11 Electromagnetic Survey Techniques

Electromagnetic induction technology (EMI or EM) and other soil conductive technologies (e.g. resistivity) have been used for decades to map ground conductivities in mineral exploration (Keller and Frischknecht 1966). Early application in agriculture was for salinity management in irrigated systems (Dejong, et al. 1979). There is now great interest from dry-land farming enterprises, particularly the grains industry, where the management of crops at a greater spatial resolution is now achievable (Corwin and Lesch 2003).

EM sensors only measure bulk soil electrical conductivity. Other soil properties may be inferred using EM data; however calibration of EM readings against other observed data is necessary. For agricultural applications the most common variables that have been found to correlate well with EM data are: soil water content, soil clay content and soil salinity (Johnson, et al. 2001). Unfortunately, temperature (air and soil) effects make universal calibrations complex. Additionally, the mineral type and content of the soil will also affect the calibration. As a result, universal calibrations, whilst theoretically attractive, prove very difficult in practice (Corwin and Lesch 2003).

The lack of a workable universal calibration to relate ECa to other soil properties makes it necessary to establish these correlations for each individual survey site. This may be achieved through analysis of soil cores taken at the same time as the soil conductivity survey (Corwin and Lesch 2003). Other variables, like potential rooting depth, that are functions of water, clay and salt content may also be applicable in some places. The detection of specific elements or compounds (e.g. phosphorous) can only be accommodated to the extent of the strength of the ECa co-correlation with water, salt and clay (Kitchen, et al. 2005). Other variables like drainage cannot be measured directly with EM because of the complex relationship between other components of the water balance equation and time. Thus, customised calibrations must be derived after a survey to establish what can and can not be measured with EM sensors. It is very site specific (Kitchen, et al. 2005).

11.1 Electromagnetic Induction

The electromagnetic (EM) geophysical survey method determines electrical properties of earth materials by inducing electromagnetic currents in the ground and measuring the secondary magnetic field produced by these currents. An alternating current is generated in a wire loop or coil above the ground’s surface. This alternating magnetic field generates circular eddy current loops in the soil below the coil. Each current loop generates a secondary electromagnetic field that is proportional to the current flowing in the eddy current loop. A fraction of this secondary electromagnetic field is intercepted by a second coil and the sum of these signals is amplified and formed into an output voltage, which is related to a depth-weighted bulk soil conductivity.
The receiver coil measures amplitude and phase of the secondary electromagnetic field. The amplitude and phase differ from the primary coil fields as a result of the soil properties, spacing of the coils, orientation of the coils with respect to the soil surface, and distance from the soil surface (Corwin and Lesch 2003). After compensating for the primary field, both the magnitude and relative phase (in-phase and quadrature-phase) of the secondary field are measured. The quadrature-phase component is converted to a value of apparent soil electrical conductivity (EC). This value represents an estimate of the local average soil EC. The depth of measurement is dependent on the instrument’s coil spacing, orientation, operating frequency, and the actual subsurface EC variations. The EC measurement for soils with EC < 100 mS m\(^{-1}\) is given by (Corwin and Lesch 2003):

\[
EC = \frac{2}{\pi \mu_0 f^2 s} \left( \frac{H_s}{H_p} \right)
\]  

(11.1)

where \(H_p\) and \(H_s\) are the intensities of the primary and secondary magnetic fields (A m\(^{-1}\)), \(f\) is the frequency of the system (Hz), \(\mu_0\) is the magnetic permeability of free-space (4\(\pi\) x 10\(^{-7}\) H m\(^{-1}\)), and \(s\) is the inter-coil spacing (m).

EM systems have been developed using a number of standard coil spacings and frequencies. Commonly used systems include EM31, EM34, EM38 and EM39.

### 11.1.1 EM31

The EM31 system uses a frequency of 9.8 kHz, with an inter-coil spacing of 3.66 m. The EM31 systems maps geological variations, groundwater contaminants or any subsurface feature associated with changes in the ground conductivity using an electromagnetic inductive technique that makes the measurements without electrodes or ground contact. With this inductive method, surveys can be carried out under most geological conditions including those of high surface resistivity such as sand, gravel and asphalt. The effective depth of exploration is about six meters, making it ideal for many geotechnical and groundwater contaminant surveys.

Important advantages of the EM31 over conventional resistivity methods include:

1. the speed with which surveys can be conducted.
2. the precision with which small changes in conductivity can be measured.
3. the continuous readout and data collection (logging) while traversing a survey area.

