background resistivity ranging from 119Ωm to 186Ωm. We can observe from the ERT profile in Figure 27 that the ERT records a body with a low resistivity of 31Ωm at the maximum depth of the profile towards the south-western side of the target area from Line 1, indicating a body with a high conductivity is present. We can observe the shape of the top of an anomaly as being curved from the bottom of the ERT profile, giving us an insight into the geometry of the conductive body. This shows that both ERT and EM-34 surveys show characteristics of the anomaly. However, the EM-34 surveys have enabled us to acquire information of the extend of the conductor that cannot be seen from an EM-34 survey, and so more information is gained from EM-34 surveys due to the larger exploration depth. It can be argued that increasing the electrode separation will give a larger exploration depth, yet conductive contrasts can be detected with a smaller intercoil separation than electrode spacing, so increasing the electrode spacing will result in a loss of detail in conductive contrasts of the underlying geology. Furthermore, the EM-34 profiles display conductivity contrasts with a larger resolution as values are directly recorded at each point along a traverse, allowing us to observe the number of conducting bodies in the subsurface. However, an ERT survey displays resistivity profiles in the form of an image which categorises resistivity in the form of different colours in a scale bar. This means that resolution is lost on resistivity readings, questioning the accuracy of results of an ERT survey as EM-34 surveys can detect lateral and vertical variations in ground conductivity to a larger amount of detail, forming the basis of a more rigorous interpretation of terrain conductivity. Moreover, the EM-34 is a passive survey and does not rely on a stable connection into the ground. However, an ERT relies on a good connection between the electrodes and the ground. This connection can be affected by wet or arid ground conditions, as well as certain geological conditions including a high surface resistivity such as sand or gravel.

On the whole, the ERT technique displays the electrical properties of the subsurface, displaying near-surface features, yet the EM-34 can reach a larger exploration depth with a variety of intercoil spacing and coil orientations. Also, the inductive technique that the EM-34 uses is not affected by near-surface conditions. The station by station technique along traverses of the EM-34 allows for a greater spatial resolution of ground conductivity, with electrical contrasts observed to a larger accuracy than the ERT technique.

