D5 Time-domain electromagnetic (EM) methods

D5.1 Introduction

- Frequency domain electromagnetic methods detect near surface conductors through the secondary magnetic fields that are induced by the primary magnetic field.

- In frequency domain, the primary field is **transmitted continuously**, usually as a sine wave of a **single frequency**.

- With systems such as the EM31 and EM34 the strength of the secondary magnetic field can be 10-20% of the primary magnetic field. In this case it is easy to measure the secondary field.

- As the conductor becomes deeper, the secondary magnetic field becomes weaker. It can be difficult to detect a weak secondary field in the presence of the stronger primary magnetic field.

- In airborne EM surveys, secondary magnetic fields are typically expressed as parts-per-million (ppm) of the primary magnetic fields.

- Time-domain EM methods represent an alternative approach to detecting weak secondary magnetic fields. This works by simply **switching the primary field off** and observing the decay of the secondary magnetic fields.

Sketch a simple figure of time series for both FD and TD, with primary and secondary magnetic fields..

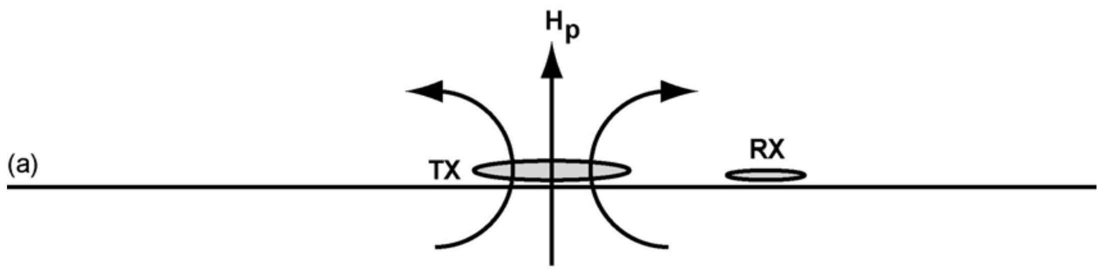
- This method is often referred to as transient electromagnetic exploration (TEM) or time-domain electromagnetic (TDEM) exploration.

- One of the first applications of TEM was described by Ward (1938).

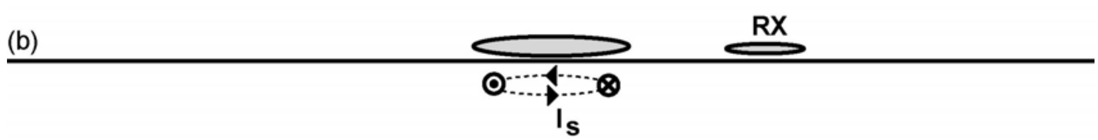
- More details of the development of airborne EM instrumentation can be found in Fountain (1998).

D5.2 Basic physics of time-domain EM

D5.2.1 Qualitative solution



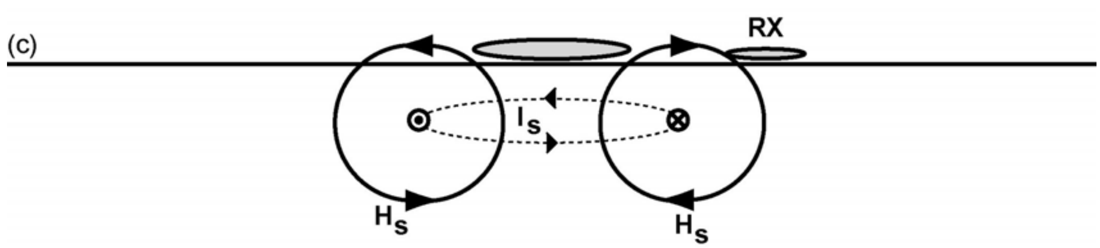
- Electric current flows through the transmitter loop and generates a **static** primary magnetic field (H_P).



- The transmitter current is then **switched off** and the primary magnetic field immediately falls to zero. This change in magnetic field induces a secondary electric current in the Earth.

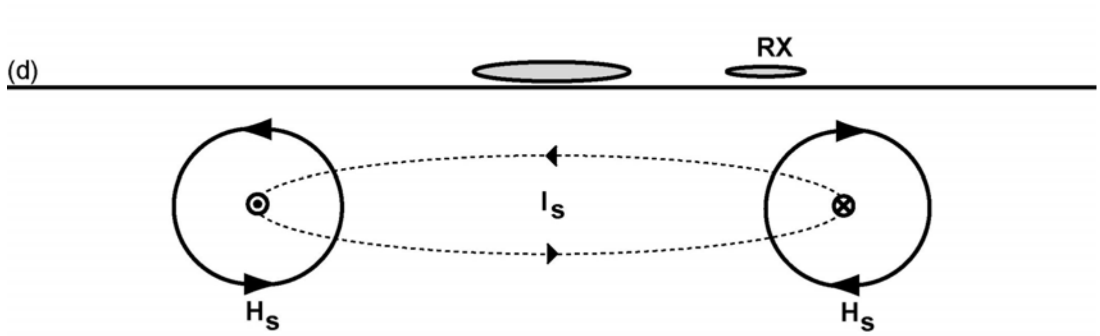
- The secondary current acts to oppose the decrease in the primary magnetic field (Lenz's Law).