The in-phase component is especially useful for detecting shallow ore bodies and buried metal waste.
11.1.2 EM34

The EM34-3 has been particularly successful for mapping deeper groundwater contaminant plumes and for groundwater exploration. Using the same inductive method as the EM31, the EM34-3 uses 3 inter-coil spacings with separate operating frequencies (Table 11.1) to give variable depths of exploration down to 60 meters. With the 3 spacings and 2 dipole modes, vertical EC soundings can also be obtained.

Table 11.1: Inter-coil spacing and Operating Frequencies for EM34 system.

<table>
<thead>
<tr>
<th>Inter-coil Spacing (m)</th>
<th>Operating Frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>6.4</td>
</tr>
<tr>
<td>20</td>
<td>1.6</td>
</tr>
<tr>
<td>40</td>
<td>0.4</td>
</tr>
</tbody>
</table>

11.1.3 EM39

The EM39 system uses a frequency of 39.2 kHz. The EM39 provides measurement of the electrical conductivity of the soil and rock surrounding a borehole or monitoring well, using the inductive electromagnetic technique. The unit employs coaxial coil geometry with an inter-coil spacing of 50 cm to provide a substantial radius of exploration into the formation while maintaining excellent vertical resolution. Measurement is unaffected by a conductive borehole fluid or the presence of plastic casing. The instrument operates to a depth of 500 metres.

11.1.4 EM38

The EM38 system uses a frequency of 14.6 kHz, with an inter-coil spacing of 1.0 m. These systems are designed to be particularly useful for agricultural surveys measuring soil salinity. The EM38 system, shown in Figure 11.1, can cover large areas quickly.
In a relatively homogeneous soil profile, the EM readings from both the vertical and horizontal dipole modes are given by (Huth and Poulton 2007):

\[
EC = \int_0^\infty EC(z) \phi_c(z) \cdot \partial z
\]  \hspace{1cm} (11.2)

\[
EC = \int_0^\infty EC(z) \phi_h(z) \cdot \partial z
\]  \hspace{1cm} (11.3)

where \( z \) is the ratio of depth into the soil to inter-coil spacing, \( EC(z) \) is the electrical conductivity at depth \( z \) and:

\[
\phi_c(z) = 4z \left( 4z^2 + 1 \right)^{-\frac{3}{2}}
\]  \hspace{1cm} (11.4)

\[
\phi_h(z) = 2 - 4z \left( 4z^2 + 1 \right)^{-\frac{1}{2}}
\]  \hspace{1cm} (11.5)

The vertical and horizontal mode responses of an EM38 instrument are shown in Figure 11.2.

Soil water is a major driver of EM38 response. As moisture content changes and water redistributes within the soil profile the EM response will change (Johnson, et al. 2001). There can often be a direct correlation between soil volumetric water content.
Electromagnetic Induction

and the EM data in soils with uniform profiles; however the EM38 instrument also responds to dissolved ions, charged clay particles, soil structure, and organic matter. The EM38 system is particularly well suited to being mounted on a sled for towing behind an all-terrain vehicle with a Differential GPS and automatic data logger to acquire EM data at regular intervals as the vehicle travels back and forth across the area of interest. This process captures point data (Figure 11.3) that can be interpolated using tools such as a Geographic Information System (GIS).

Figure 11.2: EM instrument response as a function of soil depth and dipole orientation.

Figure 11.3: EM point data from a survey at Dookie Campus of the University of Melbourne.
Because GPS and GIS play a critical role in the capture and interpretation of EM data, it is useful to understand some basic concepts of these supporting technologies as well.

### 11.2 Global Positioning System

The Global Positioning System (GPS) is a worldwide radio-navigation system based on a constellation of at least 24 satellites, as shown in Figure 11.4, and their ground stations (El-Rabbany 2002). Often there have been more than 24 fully operational satellites. GPS uses these satellites as reference points to calculate positions. To ensure world-wide coverage, these satellites are deployed into six orbital planes with four satellites in each plane (El-Rabbany 2002). With this geometry, at least four satellites will be visible in the sky from anywhere in the world at any time (El-Rabbany 2002).

![Figure 11.4: An illustration of the constellation of GPS satellites in orbit around the earth.](image)

At the other end of the system, GPS receivers have been miniaturised to just a few integrated circuits. Currently GPS is finding its way into cars, boats, planes, construction equipment, movie making gear, farm machinery and even hand held computers.

