2004 ANCID/Sustainable Irrigation Travel Fellowship

A Review of Geophysical Equipment applied to Groundwater and Soil Investigation.

by David Allen, Allen Hydro-Geophysics
David@AllenHydrogeophysics.com.au
Phone 02 63323895, 0418 964097
PhD student at the National Centre for Groundwater Management,
University of Technology, Sydney.

Introduction

Using the 2004 ANCID/Sustainable Irrigation Travel Fellowship, David Allen conducted an international survey of over 100 geophysical instruments applicable to irrigation problems. After attending the Symposium on Application of Geophysics to Engineering and Environmental Problems in Atlanta, Georgia, USA he visited equipment manufacturers and researchers in Canada, Denmark and Sweden. The survey of equipment details and prices is to be published on the ANCID web site. David was able to discuss with overseas manufacturers and researchers his own PhD work on electrical conductivity imaging of aquifers connected to watercourses. He got to present his work at three public gatherings and received much feedback on how it could be integrated with technical advances made by the audiences.

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Groundwater and Soil Investigation Applications of Hydro-Geophysics.

The latest hydro-geophysical technology permits new approaches to water management including:

- Imaging of shallow aquifers so that they can reliably be developed as underground water storages resulting in diminishing waterlogging and topsoil salinization problems. Using geophysical imagery, pockets of freshwater could be extracted from otherwise saline aquitards, reducing downward groundwater movement and mixing of mid level saline aquifers with deeper extensive freshwater aquifers.
- Imaging of connectivity of aquifers with surface water bodies (ie. seepage and saline inflow) so that they can be conjuctively managed.
- Imaging of aquifers to improve bore siting and groundwater modeling.
- Multi-depth imaging of soil properties for management of water application and deep leaching.
- Borehole logging for responsible borehole development and detection of cross contamination of aquifers through poorly cased bore holes.

The most commonly imaged property - Electrical Conductivity

Geophysical instrumentation used in groundwater and soil investigation measures many properties, however, instrumentation typically used in production mode generally measures electrical conductivity. Use of the property of electrical conductivity (EC), or its inverse, resistivity, as well as other geophysical properties for measuring variation in soil and groundwater should no longer be a case of arbitrarily trialing geophysical instruments in order to see if they are useful. Both the relationship of EC to soil properties and the capabilities of the detecting instruments are now well known and documented. Modeling and simulation can be conducted cheaply before surveys to prove which survey instruments, if any, can supply viable information and at what cost. This survey of equipment as well as various software tools are guides on equipment applicability. Software tools include:

- GeoPASS (www.Hygeia-eu.org) - free,
- HydroGeoImager config. analyst (www.AllenHydroGeophysics.com.au) – free
- Res2DInv, Res3DInv (www.Geoelectric.com) - free,
- EMMA (http://www.geofysiksamarbejdet.au.dk/?id=201) – free
- GeoTutor II Mag/Res/EM (www.PetRosEiKon.com) US$999 or US$499Academic.

EC can be measured in soil and other sediments using a bewildering array of instruments. To the novice, it may appear that such instruments all measure different properties and therefore all should be tried so that more information can be gathered to address certain problems. In reality, only one, or, at the most, two such instruments should be used to map sediment and groundwater at a site. Instruments should be selected according to their ability to map appropriate depth intervals at the most economical rate. Usually, a multi-depth detecting instrument will be most appropriate because it can separate the effects of variation at different depths from each other thus reducing ambiguity. Inversion, a type of processing, can convert apparent electrical conductivity data from multi-depth devices into layered true EC data, that is, it does not smear effects of features at different depths into each other. This means that multi-depth instruments can directly relate to soil and rock properties without so much need for correlation with soil samples. The graph below shows how multi-depth data may be processed to resolve true sharply layered EC variation with respect to depth from 'smeared' multi-depth EC_a data.

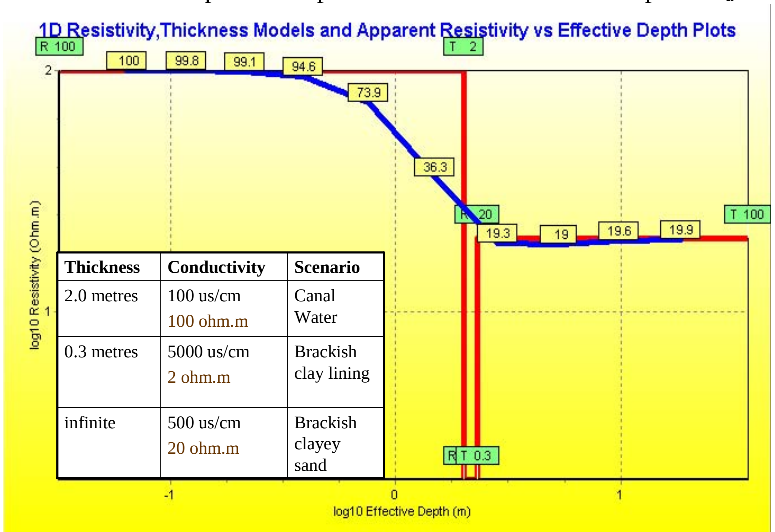

Figure 1 Conversion of multi-depth EC_a (or apparent resistivity) data to true layered EC or (resistivity) data. The blue curve is the EC_a data and the red curve is the real EC data, plotted with respect to depth.

In Australia where labor costs are high, typically, the predominant cost of a survey will be the man and vehicle hours involved both in mobilization and survey rather than the costs related to the complexity of the equipment utilized.