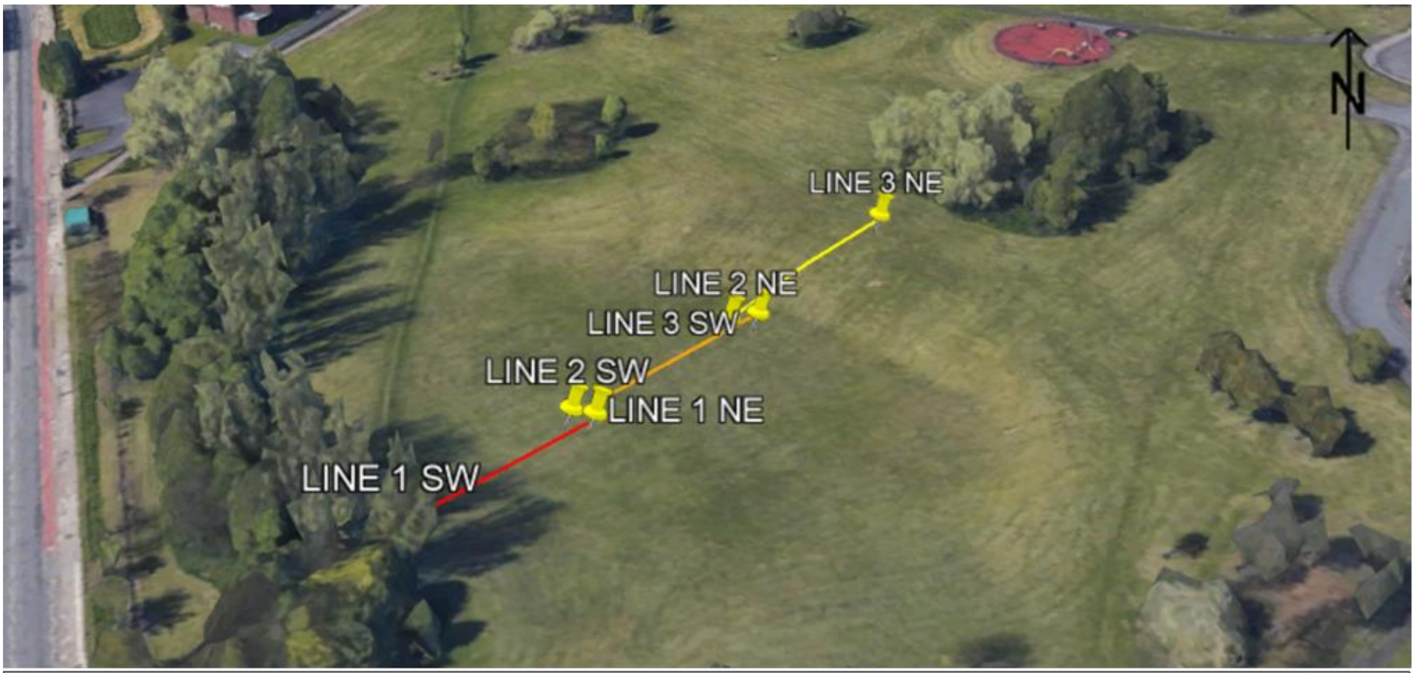


Figure 26 – The locations of all ERT surveys performed in Everton Park.

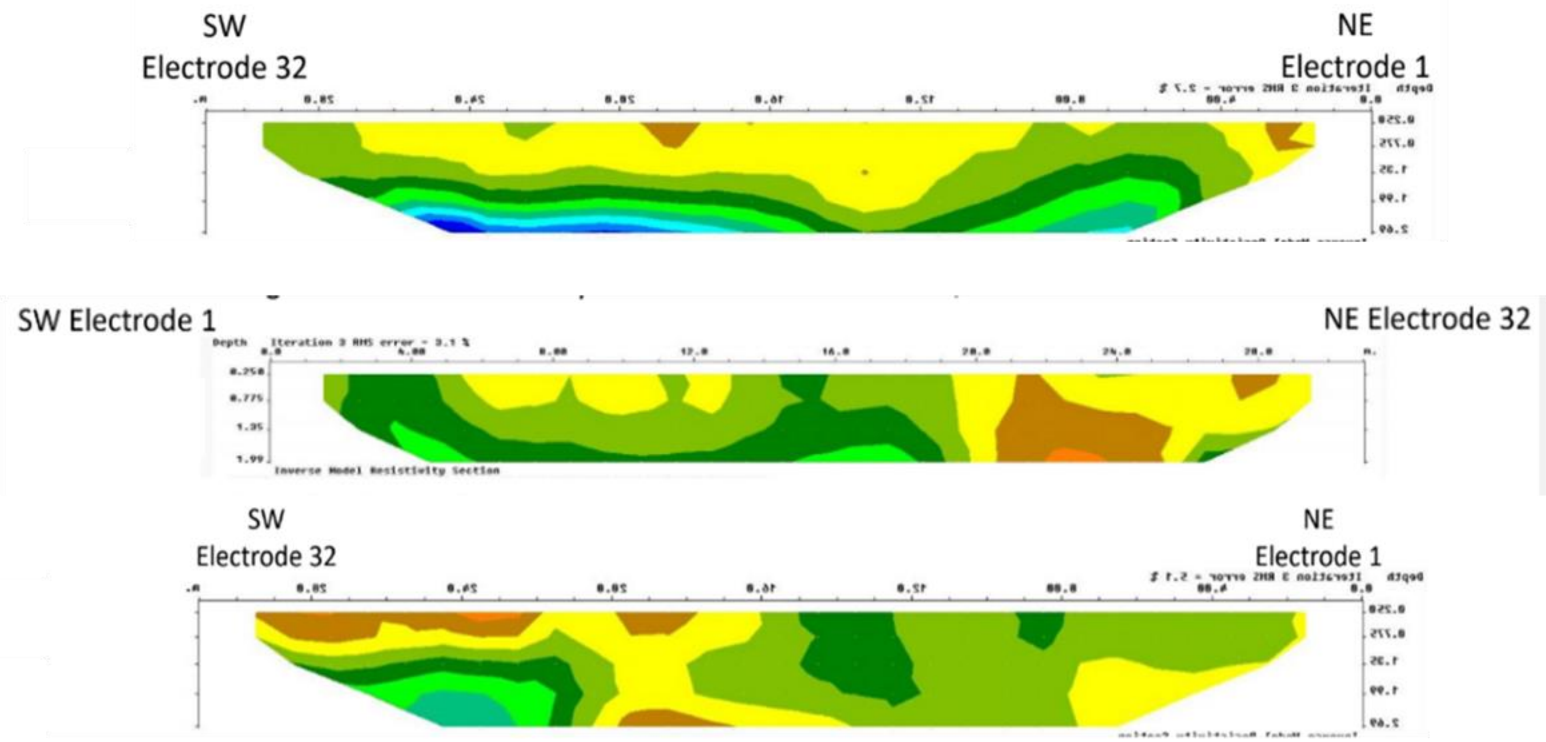


Figure 27 - A combination of all ERT surveys performed in Everton Park, all running from south-west to north-east.
Top – ERT profile of Line 1
Middle – ERT profile of Line 2
Bottom – ERT profile of Line 3