The global positioning system (GPS) makes use of medium altitude satellites to determine position, velocity and time at the receiver. GPS receivers can access the L1 (1.575 GHz), L2 (1.227 GHz), and L5 (1.176 GHz) bands (Falade, et al. 2012). Antennae on GPS receivers vary in their configuration, but micro-strip patch antennae are becoming more common because of their low profile, light weight, low cost, ruggedness, and
conformability (Chang, et al. 1986). Patch antennae provide variable bandwidths. For example, the stacked patch antenna, designed by Falade, et al. (2012), provides negative 10 dB attenuation outside its operating bandwidths for GPS L1, L2, and L5 frequency bands are 1.160–1.182 (2.0%), 1.214–1.232 (1.5%), and 1.568–1.598 GHz (2.0%), respectively.

11.2.1 Principles of GPS Operation

GPS works by following five logical steps:
1. The basis of GPS is “triangulation” from satellites.
2. To “triangulate,” a GPS receiver measures distance using the travel time of radio signals.
3. To measure travel time, GPS needs very accurate timing which it achieves with some tricks.
4. Along with distance, the exactly location of the satellites in space must be known. High orbits and careful monitoring are the secret.
5. Finally corrections for any delays the signal experiences as it travels through the atmosphere must be made.

11.2.2 Step 1: Triangulating from Satellites

The idea behind GPS is to use satellites in space as reference points for locations on earth. GPS satellites generate two signals, one at 1,575.42 MHz and the other at 1,227.60 MHz (El-Rabbany 2002). Calculating distances from three satellites using these signals results in a series of intersecting spheres, whose radii are equal to the distances from the satellites. The calculations narrow the final position down to two points, one of which is so obviously wrong that it can be ignored.

11.2.3 Step 2: Measuring distance from a satellite

Distances from the satellites are calculated using accurate timing and by knowing how fast the radio signal travels between the satellite and the receiver. To help clarify this a little, if a car travels along a highway at exactly 100 km/h for 2.5 hours, it is clear that the car has travelled 250 km in that time. In the case of GPS the signal velocity is the speed of light which is roughly 300,000 km/s. By determining how long it has been since the signal left the satellite determining the distance between the satellite and the receiver becomes a relatively simple calculation.

The problem is measuring the travel time. If a satellite were right overhead the time taken for the signal to travel in intervening 20,200 km between the satellite and
the receiver (El-Rabbany 2002) would be approximately 0.07 seconds. So a very precise
clock is needed. Assuming precise clocks are available the process of measuring travel
time is done by comparing the phase shift due to travel time between the signals sent
from the satellite and an equivalent signal at the receiver.

To make sure that the receiver does not accidentally lock onto some other satellite
transmitter and allow information theory to amplify the signals, the GPS satellites
generate a signal, which is so complex that it almost looks like random electrical
noise. This signal is called a Pseudo Random Code (PRC). Another reason for using
such a complex signal is that it makes it more difficult for a hostile force to jam the
system.

11.2.4 Step 3: Getting perfect timing

Accurate timing is the key to GPS; therefore the clocks used in the system must be very
good. On the satellite side, timing is provided by atomic clocks. However the receivers
are not equipped with atomic clocks. The key to good positioning is that three perfect
measurements can locate a point in 3-dimensional space however four imperfect
measurements can do the same thing. By using an extra satellite measurement and
some algebra a GPS receiver can eliminate any clock inaccuracies by comparing the
four calculated locations generated from imperfectly timed signals from the four
satellites. It is important to remember two important principles:

1. If perfect timing were available there would only be two possible positions as the
   positions calculated from all satellite combinations would coincide. Imperfect
timing results in four locations, arranged in closely located pairs.
2. After discarding two positions because they are so obviously wrong the difference
   between the remaining two positions must be due to clock timing error.

Since any clock error will affect all the measurements simultaneously, the receiver
calculates a single correction factor that can be subtracted from all its timing
measurements to cause them to intersect at a single point. This correction brings the
receiver’s clock back into synchronization with universal time. Thus it is possible
to produce atomic clock accuracy in a hand held device. This particular attribute of
GPS technology has some profound field applications. Being able to measure time
accurately to millionths of a second in the field could revolutionize many monitoring
experiments. Unfortunately space constraints do not permit a full exploration of this
at the moment.
11.2.5 Step 4: Knowing where a satellite is in space

On the ground, all GPS receivers have an almanac programmed into their computers that indicates where each satellite is, moment by moment. The basic orbits are quite stable, but just to make sure, the GPS satellites are constantly monitored by the US Department of Defence. It uses radar to confirm each satellite’s altitude, position and speed. Errors due to the gravitational pulls from the moon and sun or the pressure of the solar wind on the satellites are calculated and broadcast via the GPS satellites to all receivers.