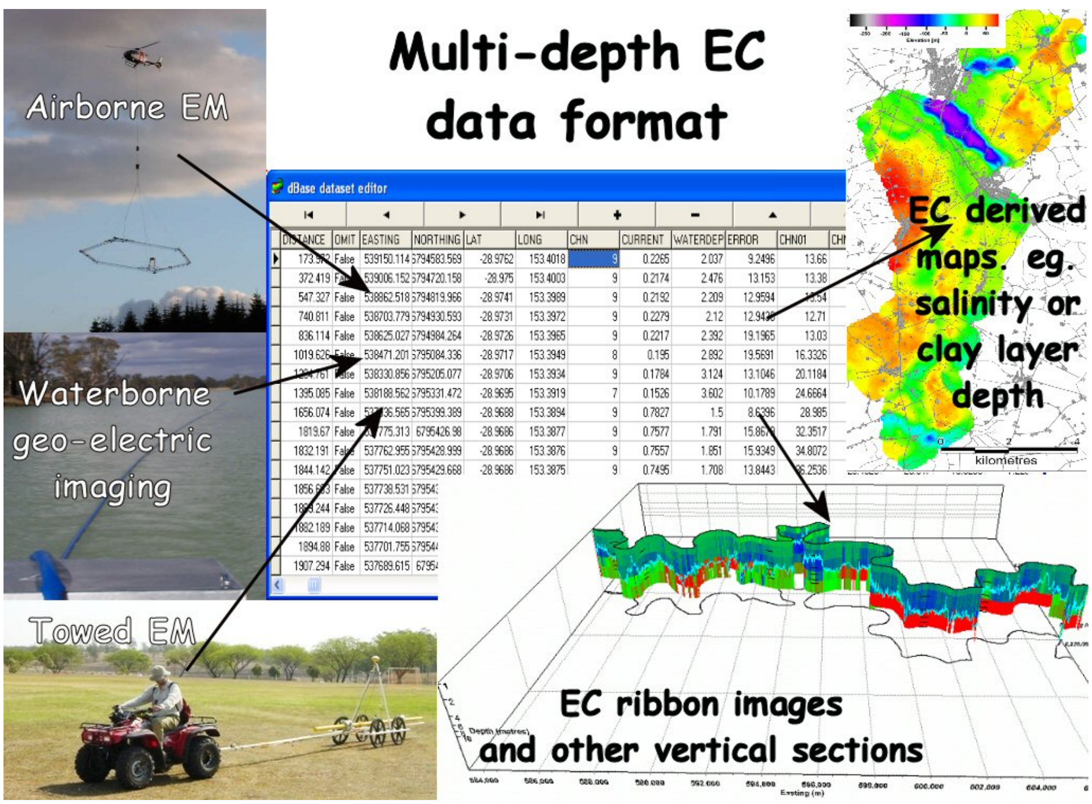

Figure 2 The possibility of combining diverse sources of EC data into one database with facilities for outputting diverse forms of imagery tailored to particular applications has been proposed to the National Water Commission.

All EC image data, regardless of the source, can be combined into a common format and output in diverse ways as suggested in Figure 1. The author has proposed this to the Australian National Water Commission in the hope that a national web based service could be provided for public use. A working example of a national multi-depth EC database posted on a web site is available at http://www.gerda.geus.dk/ . The database is used as the principle tool for managing the groundwater resources of Denmark. It is MapInfo based rather than ESRI based as suggested for Australia. The site does not include interpretive tools, however, screen dumps of the associated interpretive tools are available at www.SkyTEM.com . It includes user friendly queries for generating maps of depths to high EC (clay) layers, thickness of those layers, EC at particular depths and other possible maps. Further information on the multi-depth EC database proposal is available in the latest edition of the ASEG Preview magazine (Allen, 2005).

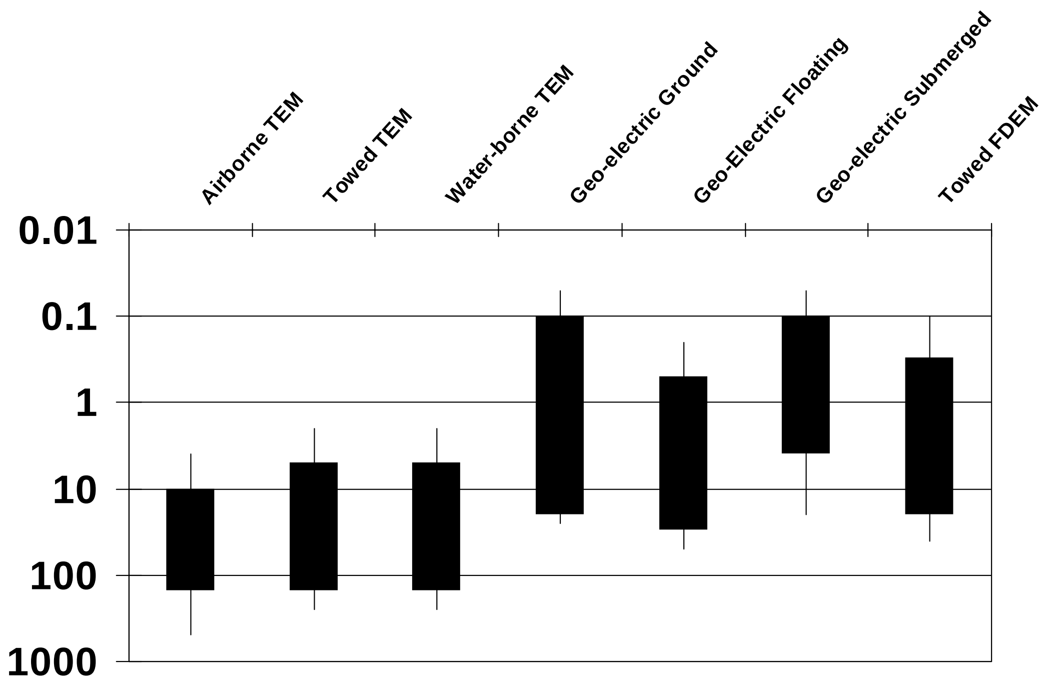

Figure 3 Ranges of detectable depths of various EC imaging devices (in metres). Note that airborne FDEM (not shown) has a range similar to but shallower than airborne TEM.

Figure 2 presents ranges of depth of exploration of various multi-depth EC device types, that will be discussed below, while Table 1 compares the various EC measuring devices, all of which are discussed below. Depth of exploration, productivity and resolution, both vertically and horizontally, should be principle components of any choice of EC equipment for a particular application. EC data on its own is of limited use so, in addition to selection of an instrument for acquiring data, appliers must select a correlation, or calibration, procedure for converting EC data to desired properties. On many occasions, the best correlation will be achieved by an ad-hoc, speculative analysis of the data within the context of all other available information. On other occasions, extra information such as multi-depth soil samples should be acquired and correlated with the EC data using a program such as the United States Department of Agriculture salinity assessment computer program – ESAP (free from their website). Should a refined form of such software be set up on an Australian publicly available website, then users could submit their data and have it processed, calibrated using their own soil sample data. The user could have the option of letting the government then make the data publicly available so that region-wide analysis can be conducted. Such a scheme has been proposed to the

National Water Commission as part of the national EC database proposal mentioned above. Government storage of the data would eliminate the current wastage of data resulting from farmers storing data only as paper printouts which tend to get lost.