Chapter 7

Summary and Future Work

7.1 Summary

The EM-34 has been proved to be a successful technique for the acquisition of terrain conductivity, leading to the ability to map deeper groundwater features, such as contaminant plumes, successfully for groundwater explorational purposes. The low induction number condition allows for measurements of conductivity to be made based on the phase of the secondary magnetic field to the primary magnetic field, with the phase differences between the 2 fields providing a link to the conductivity of the ground. The effective exploration depth of the technique can reach up to 60m with the use of 3 intercoil spacings and 2 intercoil separations. By varying the intercoil survey along a traverse, we can gain more terrain conductivity information by observing the variation of conductivity to depth. The station by station technique along traverses allows for a survey with a high spatial resolution, accompanied with a measure of accuracy for each reading with the separation output of the EM-34. The survey technique can act as a useful complement to other methods of conductivity determination as we can gain characteristic information of any anomalous conductive bodies, including the depth and shape of the body. The profile display of EM-34 results allows for more interpretations to be made of a target area including underlying conductive bodies in comparison to the EM-31, as well as recording terrain conductivity to a higher spatial resolution as lateral variations in terrain conductivity was observed to a greater level of detail during EM-34 surveys. Any electrical contrasts in the subsurface can be detected with a smaller intercoil spacing than electrode spacing, allowing the EM-34 to provide surveys of a larger exploration depth while maintaining a high level of accuracy on conductivity readings. We have also outlined the ability for an EM-34 survey to be reproducible between surveys created on separate days in the same location, yet for this to be maintained, the sensitivity range needs to be constant between surveys. We have also have highlighted that the EM-34 relies on the coils to be exactly co-planar and at the correct separation, as conductivity values can diverge from the true value of conductivity at a certain point with the coils not co-planar or at the correct spacing. This leads to the device becoming sensitive to errors on conductivity readings Also, problems arise when any EM-34 surveys are conducted on land that is not flat, as the LIN condition is not obeyed and so inaccurate conductivity readings may be produced, especially in the vertical coil orientation.

7.2 Future Work

If the opportunity was available to explore the EM-34 in greater detail, then the usage of the 40m intercoil spacing for an EM-34 survey would provide an insight to terrain conductivity at a larger exploration depth, since the 40m separation cable was not used in any surveys discussed. Conducting ERT/EM-31 and EM-34 surveys simultaneously would allow for a more accurate assessment of how the EM-34 is useful complement to other methods of conductivity determination. In particular, surveying over a conductive body with known characteristics and depth would determine which survey would portray the conductive body to the largest level of accuracy, as well as observing if the anomalous negative conductivity response of the EM-34 is consistent with other future surveys and if the negative conductivity response can give more characteristics of a conducting body other than the location along a traverse. Conducting an EM-34 survey with all 3 intercoil separation along the same traverse with a changing coil orientations would allow us to back up the ability of an EM-34 survey to be reproducible. Conducting this type of survey would also allow for a different survey output, as programs such as IX-1D v3 (Reynolds, 2011) can be used to produce a layered Earth model. The opportunity to display survey results other than the form of a conductivity profile would allow for more conclusions of the terrain conductivity to be made, including the ability to estimate layer thicknesses.

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7.4 Appendix

EM34-3 Simplified Operating Instructions Manual

INTRODUCTION

This simplified manual supplies information regarding the operating information of the EM34-3. The EM34-3 measures the average conductivity of a volume of the ground below the instrument, depending on the intercoil separation, for groundwater exploration. There is a selection of 3 intercoil spacings (10m, 20m, and 40m) and two dipole modes (horizontal and vertical dipole modes) to obtain vertical electrical sounding. The horizontal dipole mode involves holding the coils perpendicular to the ground (see Figure….) so that the coils are upright. This is usually achieved by holding the coils in between the operator's legs. The vertical dipole mode involves lying the coils flat on the ground so that the coils are parallel to the ground. There is a selection of 3 conductivity ranges (10,100,1000mS/m). A full equipment list is shown below…

- A transmitter and receiver coil
- Self-contained dipole transmitter console
- Self-contained dipole receiver console
- Separation cable (10m, 20m or 40m)
- Receiver short cable
- Transmitter short cable

POST SET UP

Before conducting any surveys, an initial set up is required. Make sure that the survey area is free of any cultural interference and man-made conductors, such as power lines, buildings etc. Another requirement is to check the battery level of the machine to make sure that a survey can be conducted. To do this, connect the transmitter console to the transmitter coil using the appropriate short cable. Note that when connecting cables to any console, a click should be heard when the connection has fully been made. This is achieved by turning the connectors clockwise when connected until a click is heard. Put the level switch to the normal position and switch on the console. The needle on the battery monitor indicator should be in the green area. This shows that the console is at a significant battery level. To check the battery level on the receiver on, turn the power on and change the separation switch to BATT+. If the reading is above 4.5, then the console is at a significant battery level.