- The secondary electric current distribution can be approximated as a horizontal **loop of current** and generates a secondary magnetic field, H_S (*t*).



- Over time the secondary electric currents spread out (diffuse) in a pattern that is similar to a smoke ring.

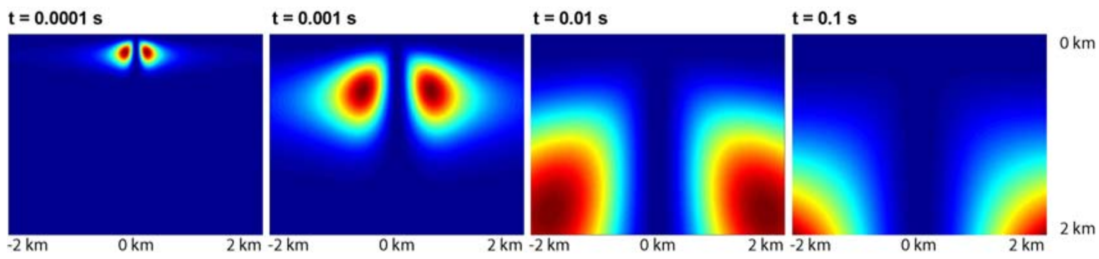
- The secondary currents move deeper as time increases, and thus gives information about progressively deeper structure. Initially the magnetic field is oriented downwards at the RX.



- As the current ring passes beneath the RX, the **sign** of H_S changes.

- Nabighian (1979) described the pattern of electric currents as being like smoke-rings. An additional description of the physics and mathematics can be found in Hoversten and Morrison (1982).

- This process can also be visualized as a contour plot of electric current density.



- Note that the voltage (V) generated in the RX coil is caused by **changes** in H_S

  Can write as $V = -\dfrac{dH_S(t)}{dt}$

D5.2.2 Depth of penetration in a halfspace

- Depth of EM signal penetration can be expressed in an analogous way to the skin depth that was used in frequency domain EM methods.

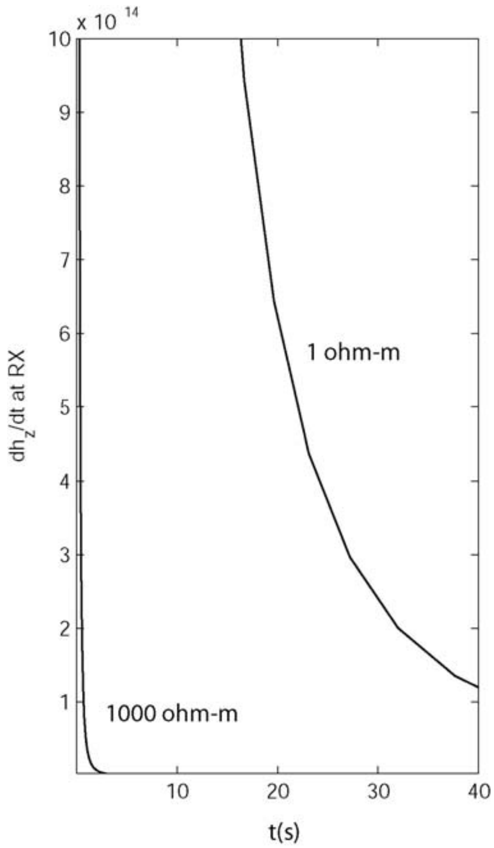
- If the TX is switched of at time t = 0, then after a time t, the depth being sampled is given by $\delta_T = \left[\dfrac{2t}{\sigma\mu_0}\right]^{\frac{1}{2}}$ where σ is the conductivity of the Earth and μ_0 is the magnetic permeability.

- During the first part of the decay, behaviour is mathematically quite complicated, however at late times $\dfrac{\partial H_z}{\partial t}(t)$ decays with a relatively simple form

- $$\frac{dH_z(t)}{dt} = \frac{IA}{20}\left(\frac{\mu\sigma}{\pi}\right)^{\frac{3}{2}} t^{-\frac{5}{2}}$$

- Thus at a given time (t) after switch off, the value of $\frac{dH_z(t)}{dt}$ at late time will become **larger** as the ground becomes **more conductive**.