Categorization of all types of geophysical devices useful for soil and groundwater management

Devices may be grouped into the following categories:

- EC Imaging - frequency domain electromagnetic devices,
- EC Imaging - Geo-electric devices – Terrestrial and Waterborne,
- EC Imaging - Time domain (Transient) electromagnetic devices – Terrestrial and Waterborne,
- EC Imaging - Airborne active source electromagnetic devices,
- EC Imaging - Magnetotellurics.
- Software for resolution enhancement, calibration and visualization.
- Borehole geophysical devices,
- Soil Moisture and Soil Suction Sensors,
- Remote sensing such as aerial photography and satellite imagery and
- Other types of geophysical instrumentation.

Devices in the first 4 of these categories simply measure electrical conductivity and thus can be used interchangeably to some extent as proposed above. It is emphasized to the reader that the multi-depth EC sensing devices are far superior to single or dual depth devices, even if the client is only interested in data at a particular depth, if data is processed rigorously. A single depth device may cover a large depth interval but, to such a device, a deep extreme EC variation may appear in the same way as a minor shallow EC variation. The multi-depth sensing device can be used to separate such responses.

An example of hydro-geophysical equipment selection for an innovative water saving application.

Lets consider farmer X who has a reservoir that leaks and causes waterlogging problems. Farmer X also loses 1.7m of water from his reservoir each year due to evaporation. Due to legislation increasing his difficulty of accessing water in a timely manner he needs more long term water storage capacity and his high loss rate reservoir is not economically viable for long term water storage. He needs a better solution. Farmer X has drilled some shallow bores on his property that indicate that sandy braided streams run under his property. These streams must be where most of his water is leaking. If these prior stream channels can be imaged in three dimensions then he can determine how to use them to store his water underground, but not deep underground where pumping costs for recovery would be large. He will plan to modify his existing surface reservoir for managing recharge and recovery of water from his shallow aquifers as shown in figure 3. He will plan then to recover water he has already lost to the shallow aquifers that is causing water logging problems. After that he will recharge the aquifers to a lower level that will not cause waterlogging when more water is delivered to him.
Farmer X now needs to determine what geophysical devices will best image his aquifers. We know that remote imaging will be much more efficient and effective than grid drilling – we will look at the normal choice of tool – electrical conductivity imaging. EC imaging will differentiate saline groundwater from fresh groundwater and will differentiate clay from sand. Figure 2 presents depth of exploration of various types of devices. Farmer X knows that his underground storage must sit above a known saline aquitard that exists at 40m depth.

Figure 2 shows that he can use TEM or floating or terrestrial geo-electric arrays to image this depth range. TEM may however not detect surface layers less than 5m deep that could prevent recharge. Using table 1 and the instrument discussion below, we can narrow down instrument selection. We will look for instruments with cheap mobilization costs, good vertical resolution over his desired exploration depth range and fast cheap coverage rates. Waterborne geo-electric arrays are suitable for use on his existing reservoir and adjacent canal network for identifying the very shallow geology very cheaply, and comprehensively. On the ground he can use geo-electric arrays but they could be too slow to use on ground. Capacitively coupled geo-electric arrays could be ideal but they are likely to see only to about 25m deep. Towed TEM can rapidly image more deeply but cannot resolve the near surface layers. A multi-depth FDEM device could fill in the shallow data missed by the towed TEM while also giving the farmer valuable information on his soil. If, collectively, his neighbors wish to develop similar underground water storages, then mobilization cost of an airborne EM system may become justifiable, however, on cleared land, it may struggle to compete with a towed TEM system on a kilometer rate. To make a final decision on what equipment to use, quotes from providers of all this equipment could be sought.

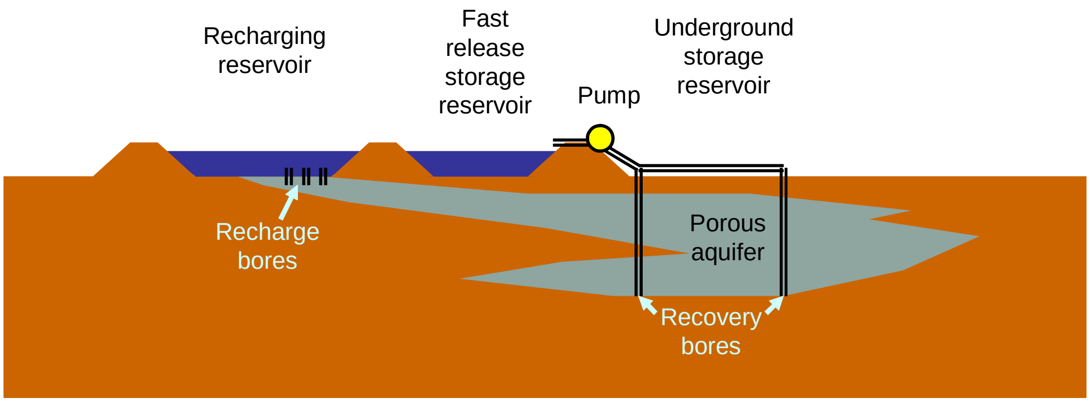

Figure 4 An example application of geophysical technology discussed in the text.

Now farmer X has a selection of geophysical tools he can use, he needs the data processed in an efficient data management and imaging system if he is to economically make use of the data. He will also need the data calibrated with deep penetrometer or borehole log data from shallow investigation holes he will need to drill. Some simple hydro-geological modeling could be done using the aquifer boundaries defined by the geophysics. Then full development could take place, bureaucracy permitting, and farmer X could have his underground water storage.

Table 1 A comparison of EC imaging devices. Note that prices are for April 2005 at country of origin before tax unless specified otherwise and are only approximate! Many options vary prices of most instruments.

