APPENDIX 1
THEORY - TEM

TEM Introduction and Theory

Upon acquisition of the first ground-based TEM instrument in the early 1990's, Ramboll has been among the global pioneers when it comes to applying TEM methods for subsurface mapping. Over the last 20 years, the accuracy of the instruments and their ability to obtain information about aquifers and hydrogeological properties has improved significantly. The TEM method is now one of the most efficient geophysical technologies for groundwater investigations.

Within the last 15 years, airborne TEM systems have been developed and introduced. Using the airborne systems, the ability to survey large areas has been significantly improved. The towed TEM (tTEM) and WalkTEM systems are basically a downscaled version of the TEM system on an airborne platform named SkyTEM.

TEM Theory

A direct current is injected in a transmitter loop. When the current stabilizes, the transmitter is abruptly turned off. By abruptly turning off the transmitter current, short-duration eddy currents are induced in the ground. The receiver coil located in the center of the transmitter loop (central loop configuration like WalkTEM) or outside the transmitter loop (off-set configuration like tTEM), measures the decaying magnetic field derived from the eddy currents.

Noise in TEM Data

TEM data are comprised of different type of noise components. Noise can cause bias signals and affect the depth of investigation and if not properly identified and removed, can result in incorrect geological and hydrological interpretations. The different sources of noise are described below:

1. Galvanic coupling is caused by the electromagnetic signal induced in a metal object, such as a metal pipe, metal fence or the loop, following the ground-wire through the power-masts to the ground as sketched below. The challenge is that the signal component caused by a galvanic coupling can be hard to detect as the nature of the decay is similar to the response from the ground as illustrated Figure A1- 1. Galvanically-coupled data are identified by looking at the data along the survey lines while paying attention to the signal level and its correlation with potential coupling sources on the GIS map.

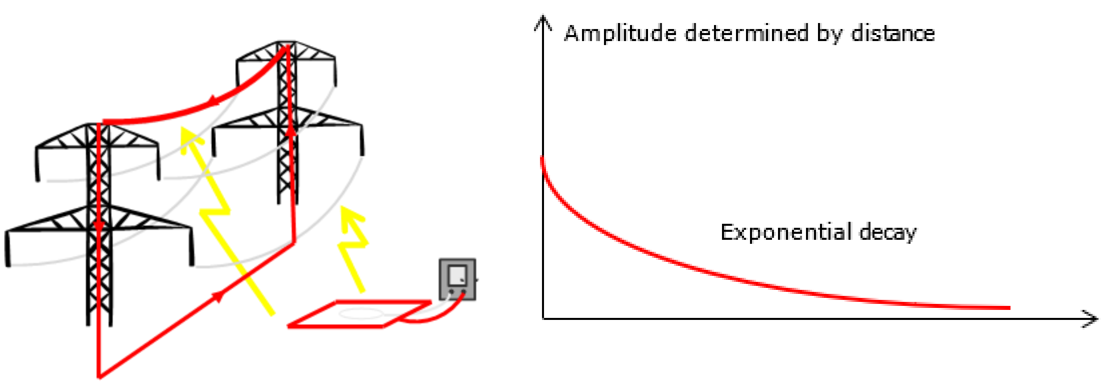

Figure A1- 1 Illustration showing the effects of galvanic coupling.

2. Capacitive coupling is caused by the induced electromagnetic signal in an insulated installation such as a power cable. The noise creates an oscillating signal as illustrated in Figure A1- 2. It is normally easy to distinguish capacitive coupling noise from the ground response.

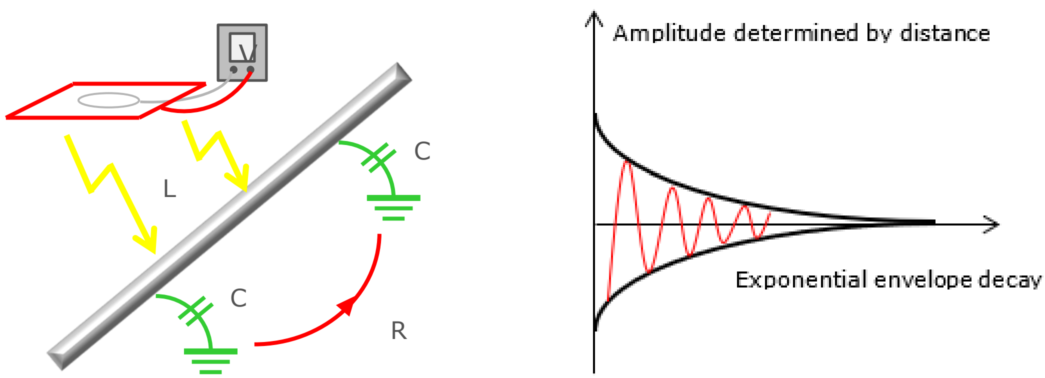

Figure A1- 2 Illustration showing the effects of capacitive coupling.

3. Coherent noise from electrical powerlines has the same pattern as sketched for the capacitive coupling. It is often easy to identify these features during processing of the data.
4. Atmospheric noise is more random in nature and is typically handled by none-spike filtering and by simple averaging of the data. In case of a strong lightning or an electromagnetic storm the background noise can prevent the collection of data with satisfactory signal-to-noise ratio.
5. Motion induced noise due to vibrations in the receiver coil. Vibration of the receiver coil in the earth magnetic field will create a noise component. It is only a problem for moving systems, such as SkyTEM (airborne) or the tTEM system. This noise is minimized by suspending the receiver coil and keeping the survey speed within recommended limits.
6. Internal noise in the instrumentation.