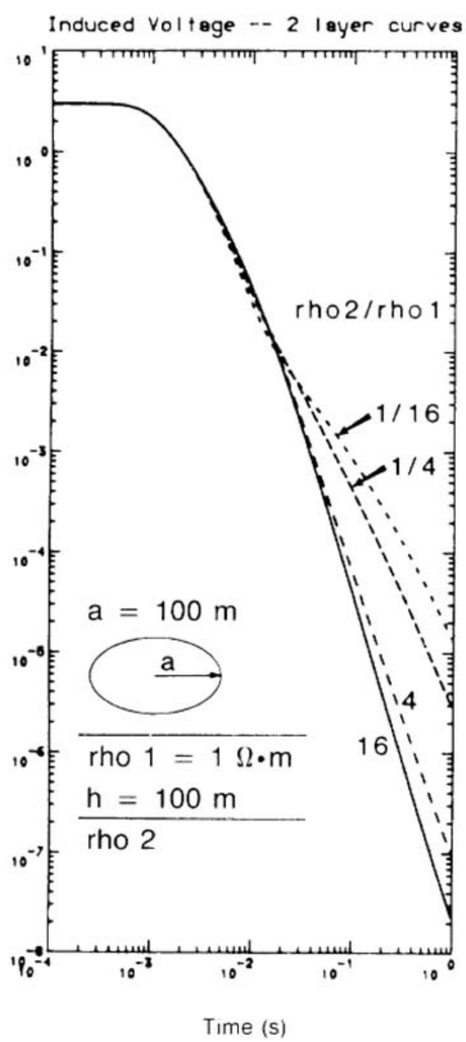
- In the figure below $\frac{\partial H_z}{\partial t}(t)$ decays **slowly** for the 1 Ωm halfspace and **quickly** for the 1000 Ωm halfspace with the RX at 100 m from the TX.



Summary: H_s decays slowly in conductors and quickly in resistors.

D5.2.3 Layered Earth

- In a layered Earth, the ring of electric current will propagate downwards and outwards through the various layers.
- In a **low resistivity layer** the decay will be relatively **slow**.
- In a **high resistivity layer**, the decay will be relatively **fast**
- Thus observation of the decay of H_S with time can tell us how resistivity varies with depth.
- The example below is taken from Fitterman and Stewart (1986) and shows the transient response of a two layer Earth. All models have the same upper layer, but the lower layer has a range of resistivity values.
- Note that **voltage** is plotted on the vertical axis. This is the time derivative of the secondary magnetic field at the receiver (the quantity actually measured).
- At early time ($t = 0$ to 10^{-2} s) all the curves are identical. This is because the secondary current system has not yet reached the lower layer.
- When rho2/rho1 < 1, the resistivity decreases with depth. In this scenario, the late time response shows a relatively **slow decay**.
- When rho2/rho1 > 1, the resistivity increases with depth. The late time response shows a relatively **fast decay**.



D5.3 Airborne time-domain EM systems

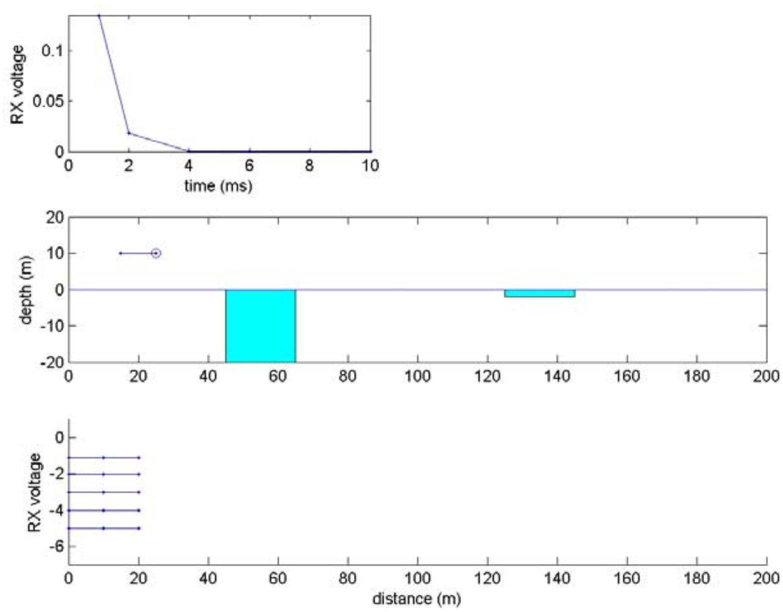
- A range of airborne time-domain EM systems have been developed. First we will consider the basic principles and then consider specific systems.

- The decay is fast for a **bad conductor** and slow for a **good conductor.**

- The model below has **two conductors** which are shown as shaded boxes. The conductor on the left represents a sulphide body that is a large conductor. The smaller conductor on the right has limited depth extent and could represent a region of overburden, or a swamp. The host rock (shown in white) is very resistive.

- The time decay is measured at 5 discrete times after the primary magnetic field is switched off. These five points define the transient from 1-10 milliseconds.