Device	***Price***	***Coverage Rate***	***Configuration***	***Depths of Investigation***	***Development stage***	***Manufacturer***
FREQUENCY DOMAIN ELECTROMAGNETIC DEVICES – TERRESTRIAL and WATERBORNE						
EM38	US$9275 + $1500 for real time output	<10km/hr	HCP or VCP	0-0.75m VCP or 0-1.5m HCP	Production Extensively used in Australia	Geonics www.Geonics.com
EM38DD	US$22200	<10km/hr	HCP and VCP	0-1.5m in 2 layers	Production Extensively used in Australia	Geonics www.geonics.com
EM31-Mk2	US$22200 Contractors charge approx $1500 per day.	<10km/hr	HCP or VCP	0-6m HCP	Production Extensively used in Australia	Geonics www.Geonics.com
EM31-SH	US$21350	<10km/hr	HCP or VCP	0-3m HCP	Production	Geonics www.Geonics.com
EM34-3	US$26850	With 3 spacings/depths, 1 sounding every 5 to 10 minutes. Towed mode up to 10km/hour by special order.	3 x HCP or VCP, 10, 20 and 40m separations	0-60m in 3 fixed thickness layers, or 6 fixed thickness layers if both HCP and VCP are measured.0-40m in 3 layers	Production Limited history of use in Australia	Geonics www.Geonics.com

Device	***Price***	***Coverage Rate***	***Configuration***	***Depths of Investigation***	***Development stage***	***Manufacturer***
EM34-3XL	US$29350	With 3 spacings/depths, 1 sounding every 5 to 10 minutes. Towed mode up to 10km/hour by special order.	3 x HCP or VCP, 10, 20 and 40m separations	0-60m in 3 fixed thickness layers, or 6 fixed thickness layers if both HCP and VCP are measured.	Production	Geonics www.Geonics.com
EM31-3 Multi Rx Coil FDEM	<US$30000 predicted by April 2006	<10km/hr	3 xHCP or 3 x VCP	0-6m in 3 layers	Research ready. Production model proposed for April 2006.	Geonics www.geonics.com
DualEM2+4	Ask	<10km/hr	2 x HCP and 2 x perpendicular	0-6m in 4 layers	Production (new design)	DualEM www.DualEM.com
DualEM1s	Ask	<10km/hr	HCP and perpendicular	0-1.5m in 2 layers	Production	DualEM www.DualEM.com
DualEM2s	Ask	<10km/hr	HCP and perpendicular	0-3m in 2 layers	Production	DualEM www.DualEM.com
DualEM4s	Ask	<10km/hr	HCP and perpendicular	0-6m in 2 layers	Production	DualEM www.DualEM.com
DualEM2/4	Ask	<10km/hr	HCP and perpendicular	0-6m in 2 layers or 0-3m in 2 layers interchangeable	Production	DualEM www.DualEM.com
DualEM1+2+4s	Ask	<10km/hr	3 x HCP and 2 x perpendicular	0-6m in 5 layers	Production (new design)	DualEM www.DualEM.com

Device	***Price***	***Coverage Rate***	***Configuration***	***Depths of Investigation***	***Development stage***	***Manufacturer***
DT Barlow FDEM-8 System	US$6450 ex Johanesburg	One sounding each 15 seconds plus walking time.	HCP or VCP Operating at 8 frequencies to give, limited multi-depth information.	0-40m assumed Depth resolution of frequency sounding instruments is poor	Production	Red Dog Scientific www.geoafrica.co.za/reddog/barlow/emsystem.htm
Max Min	Ask	With 3 spacings/depths, 1 sounding every 5 to 30 minutes	HCP normally	0-200m in as many layers as the user wishes to individually measure	Production for fracture zone definition	Apex Parametrics, Tapio Vaarre, Canada, Phone +1 905 852 5875 (fax +1 905 852 9688)
Promis EM	not yet in production	With 3 spacings/depths, 1 sounding every 5 to 30 minutes	10 to 400m coil separation 10 frequencies from 110Hz to 56320Hz	0-200m in as many layers as the user wishes to individually measure	Design/ Construction	Iris Instruments www.Iris-Intruments.com
GEM 2	US$19600	<10km/hr	HCP or VCP with multiple frequencies $3A.m^2$	0-4m. Multiple frequencies do not significantly help resolve depths	Production	Geophex www.Geophex.com
GEM2H	>US$19600	<15km/hr – high moment receiver coils can allow faster survey if mounted with good suspension.	As for GEM2 but with large high moment receiver coils that allow one to collect high moment data.	As for GEM2	Production	Geophex www.Geophex.com

Device	***Price***	***Coverage Rate***	***Configuration***	***Depths of Investigation***	***Development stage***	***Manufacturer***
EM4 Genie HLEM	not yet available	<10km/hr	HCP or VCP with multiple frequencies. (smaller freq. range than GEM 2)	Not advertised but estimated at 0-4m	?	Scintrex www.LRScintrex.com
CM031	US$15390	<10km/hr	3.74m HCP or VCP	0-6m	Production, robustness limitations	GF Instruments www.giscogeo.com
CM032	US$14310	<10km/hr	2m HCP or VCP	0-3m	Production, robustness limitations	GF Instruments www.gfinstruments.cz
CM138	US$12690	<10km/hr	1m HCP or VCP	0-1.5m	Production, robustness limitations	GF Instruments www.gfinstruments.cz
MiniEM	US$6950 (Aug 2005) + case US$490 outside USA	<10km/hr	Coil separation 2m. 45 degree sloped Tx coil gives HCP + VCP $3A.m^2$	0-3m in two layers	Production predicted at Dec 2005	L and R Instruments www.L-and-R.com
GEO-ELECTRIC SYSTEMS – TERRESTRIAL and WATERBORNE						
Ohm-Mapper TR4	US$48880 including 5 receiver dipoles, a replacement parts kit and an ATV tow quick release device.	Up to 10 km/hour	Geo-electric bipole-bipole array with linear electrodes of 0.5m, 1m, 2m, 4m and multiples of 4m long.	0 to 30m except in highly conductive areas.	Production	Geometrics www.Geometrics.com