11.2.6 Step 5: Correcting errors

GPS satellite signals, like any form of light, are refracted, reflected and attenuated by the atmosphere and other objects around the receivers. Refraction slows the light and can be observed on hot days as a “shimmering” effect, which is so commonly observed when looking out over a distant landscape. Reflections cause double images of the signal sources and often result in “ghosting” of the signals similar to that observed on some television sets. Consequently, accuracy can be compromised. Another critical factor in determining accuracy is the policy called Selective Availability (SA) introduced by the US government (El-Rabbany 2002). The idea behind it is to make sure that no hostile force or terrorist group can use GPS to make accurate weapons. Fortunately all of these inaccuracies usually provide a position within 100 m of the true location and a form of GPS called “Differential GPS” can significantly reduce these problems.

11.2.7 Differential GPS

Differential GPS involves the cooperation of two receivers. One is a stationary receiver located over a precisely know point on the earth’s surface while the other moves around making position measurements. The stationary receiver is the key. It ties the satellite based measurements into a known local reference (El-Rabbany 2002).

Because the reference receiver can compare its true location to the location expressed by the satellite signals, the error can be calculated. The reference receiver then transmits this error information to the roving receiver so it can correct its own measurements. The roving receivers get a complete list of errors for each available satellite and apply these corrections for the particular satellites being used. Using differential GPS can provide positions on the earth’s surface to within 0.02 m of the true location.

El-Rabbany (2002) rightly points out that a real time differential GPS with a single reference station has the disadvantage of only being able to provide corrections for
11.3 Geographic Information Systems

An information system is a computer program that manages data. A Geographic Information System (GIS), then, is a type of information system that deals specifically with geographic or spatial data.

By convention, most GIS systems express Latitude and Longitude as decimal degrees. This implies that latitudes which are south of the equator are expressed as negative numbers. Similarly, longitudes which are west of Greenwich are expressed as negative numbers. Latitudes and longitudes are usually expressed as a single number in GIS software coordinates rather than as degrees, minutes and seconds. Conversion to a single number from field notes and GPS receivers may be necessary before entering data into a GIS.

Like other information systems, a GIS is a data base and should be treated as such. The distinguishing feature of a GIS is its ability to interpret and display geographic information in a user-friendly form. The geo-location of objects can be expressed as latitude and longitude coordinates, but in most cases more complex grid systems are used.

GIS has a wide range of capabilities, but it also has some limitations. Contrary to popular belief, GIS is not simply a map-making tool. While the most common product of a GIS is often presented in map form, the real power of GIS lies in its ability to analyse. A GIS manages data. Knowing how to extract that data and apply it in a meaningful way is the key to GIS analysis.

11.3.1 Integration

One of the most powerful and fundamental tools of GIS is integrating the data (Longley, et al. 2005) in new ways. One example is overlaying different data sets.

GIS can integrate data mathematically by performing operations on certain attributes of the data. For example, streams could be categorised by comparing the population near the stream to its water quality. Poor quality streams with a large population nearby should probably receive more attention than others. This simple example could be performed with a set of mathematical operations.

However, visual integration, rather than mathematical, is sometimes more subtle and effective. For instance, Figure 11.5 shows a satellite image of some farming land,
overlaid with contour data. It becomes evident that the lower land has been cleared for agricultural purposes while the hilly areas are still forested. Although this is a rather trivial example, techniques such as this provide quick and usable information to decision makers.

The power to integrate data is one of the cornerstones of GIS use. It enables GIS to take the data to a new level of complexity and meaning.

Figure 11.5: Satellite image overlaid with contour data.

11.3.2 Limitations

Despite these powerful applications, GIS does have some limitations. GIS software companies are focusing on these limitations, because if they can be overcome, GIS will enter a new era that increases its power many fold.

For instance, it is currently impossible to account for temporal changes in GIS. Although it is obvious that a dataset such as the weather and climate may change over time, existing GIS technology is not able to incorporate those changes for analysis purposes. Although there are ways to “fake it”, real time analysis is still in the developmental phase. Temporal analysis could be used to track urban growth, monitor changes in water quality over time, and many other powerful applications.

Another priority in the GIS field is the support of three dimensional analyses in GIS. Three-dimensional GIS would allow analysts to see how vertical layers interact with each other. This could include layers of air, soil, rock, or water. As with temporal analysis, some programs are able to simulate a “pseudo-3-D” mode, but no real 3-D applications are available. This would have tremendous applications for geology, air and weather, which, in turn, would affect groundwater and air pollution control, to name just a few.
References