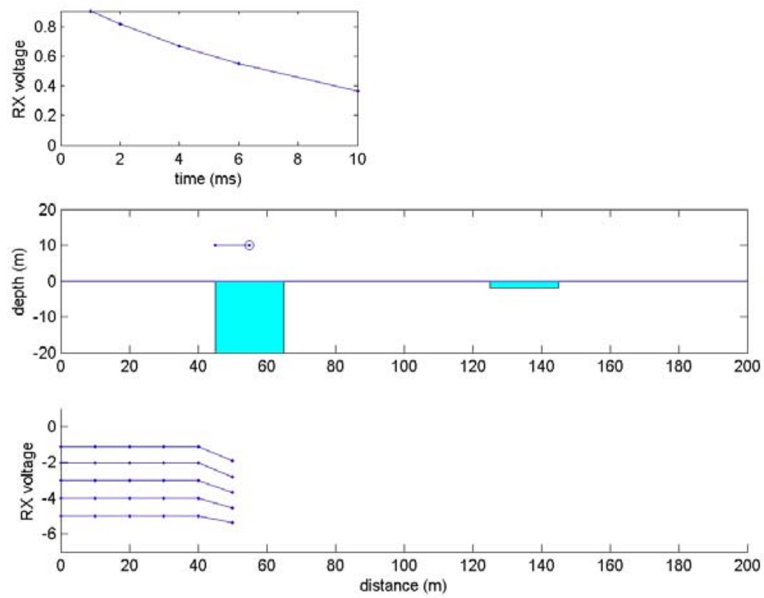
- As the survey proceeds a transient is recorded every 10 m along the profile. The transients are displayed as follows. Figures generated with **D5_time_domain_v1.m**



- The time-decay of the individual transient is shown in the upper figure.

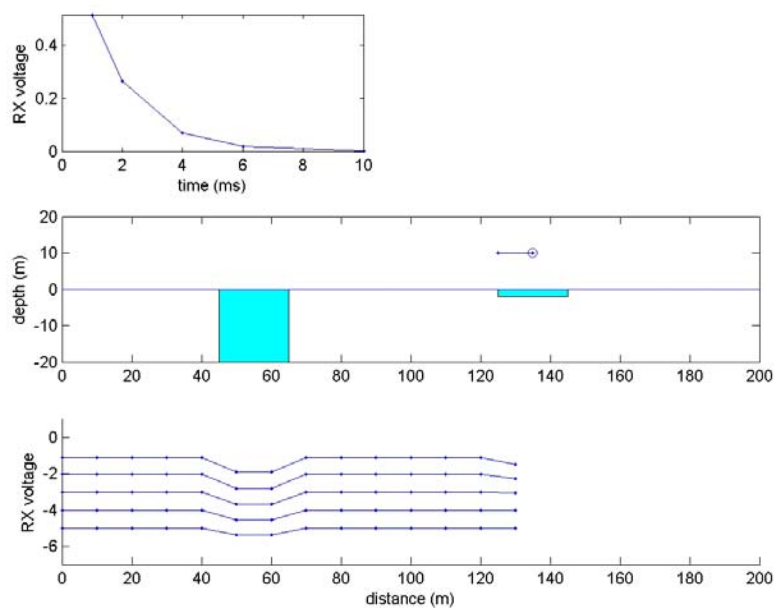
- The resistivity model and TX-RX location are shown in the middle figure.

- The transient above shows a **fast decay** because TX-RX are over the resistive rock.



- When the TX-RX are above the sulphide, the time decay of the transient is slow and a non-zero voltage is seen at all five time measurements.

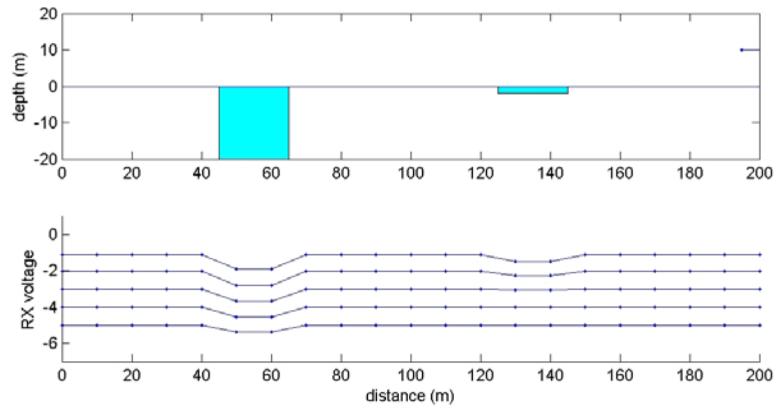
- Note that the (negative of the) voltage on each time channel is plotted in the lower figure as a line. Note that for display purposes there is a vertical offset between each horizontal line.