Device	***Price***	***Coverage Rate***	***Configuration***	***Depths of Investigation***	***Development stage***	***Manufacturer***
TerraOhm RIP924 receiver and ABEM ET200 transmitter	€16706 or SEK153700 ES10-64 switchbox SEK90000 5m roll along cables SEK90000 Alternate transmitters may be substituted for the ET200	<=10km/hr waterborne, approx 500m per hour using stakes and roll along cables on ground or much faster using a ripped in cable.	8 isolated channel continuous acquisition geo-electric system	8 layers as determined by geo-electric array configuration. Array is 5 times as long as depth of exploration.	Production ready	Terraohm Instruments AB Torleif.Dahlin@tg.lth.se
Terrameter SAS4000 LUND imaging system	Terrameter SEK 125000 ES10-64 switchbox SEK 90000 5m roll along cables SEK 90000	Dependant on time taken for field crew to hammer stakes into the ground.	Terrestrial geo-electric arrays – 5m interval roll along cables are commonly used.	0 to 30m typical in several layers/2D.	Production	ABEM Instruments AB www.ABEM.com
PACES (Pulled Array Continuous Electrical Sounding)	€550 per linear km including presentation, comprehensive reporting and interpretation	Walking speed. Advanced route planning advised.	A combination of Wenner and Pole dipole configurations in a 90m long pulled geo-electric array.	0-30m in several well resolved layers.	Production. 10's of 1000's of km covered.	Aahrus University Hydro-geophysics Group. www.hgg.au.dk

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
Corim	€17000 ex France	<10km per hour	6 capacitive dipoles placed perpendicular to array axis (Vol-de-Canards).	0-2m very well resolved.	Production but application appears to have only occurred in fields other than irrigated soils management.	Iris Instruments www.iris-instruments.com
Syscal Pro Switch, Sysmar	Syscal Pro Switch system with automated switching and multi-take-out cables €46000 ex France Sysmar software and calbes approx €2000.	<10km per hour in continuous waterborne mode. Terrestrial mode dependant on speed at which stakes can be hammered in and connected to cables.	Any geo-electric array may be connected but the device is designed for dipole-dipole arrays.	Dependant on electrode array design. 0 to 30m is typical. The instrument has ten input channels that permit many layers to be resolved if used appropriately.	Production	Iris Instruments www.iris-instruments.com
SuperSting R8, SuperString Marine.	Unknown	<10km per hour marine. Terrestrial rates determined by crew hammering in electrodes	Dipole Dipole arrays of various sizes are offered	0 to 30m typical	Production	Advanced Geosciences Incorporated. www.AGIUSA.com

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
GDP32-2	Ask	With roll-along cable, depends on speed at which electrodes are hammered into the ground. Waterborne <10km/hr.	Any geo-electric array may be used on water or land with the 8 channel receiver. May be used for Spectral IP measurement of hydraulic permeability of sandstones	0 to 30m with multi-layer resolution is typical. Any depth is possible.	Production. The multi-function equipment is suitable for experimentation with new techniques.	Zonge www.Zonge.com
SIP-256	Unknown	Up to approx 500m per hour estimated	Roll along cable instrument with digitizers on each dipole to reduce noise. Designed specifically for measurement of spectral induced polarization data useful for hydraulic permeability measurement.	0 to 30m typical with multi-layer resolution	Production	Radic Research www.radic-research.de

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
RESECS	Approx €36000 for a 48 electrode system.	Up to approx 500m per hour	Geo-electric array for use with a switchbox and hammer in electrodes. Up to 960 electrodes can be controlled by the switchbox.	Dependant on electrode array design. 0 to 30m is typical.	Production	Deutshe Montan Technologie GmbH www.dmt-gmbh.net/G5_EG/doc/mm_doc_03.html
Handy-Arm	Unknown	Approx 500m per hour	Roll along cables with hammer in electrodes. 90V 100mA	8 layers as determined by geo-electric array configuration. Array is 5 times as long as depth of exploration.	Production but documented in Japanese	OYO Corp. +81-29-851-6621 www.oyo.co.jp
MUCEP	Unknown	Walking speed.	Vol-de-Canards towed by motorized vehicle or Quadropole devices towed by a person Devices made of pronged wheels and/or capacitive wheels.	0 to 0.3m quadripole and 0 to 0.7m Vol-de-canards MUCEP with 3 layer resolution.	Research	Dept. de Geoph. Appliquee, Univ. Pierre et Marie Curie cpanissod@ccr.jussieu.fr
Veris Multisensor platform	Ask	<10km/hour – towed by 4wd or tractor	Wenner array of 6 plough disks approx 3m wide. pH is also sampled every 12 seconds.	0 to 0.6m in two layers.	Production – intensively marketed for precision soils management.	Veris Technologies www.veristech.com

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
TIME DOMAIN ELECTROMAGNETIC SYSTEMS – TERRESTRIAL and WATERBORNE						
NanoTEM	Ask	<10km/hour in towed mode.	TEM with turn off time as low as 2 us.	4-40m with 8 m x 8 m loop. Deeper with larger loops. Multilayer interpretation is possible.	Production, for use in towed mode, a sensor platform needs to be designed and constructed (see David.A1@bigpond.com for progress on platform).	Zonge Engineering and Research Organization. www.Zonge.com Zonge Australia office Adelaide -phone 08 83404308
terraTEM	A$45000 with continuous imaging option. Roving vector receiver coil A$6500	<10km/hour in towed mode.	TEM with turn off time as low as 2 us.	4-40m with 8 m x 8 m loop. Deeper with larger loops. Multilayer interpretation is possible.	Production, for use in towed mode, a sensor platform needs to be designed and constructed (see David@Allenhydrogeophysics.com.au for progress on platform).	Alpha GeoInstruments www.alpha-geo.com
PATEM (Pulled Array TEM)	€750 per linear km (Denmark) including presentation, comprehensive reporting and interpretation.	Walking speed	TEM with turn off time as low as 2 us. Slingram config.	Approx. 10 to 150m	Development but now replaced by SkyTEM in Denmark. Over 10000km surveyed.	Aarhus Universtiy HydroGeophysics Group. www.hgg.au.dk