Depth of Investigation

The depth of investigation (DOI) depends on the geological and hydrogeological settings within the survey area and the signal-to-noise ratio determined by the power of the transmitted electromagnetic field, internal noise in the instrumentation and the actual ambient noise during the survey.

The length of the TEM decay curves, i.e. how late in time the signal can be measured before reaching the noise level, determines the DOI. As an example, in Figure A1- 3, the earth response (the green curves) reaches the noise floor for the system at ~ 500 μs. The depth of investigation can be increased by increasing the induced signal. This is typically done by injecting higher current, increasing the size of the transmitter loop and/or increasing the number of decay curves being averaged (stack size).

Inversion

The inversion process is the step where the measured voltage values are fitted with the TEM response of the geophysical model. The model is described by its layer thicknesses and corresponding electrical resistivities. The results are typically presented as smooth (multi-layer) resistivity models.

The processed data were inverted by applying vertical constraints, where neighboring layer resistivities are constrained in a multi-layered inversion scheme.

An in-depth description of the modelling scheme can be found in the references listed below.

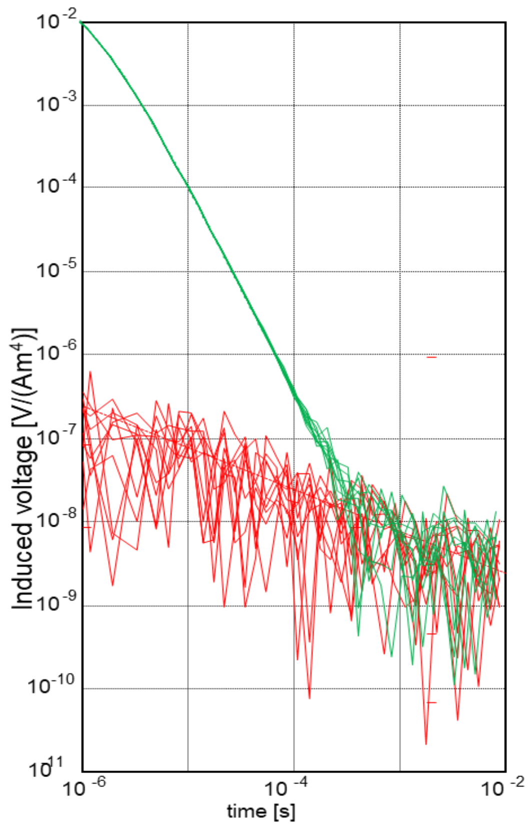

Figure A1- 3 An Example of decay curves created by a TEM system (Green curves) and the background noise floor (Red curves).

References

Selected references describing TEM systems like the tTEM and WalkTEM systems, the calibration of a TEM system at the national Danish Test site and the applied modeling technique.

Auken, E., Foged, N., Larsen, J. J., Lassen, K. V. T, Kumar Maurya, P, Dath, S. M., and Eiskjær, T. T., 2019, tTEM — A towed transient electromagnetic system for detailed 3D imaging of the top 70 m of the subsurface, Geophysics, Vol. 84, NO. 1 (Jan-Feb 2019); P. E13–E22, 11 Figs., 1 Table. 10.1190/GEO2018-0355.1

Auken, E., Foged, N. and Sørensen, K., 2002, Model recognition by 1-D laterally constrained inversion of resistivity data: Proceedings – New Technologies and Research Trends Session, 8th meeting, EEGS-ES.

Auken, E., Christiansen, A. V., Jacobsen, B. H., Foged, N., and Sørensen, K. I., 2005, Piecewise 1D Laterally Constrained Inversion of resistivity data: Geophysical Prospecting, 53, 497–506. Christiansen, A.V. and Auken, E., 2012, A global measure for depth of investigation: Geophysics, vol 77, No. 4, 171-177.

Auken, E., A.V. Christiansen, C. Kirkegaard, G. Fiandaca, C. Schamper, A.A. Behroozmand, et al. 2015. An overview of a highly versatile forward and stable inverse algorithm for airborne, *ground-based and borehole electromagnetic and electric data. Explor. Geophys. 46:223–235. doi:10.1071/EG13097*

Foged, N., E. Auken, A. V. Christiansen, and K. I. Sørensen, 2013, Test site calibration and validation of airborne and ground based TEM systems: Geophysics, 78, no. 2, E95–E106, doi: 10.1190/geo2012-0244.1.

McNeill, J. Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers; Technical Report TN-6; Geonics Limited: Mississauga, ON, Canada, 1980

Sørensen, K. I., and Auken, E., 2004, SkyTEM – A new high-resolution helicopter transient electromagnetic system.: Exploration Geophysics, 35, 191–199.

Sørensen, K. I., 1997, The pulled array transient electromagnetic method: Proceedings of the 3rd Meeting of the Environmental and Engineering Geophysical Society, European Section, 135–138

Viezzoli, A., A. V. Christiansen, E. Auken, and K. I. Sørensen, 2008, Quasi-3D modeling of airborne TEM data by Spatially Constrained Inversion, Geophysics, 73, 3, F105-F113