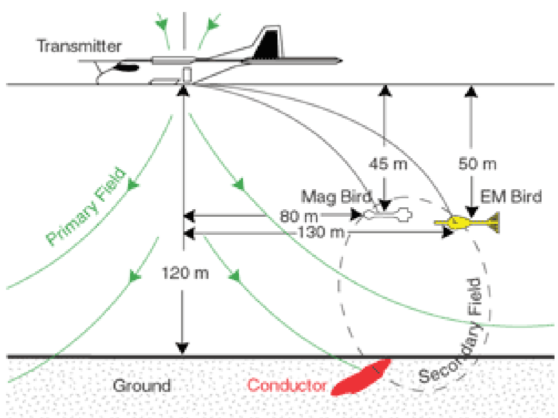
- Over the shallow conductor the secondary magnetic fields decays at a medium rate and the voltage is essentially zero after the time of channel 4.

- Thus the **shallow conductor** is only observed in the **early time channels** plotted at the top of the lowest panel.

- The whole survey line is shown below. Note that the large deep conductor gives a response on all time channels. In contrast the shallow conductor only gives a response at early time.



D5.3.1 INPUT (Induced Pulse Transient System)



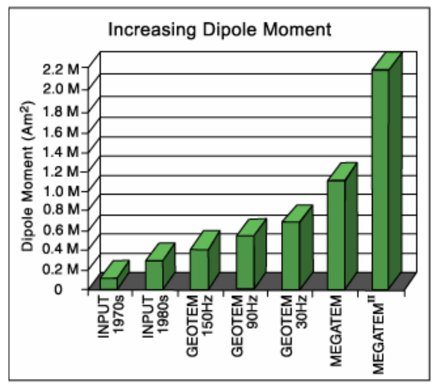
- INPUT was one of the first airborne time-domain systems to be developed. Transmitted waveform is a series of positive-negative half sinusoids with off-time in between. See my Geophysics 424 notes for details of the waveform for good-bad conductors.

- INPUT data can generally image deeper than corresponding frequency domain EM data. The quiet period of recording without the primary fields allows secondary fields to be detected from greater depths.

D5.3.2 GEOTEM

- Transmitter is mounted around the wings of a small aircraft (Casa 212). It uses the same half sinusoidal waveform as INPUT

D5.3.3 MEGATEM



- Deeper exploration can be achieved with a larger transmitter dipole moment (M) that is defined as

$$M = NIA$$

  where I is the current in the transmitter, A is the area of the transmitter and N is the number of turns of wire.

- The larger the dipole moment, the stronger the secondary magnetic field. If the secondary magnetic field starts at a larger value, then it will stay **above the background noise** level for a relatively long time.

- Since later times correspond to deeper signal penetration, this gives a greater depth of exploration.

- The MEGATEM system is named because it has a transmitter dipole moment in excess of 10^6 Am^2 formed by placing a large transmitter loop around the wings of a Dash-7. The receiver is in a bird that is towed behind the aircraft.

- While these systems give the deepest exploration, they have limited horizontal resolution. This is because the TX and RX are up to 100 m apart. When an anomaly is detected, it must be between the TX and RX. However the exact location is not determined.

D5.3.4 Central loop airborne EM systems

Airborne EM exploration systems have evolved in the last 50 years into two basic forms:

	Advantages	**Disadvantages**
Frequency domain helicopter EM system with rigid boom and small TX moment (e.g. DIGHEM)	Good discrimination between good and bad conductors. Good horizontal resolution because of close TX and RX.	Limited depth penetration
Fixed wing time-domain systems with towed RX and large TX dipole moment (e.g. GEOTEM, MEGATEM)	Good depth penetration due to strong transmitter	Limited discrimination between good and bad conductors. Limited horizontal resolution.

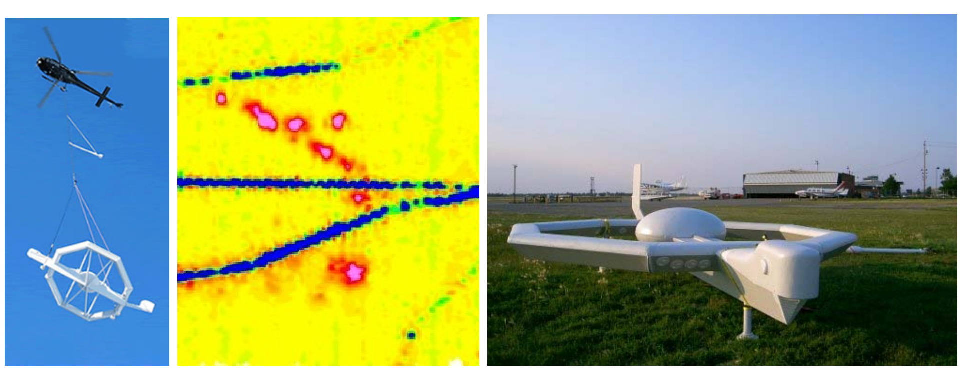
- Several attempts have been made to combine the strengths of the above systems.