Device	***Price***	***Coverage Rate***	***Configuration***	***Depths of Investigation***	***Development stage***	***Manufacturer***
PROTEM	PROTEM 47 full system ex Canada US$64150 Production cost €140 per sounding with comprehensive reporting and interpretation (Denmark)	<10km/hour in towed TEM mode (special order). Or dependant on speed at which personnel lay out loops if used in standard moving loop mode.	TEM – continuous mode operation is only available by special order	4 to 800 metres typical depending on loop size and transmitter power	Production only for the mode of operation in which loops are laid on the ground manually. 45000 soundings achieved for groundwater in Denmark.	Geonics Limited (Canada). www.geonics.com
SMARTem V Receiver (must be augmented by a transmitter and coil or electrode array).	A transmitter must be purchased separately from Geonics, Iris Instruments, or Zonge.	<10km/hour in towed TEM mode. Other modes dependant on configuration. A small mobile platform for use of SMARTem for shallow imaging is called TinyTEM	This is a multipurpose instrument set up for TEM, CSAMT and geo-electric surveying.	Typically deep but configuration is up to the user. It can mimic operation of many other instruments.	Production however the instrument has principally been marketed to the mineral exploration industry.	EMIT (Perth) www.EMIT.iinet.com.au TinyTEM – see www.Geoforce.com.au

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
AIRBORNE ELECTROMAGNETIC DEVICES						
SkyTEM	ESTIMATED at A$60-70 per kilometer at 60km/hr plus initial shipping to Australia (US$2500-3500 structure + personnel airfares) and processing. With helicopter estimated at A$100-A$120/line km.	30 to >100 km per hour depending on desired resolution, helicopter and flying height.	Rigid loop TEM with Z and X component receiver loop in a position of null coupling with transmitter loop. Dual moment with 2 us turn off time on low moment. 34us turn off time on high moment (100000 Am^2). Higher moments are planned for the future.	4 – 200m but depends on EC distribution in the ground. 5 layers AND their thicknesses can sometimes be interpreted.	Production. Much development ongoing.	SkyTEM www.SkyTEM.com
HOISTem	Ask	Not known	Flexible loop TEM suspended below a helicopter.	10 to 200m ?	Production	GPX, Western Australia www.gpx.com.au
Dighem Resolve	Ask	Up to 160 km per hour with a powerful helicopter.	Horizontal coplanar FDEM – one coil pair per frequency from 380 to 10100Hz.	Approximately 5m down to 150m in multiple layers but depends of geology.	Production	Fugro http://www.fugroairborne.com.au/Services/airborne/EM/dighem/index.shtml

Device	***Price***	***Coverage Rate***	***Configuration***	***Depths of Investigation***	***Development stage***	***Manufacturer***
VTEM	Ask	30 to 120 km per hour depending on desired resolution	Flexible loop TEM. Moments of up to 750000NIA but not simultaneously with fast turn off times	10-200m but depends on EC distribution and survey speed. Multiple layer interpretation is possible.	Production	Geotech www.Geotech.com
Humming-bird	Ask	Helicopter dependant	FDEM	Similar to Dighem but with less shallow resolution	Production	Geotech www.Geotech.com
Impulse	Ask	Helicopter dependant	FDEM	Similar to Dighem resolve but with less shallow resolution.	Production	Aeroquest www.aeroquestsurveys.com
AeroTEM	Ask	Helicopter dependant	Rigid loop TEM, Receiver in transmitter loop centre	Assumed to be similar to VTEM.	Production	Aeroquest www.aeroquestsurveys.com
GEM 2A Broadband	Ask	Helicopter dependant	5 m long FDEM bird with common Tx and Rx coils	Less than Dighem	Production	Geophex www.Geophex.com

EC Imaging using Frequency Domain Electromagnetic Devices – terrestrial and waterborne

The following frequency domain electromagnetic devices were reviewed:

- DualEM 2+4s
- DualEM2/4s
- DualEM4s
- DualEM2s
- DualEM1s
- DualEM1+2+4s
- Geonics EM31 multi
- Geonics EM34
- Geonics EM31mk2
- Geonics EM31sh
- Geonics EM38
- Geonics EM38DD
- Red Dog DT Barlow FDEM-8 System
- Iris Instruments Promis-10
- Apex Max-Min
- L & R Instruments MiniEM
- Geophex GEM2
- Geophex GEM2H
- GF Instruments CM031
- GF Instruments CM032
- GF Instruments CM138
- Scintrex FDEM

Frequency domain electromagnetic (FDEM or FEM) devices image EC in a region of the earth under the instrument using electromagnetically induced smoke rings of current that dissipate into the earth. Variable depths can be imaged by varying coil separation and/or orientation, the height of the instrument above the ground and/or operating frequency.

For efficiency of operation, FDEM instruments transmit a time-varying sinusoidal magnetic field. The sampling volume remains solely dependent on geometry as long as the frequency of the field is consistent with the low-frequency-approximation, as defined by Wait (1962.):

$$\left|(i\sigma_0\mu\omega)^{1/2}\rho\right| \leq 1/2$$

where i is the square-root of –1, σ_0 is the conductivity and μ is the permeability, respectively, of the material in the volume-of-exploration, ω is the angular frequency of the transmitted field, and ρ is the spacing between the transmitter and receiver (DualEM website, 2005). Set i to 1 use this equation for determining limits of the low frequency approximation. In Australia's salty conductive soils, the validity of this approximation is often borderline. In borderline cases, this does not prevent operators from using FDEM data in a qualitative way – calibrated using soil samples. The limitations of the approximation can be partially overcome by using rigorous inversion software such as IX1D to process the data.

Calibration of FDEM instruments is difficult and critical to their operation. Geonics argue that continuous re-calibration of FDEM instruments is necessary however this is not possible, and probably not necessary with the DualEM instruments, MiniEM or the Geophex GEM2 – only a rigorous comparative trail could tell. Although the DualEM instruments are sealed, tamper free calibration is possible and simple – it just needs to be done digitally on a computer after the survey where damage to the instrument by incompetent technicians is not possible.

Geonics have held the majority of the FDEM soil mapping market for many years.

Notes on the various FDEM instruments are as follows:

DualEM 1, 1s, 2, 2s, 4, 4s, 2/4, 2+4s and 1+2+4s

DUALEM instruments measure both in phase and quadrature signals to determine the conductivity and magnetic susceptibility of the ground, and detect buried metal. The patented DUALEM dual-geometry array simultaneously measures conductivity and susceptibility to two distinct and easily quantified depths.

DUALEM instruments are calibrated precisely and permanently at the factory using a patented technique, eliminating problematic *ad hoc* calibrations in the field. Precise calibration, base-level stability, high sensitivity and advanced digital signal processing give the instruments accuracy.