SET UP

Once battery levels are at a significant level, then the EM34-3 can be set up. Retain the connection between the transmitter coil and console and connect the receiver coil to the receiver console via the “COIL” connector with the appropriate short cable. Again, a click will be heard when the connection is complete. Having determined the coil separation used for the survey, connect the separation coil – one end to the 8-pin connector on the transmitter coil and the other end to the “REFERENCE” connector on the receiver console. Set the “SEPARATION” switch to the selected intercoil separation value. Make sure that the “LEVEL” switch on the transmitter console is switched to “NORMAL”. Machine set up is now complete.

CONFIGURATIONS

There are a series of periodic daily checks that should be made before conducting any survey to make sure that the survey is accurate,

Gain Check

This procedure is done to check that the receiver coil is working to ensure that the instrument will be operational. Maintaining the coils in a co-planar fashion, adjust the coil separation to obtain approximately a zero reading on the “SEPARATION”. When moving the coils, ensure that the coils are facing in the same direction. This is done by checking that the red circles on the bottom of the coils are facing the same direction. Set the sensitivity range to 1000mS/m and bring the receiver coil towards the transmitter coil until the “SEPARATION” reading reads 1000. The distance that the receiver coil has moved should be approximately 24.2% of the intercoil spacing. If this is true, then we have checked that the instrument is fully operational.

Electronic Nulling

This procedure is done to remove any offsets in the output circuitry. This is done by leaving the equipment set up and leaving the transmitter and receiver on. Then, depress the “NULL” buttons. Both of the meter readings should go to zero. If this does not happen, release the lock on the corresponding null control and adjust the “NULL” control to zero the meter. Once the meter reads zero, tighten the lock on the null control and release the corresponding “NULL” button.

TAKING A READING

With the instrument fully operational, we can now begin to take readings. The device will be measuring apparent terrain conductivity in mS/m in either dipole orientation. Set up a working traverse with a tape measure or a measuring device and decide an interval between taking readings. Adjust the “SEPARATION” switch to the chosen intercoil separation. At each position, it is essential to make sure that the red circles on the coils are facing in the same direction and that the operators are stood still so that clear readings can be taken. The receiver operator should place himself so that the “SEPARATION” readings should read zero ± 300. The “SEPARATION” reading is displayed to show the accuracy of the measurement (how close the reading is to zero is an indication of the accuracy of the measurement). To minimize errors, the coils should be held at a separation so that they are held at the respective separation by ±0.7m-1m. The “SENSITIVITY RANGE” switch will alter the resolution of the reading so that a full-scale meter reading will be given. Readings can be taken for each dipole orientation at each position along a given traverse based on the orientation of the coils (perpendicular to the ground = HORIZONTAL dipole mode, parallel to the ground = VERTICAL dipole mode).

NOTES ON INSTRUMENT ORIENTATION

It is important to make sure that the coils are kept in a coplanar alignment at all times during a survey. This is because, in the vertical dipole orientation, there is a greater sensitivity to misalignment of the coils, leading to an increase in the chances of an error in our results as the secondary field generated by the conducting body under inspection will be approximately 45º to the horizontal, pointing away from the transmitter. In the horizontal dipole mode, the secondary field is perpendicular to the plane of the receiver coil, leading to the measurements made in this orientation being relatively insensitive to coil misalignment. It is still important to make sure that the coils are in a coplanar orientation.

NOTES ON SURVEY INTERPRETATION

The EM34-3 is designed to map normal soil and rock electrolytic conductivity rather than the electronic conductivity of metallic minerals. This electrolytic conductivity is on a smaller magnitude than metallic conductivity. Therefore, high values of terrain conductivity (the indicated conductivity) is no longer a true representation of the actual conductivity. This effect is more severe for the vertical dipole configuration in comparison to the horizontal dipole configuration.

Furthermore, the horizontal dipole mode will be more sensitive to variations in the near-surface material, unlike the vertical dipole mode as this will be more insensitive to such changes.