- One successful development is the **AeroTEM** system that has been developed by Aeroquest Surveys. This system has a TX with a strong dipole moment (40000 Am^2), and can be towed closer to the ground than the TX in a fixed wing system (such as GEOTEM), giving relatively deep signal penetration.

- Responses can be detected at the part-per-billion (ppb) level (Boyko *et al.,* 2001; Balch *et al*., 2003).

- The coincident TX and RX give a **sharp anomaly** as the system is flown over a target. Unlike towed-bird systems, the response is **independent of flight direction**. This geometry also gives **maximum coupling** between ground conductors and the RX and TX loops.

- AeroTEM also makes measurements during the **on-time**, and this allows better discrimination of the target conductance.



- The data panel shows the early time z-axis AeroTEM response for a survey near Sudbury (Balch *et al*., 2003). The positive anomalies (red) have a maximum amplitude of about 1 ppm and are sulphide bodies and the negative (blue) anomalies are powerlines. This survey discovered a previously unknown sulphide deposit located between the two powerlines.

- Another similar system is the **HeliGEOTEM** system operated by Fugro Airborne services.

D5.4 Ground-based time-domain EM systems

- These ground-based TDEM systems can use a flexible layout and the TX size can be adjusted from 1 *x* 1 m to 2000 *x* 2000 m. Larger loops can be used to boost signal strength and give deeper signal penetration.

- Having the TX and RX stay in the same location for a period of time allows **stacking** *i.e.* record many on-off cycles of the TX and add the responses together. This allows detection of weaker signals and the removal of incoherent noise.

- The RX can be placed in the centre of the transmitter (central-loop configuration) or at a variable offset. Collecting transient data at variable offsets can give additional resistivity-depth information. It also takes advantage of the fact that it is logistically easier to move a small RX than the larger TX.

- Some widely used systems include

(1) SIROTEM (developed by CSIRO in Australia)

A SIROTEM time-domain EM system being used in a geotechnical survey in Turkey. Note the TX loop of wire on ground.

(2) Crone Pulse EM (www.cronegeophysics.com/)

(3) Geonics produce the TEM47, TEM57 and TEM67 transmitters as well as the ProTEM receiver.



Images of the Geonics ProTEM system (www.geonics.com)

D5.5 Very early time EM systems

- The need to map **shallow structure** in environmental surveys has led to the development of new systems that can measure transient responses at **very early** times. These systems map shallow structure and act as good metal detectors.

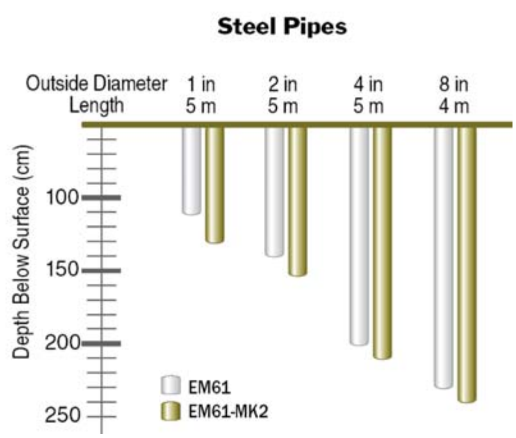
- Since early time corresponds to high frequency, care must be taken to ensure that **displacement current** can really be ignored from the data analysis.

- Also note that it takes a finite amount of time to **switch off** the TX current. This can require special electrical engineering in very early time EM systems.

- Note that shallow EM systems can detect objects that are routinely missed by magnetic surveys. This is because magnetic surveys only detect ferrous objects, while EM surveys can potentially detect all metallic objects. This can be an important advantage in searching for UXO and landmine clearance.

Geonics EM61

- The decay of the secondary field is relatively quick when the target is small. The Geonics EM61 uses early time measurements made from 216-1266 μs to detect small, shallow metal targets, such as UXO.
- This system can be hand-carried, towed on a vehicle or used underwater.



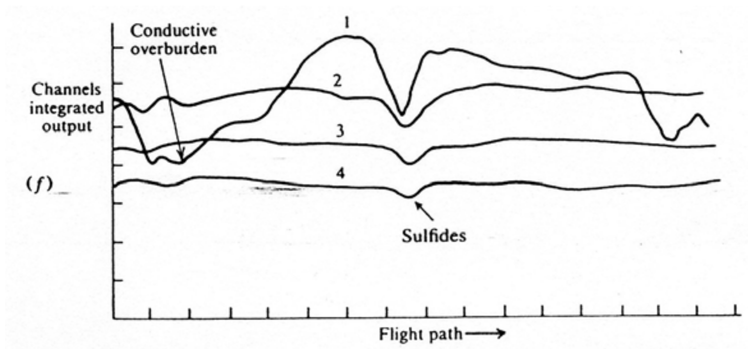
- The figure on the right shows the depth at which metal pipes of various sizes can be detected with the EM61.