DUALEM instruments provide output to their RS-232 port in either NMEA0183-standard or DUALEM format. As NMEA0183 is the standard for GPS communication, a wide variety of GPS loggers and software can record DUALEM measurements and integrate them with GPS positions. This means that the signals can be fed into and the device controlled from Trimble DGPS systems such as are typically used in Australia for soil EC surveys.

The DUALEM-2 and DUALEM-4 are complete instruments, and the DUALEM-2/4 can be configured as either a DUALEM-2 or a DUALEM-4. The instruments incorporate monitors for applied voltage, temperature and configuration.

The DUALEM-1S, DUALEM-2S, DUALEM-1+2+4S and DUALEM-2+4S are sensors intended for use with external power and logging systems. The sensors incorporate monitors for applied voltage, temperature, pitch and roll. In common with all DUALEM instruments, the DUALEM sensors provide internal storage for time, grid position and measured quantities.

Dualem Inc. can be contacted on phone 1 905 876 0201, fax 1 905 876 2753, or e-mail address listed on www.dualem.com.

The following photos show how DualEM devices are designed for use in production surveying.

Figure 5 DualEM 2

Figure 6 DualEM 2s on a rudimentary sled (Photo: John Holman, USDA-ARS)

Figure 7 DualEM 2 on a highly robust sled with lots of impact absorption for reducing movement related noise. (Photo: A. Schumann, University of Florida)

Figure 8 DualEM 2/4 being operated on a non-conductive trailer. (Photo: Alpha Geoscience Pty. Limited)

Figure 8 shows the depth sensitivity curves for the two sensors in the DualEM 2 instrument. One may divide the depth scale by 2 to get DualEM 1 graphs or multiply by 2 to get DualEM 4 graphs.

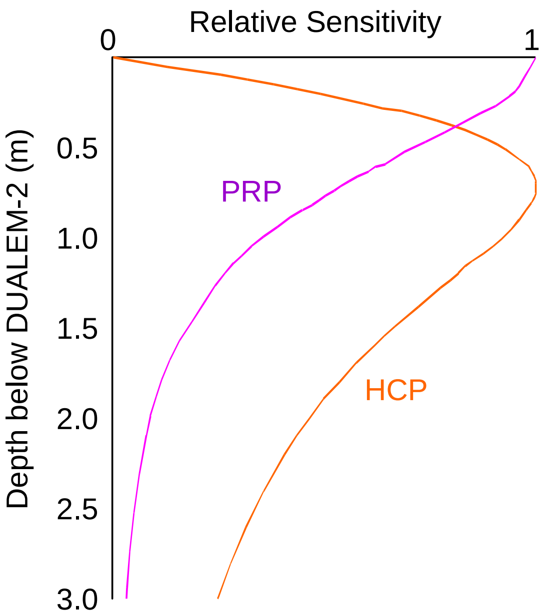

Figure 9 Incremental sensitivity with depth.

The DualEM-1+2+4s has six such depth sensitivity curves for the six different sensors it contains. This makes it an ideal instrument for precise multi-depth soil imaging. The cost of the DualEM-2+4s is however much less and the author believes that this is an instrument that will take most of the soil mapping market in the near future. This instrument can still detect four different depths. Because multiple depths have been sampled, good processing (inversion) could then resolve the shallow topsoil EC like the DualEM 1 (or EM38DD).

The DUALEM-2+4S sensor has dual-geometry receivers at separations of 2- and 4-m from the transmitter, which provide four simultaneous depths of conductivity sounding, four simultaneous depths of susceptibility sounding, and detection of metal.

Users control the DUALEM-2+4S sensor through its RS-232 port and supply power through the same connector. Users typically integrate the NMEA-format measurements with GPS positions on a logger.

The several sounding-depths of the DUALEM-2+4S enable the analysis of layering in the top several metres of the earth. The DUALEM-2+4S is suitable for towing on a sled or cart, or for carrying at hip height.

EM Systems	Horizontal Co-Planar (HCP) and Perpendicular (PRP)
System Configuration	2- and 4-m (HCP), 2.1- and 4.1-m (PRP) transmitter-receiver separations, operating at 9 kHz
Measured Quantities	HC2: HCP Conductivity in mS/m (3-m sounding depth) HC4: HCP Conductivity in mS/m (6-m sounding depth) PC2: PRP Conductivity in mS/m (1-m sounding depth) PC4: PRP Conductivity in mS/m (2-m sounding depth) HI2: 2-m HCP In-phase, in ppt of the transmitted field HI4: 4-m HCP In-phase, in ppt of the transmitted field PI2: 2.1-m PRP In-phase, in ppt of the transmitted field PI4: 4.1-m PRP In-phase, in ppt of the transmitted field Applied voltage, internal temperature, pitch and roll
Measuring Ranges ± RMS Noise	HC2, HC4, PC2 and PC4: -1000 to +1000 mS/m ± 0.1 mS/m HI2 and PI2: -300 to +300 ppt ± 0.01 ppt HI4 and PI4: -300 to +300 ppt ± 0.03 ppt
Data Capacity	50,000 records with time, grid position and measured quantities
Power Supply	external 12-V DC
Weights	11 kg operating, 30 kg shipping
Shipping Dimensions	245 by 25 by 15 cm

Geonics EM38DD

The Geonics EM38DD has a vertical coplanar coil set separated by 1 meter and a similar set in a horizontal plane. This instrument and the DualEM 1s are designed for topsoil and subsoil EC imaging. The two configurations of each of these instruments have focus depths of approximately 0.4m and 1.0m if operated at ground level, that is 70% of signal comes from 0.75m below the surface for the vertical coplanar or perpendicular configurations and 1.5m below the surface for the horizontal coplanar (vertical dipole) configuration.

Figure 10 Geonics EM38DD with GPS

Geonics EM31-mk2, EM31-SH

The Geonics EM31-mk2 has a focus depth of about 3 metres when used in horizontal coplanar mode, that means that, 70% of signal comes from above 6 metres depth. It can also be rotated 90 degrees to operate in vertical coplanar mode with a much shallower focus depth but this cannot occur during continuous acquisition. It has been the instrument of choice for most irrigation water infiltration and salinity studies in Australia for many years, being the only instrument of its type on the market until recently. In Australia it normally is operated from a quadbike using Trimble DGPS and logging solutions along with a trimble parallel swathing track bar, however, in Canada, the Geomar software used on an Allegro hand held computer is popular.