VETEM

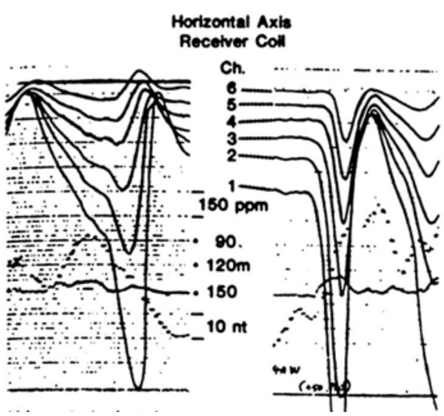
- System developed by the United States Geological Survey for Very Early Time ElectroMagnetic measurements (VETEM).

D5.6 Applications of time-domain EM

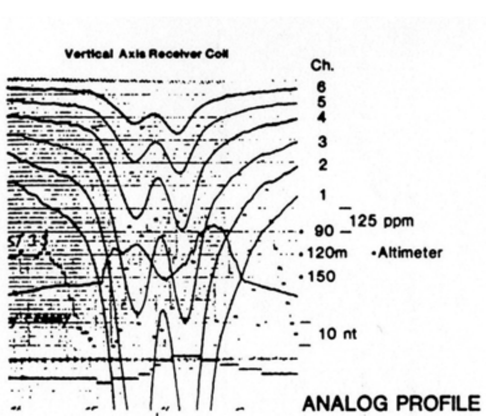
D5.6.1 INPUT exploration for massive sulphides



- Texas Gulf Sulphur Timmins (Telford Figure 7.28). The use of multiple time channels allows shallow conductors (overburden) to be distinguished from deeper conductors (sulfides). Compare this figure with the idealized version in D5.3.



- Helicopter MK VI INPUT data collected over the Goldstream sulphide body (Cu, Zn, Ag). Telford Figure 7.108b. The dashed curves shows the total magnetic field anomaly over the target. Telford shows how simple forward modelling can be used to determine the dimensions of the ore body.



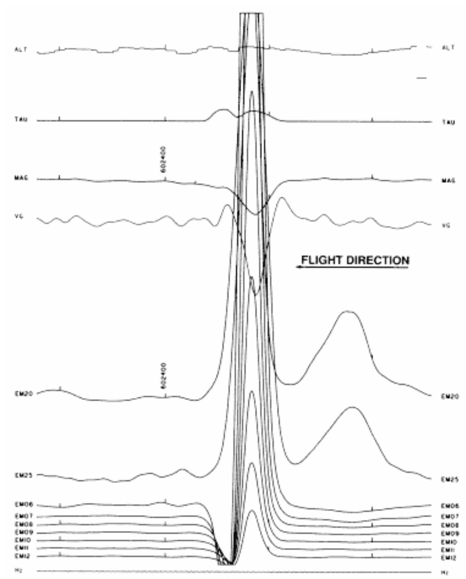
- Helicopter MK V1 INPUT over Windy Craggy sulphide body (Cu) in the Yukon. Telford Figure 7.108d

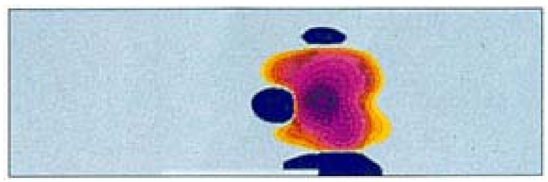
D5.6.2 GEOTEM exploration for kimberlites

- Kimberlite pipes are often characterized by a low resistivity disk at the surface. This is produced when weathering of the kimberlite produces a clay layer that has a low electrical resistivity.

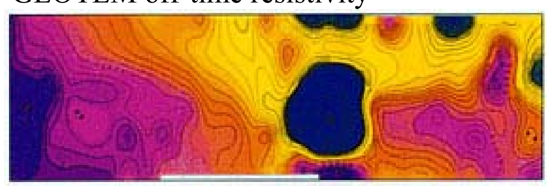
- In northern Canada, glacial erosion often creates a lake and the clay becomes water saturated, further lowering the resistivity. The combination of airborne EM and aeromagnetic data is widely used in current exploration.

Example : Willy Nilly Kimberlite pipe (www.fugroairborne.com.au)





GEOTEM off-time resistivity



Aeromagnetic anomaly

D5.6.3 Hydrocarbon exploration

- This example shows how paleo-channels can be located with AEM data. These channels can host shallow gas reservoirs at depths as shallow as 50 m and are characterized as zones of high resistivity. This example is from somewhere in Alberta, and more details can be found at www.fugroairborne.com.au by searching for “Shallow gas”.

- In typical Western Canada Sedimentary Basin (WCSB) conditions, MEGATEM and GEOTEM can give penetration up to 300 m. Costs can be as low as \$100/km for large volumes of data, which is lower than the cost of surface geophysics.

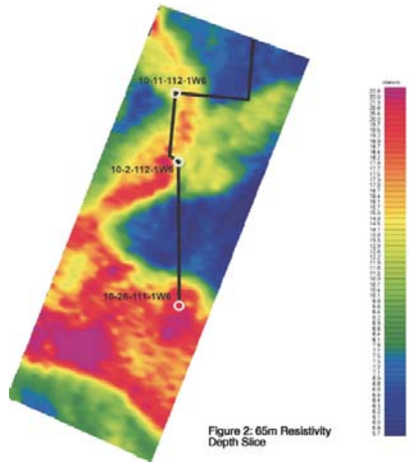


Figure 2: 65m Resistivity Depth Slice

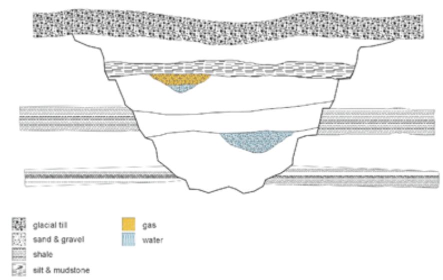


Figure 1: Simplified Paleochannel - hosted shallow gas cross section

D5.6.4 Groundwater exploration

- Time domain data can be converted into the equivalent of apparent resistivity.

- The following examples of real time-domain EM data from Southern California are taken from Taylor et al., (1992). This example shows some applications to ground water exploration. The example shows data associated with a decreasing resistivity with depth.

- Figure on right shows models that fit the data (smooth line) compared with well logs (rough line). Agreement between the model and the well log is quite good. Decrease in resistivity at depth corresponds to a saline aquifer.

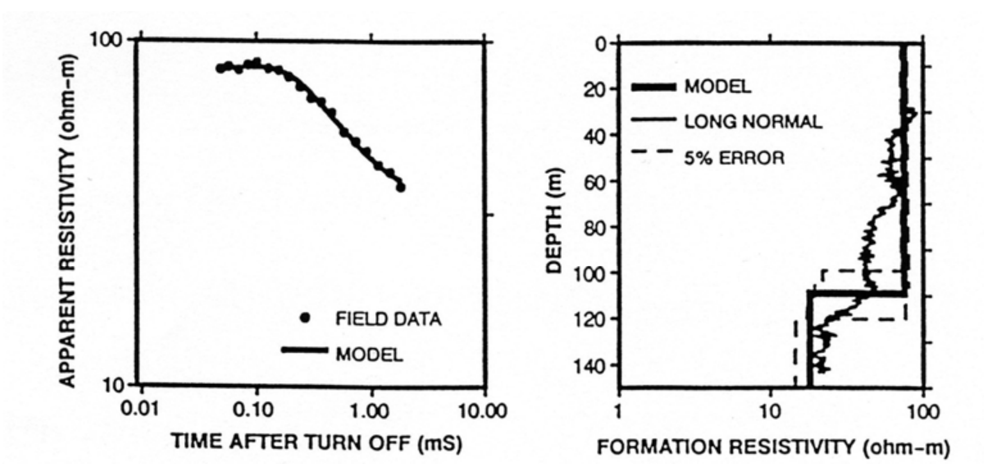
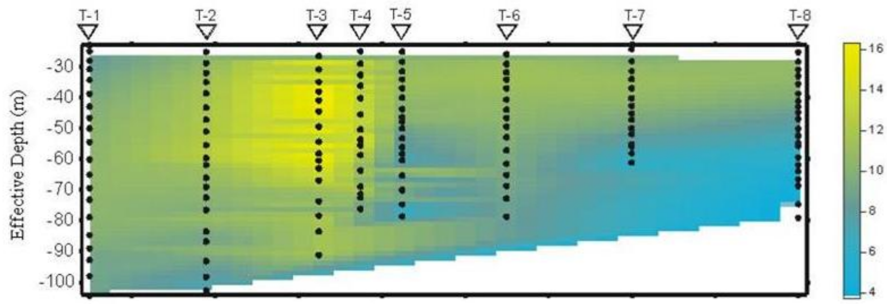


FIG. 7. Surface and borehole electrical measurements at the Cottonwood #1 site.

D5.6.5 Geotechnical exploration

- Time-domain EM study by Ersan Turkoglu in Avcilar, a suburb of Istanbul that was badly damaged by the 1999 Izmit earthquake.

- SIROTEM data were used to image resistivity in the upper few hundred metres of the subsurface, and reveal possible shallow faults. Unlike MT, this technique can be easily used in urban areas with high levels of cultural noise.



Pseudo section obtained from TEM data ρ_a Ohm.m

- This study also used DC resistivity data, and a joint inversion of TEM and DC data to overcome some of the inherent non-uniqueness.

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