The EM31-sh is a 2m long EM31 designed for slightly shallower exploration.

Figure 11 Geonics EM31 with GPS.

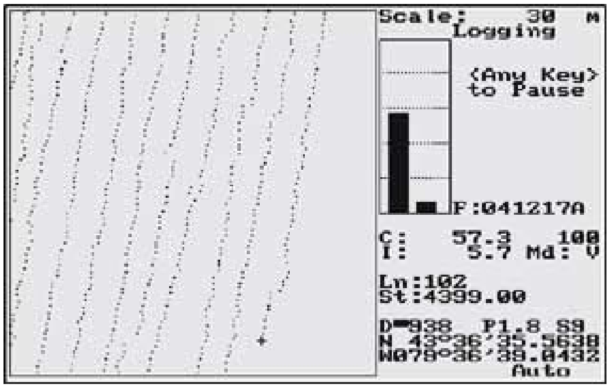

Figure 12 Geomar software – survey track plotting and signal level monitor for Geonics devices.

Figure 13 Juniper Systems Allegro handheld Windows CE computer used for new colour Geomar software currently in the process of being released. Here the Allegro is presented with the Trimble ProXH wireless connection GPS system.

Geonics EM34-3, EM34-3XL

The Geonics EM34 is a 10, 20 and 40m separation instrument for investigating depths from 3 to 60m. It can be used in horizontal or vertical coplanar mode so that six depths can be sampled. Unfortunately, each spacing and orientation combination must be set up one at a time at every sounding location. Towed mode operation is available by special order. Coil spacing is achieved by using the in-phase signal so reported EC values deviate from reality in highly conductive environments – such conductive environments are rarely encountered because, for each separation distance, a different frequency is used by the EM34 in order to optimize signal strength while keeping the instrument in the low induction number approximation range for most soil ECs.

Figure 14 Geonics EM34

Geonics EM31-multi

Geonics have built a multi-spacing FDEM instrument – the EM31-multi with 1, 2 and 3.66 meter coil spacings but have not yet refined the design. The design still has legacy aspects due to being made out barely modified EM31-Mk2 components. By April 2006 they expect to have the instrument refined. For comment on the instrument in its present form, Gary Parkin of the University of Guelph can be contacted on +519 824 4120. This instrument will hopefully become a replacement for the scenario commonly seen in Australia where contractors have quad bikes rigged up with both an EM38 and EM31. It is yet to be seen if Geonics modify the instrument for efficient trailer/sled based used rather than use carried on foot with the controller in the middle. When the controller is fixed into the middle of the instrument it is hard to rig it up for sled/trailer operation.

Geomar Software have developed the Multi31 program for logging of EM31-multi data simultaneously with GPS or DGPS data.

Figure 15 Allegro Pro4000 operating Geomar Multi31 (receiving GPS data and EM31 data from 3 different receiver coils).

DT Barlow FDEM-8 System

The DT Barlow FDEM-8 system is a very cheap South African substitute for the Geonics EM34 but has an automated reading procedure that takes about 15 seconds for all 8 frequencies scanned. Unlike with the EM34, only a single pass/separation is needed to obtain multi-depth data but this is frequency sounding data. If considering this instrument, see Geonics technical notes TN30 and TN31 regarding frequency sounding but realize that the large separations used with this instrument leave much of its data well out of the low induction number approximation. Also unlike the EM34, it uses a cable to determine separation so inphase data can be collected. Software for inversion that does not require low induction number approximations such as IX1D is needed to make sense of vertical differences in this data but for plotting of a simple map, data collected at just one optimal frequency would be chosen. In areas where cheap labor is available, this instrument could be most cost effective for imaging shallow aquifers adequately for bore siting at least in fractured rock areas.

In South Africa the instrument is used to find dykes, sills, and other features that constrain groundwater. For more details, contact reddog@geoafrica.co.za or look at www.geoafrica.co.za/reddog/barlow/emsystem.htm .

Figure 16 A Red Dog's DT Barlow FDEM-8 system coil. The system uses two coils, a transmitter and a receiver, like the Geonics EM34 but has some advantages over the EM34 including affordability.

Apex Parametrics Max Min

The Max Min is an instrument that has been used in mineral exploration for 10's of years. It is similar in design to both the FDEM-8 and EM34. It can operate at separations of up to 400m to image to depths as deep as 500m. Deep fractured rock aquifers can be isolated with this instrument. The Max-Min can be obtained from Apex Parametrics - Tapio Vaarre, Canada, Phone +1 905 852 5875 (fax +1 905 852 9688)

Iris Instruments PROMIS-10

The Promis-10 is an instrument that is very similar to the MaxMin except that it has a 3 component receiver. It has a digital controller and diagnostic display. It also is good for defining aquifers in fractured rock. Iris Instruments hope to market the Promis-10 soon.

Figure 17 Iris Instruments Promis-10 wide coil spacing triple orientation receiver coil FDEM instrument

L&R Instruments - MiniEM

The MiniEM is a FDEM device that is proposed to be on the market by the end of 2005 (see www.L-and-R.com) It is a 2m long FDEM device with a transmitter coil set at a 45 degree angle to horizontal and receiver coils in both the vertical and horizontal planes. This is a smart way of cheaply and robustly providing data at two depths by emulating both horizontal coplanar and vertical coplanar modes of operation.

Figure 18 L&R Instruments MiniEM

Geophex

Geophex have produced the GEM 2, pictured below. It is 2m long FDEM device that operates at multiple frequencies in order to visualize multiple depths as well as resolve metallic targets. Geonics have presented theory that shows that multiple frequencies are of very limited use for vertical resolution in such an instrument (see TN notes 30 and 31 on their web site) however one can observe a vertical image created using the rigorous Interpex IX1D program and data from a GEM 2 displayed in the Interpex section below.

Geophex offer a PDA with software that images GEM2 data on the fly as you watch your track, as logged by GPS, on the screen. This can help a lot with quality control in the field.

Figure 19 Eric White (USGS, OGW, Branch of Geophysics), conduct a geophysical survey in Nebraska using a Geophex GEM2 multi-frequency electromagnetic sensor.

Figure 20 Various field implementations of the Geophex GEM2.

GF Instruments

Instruments with very similar specifications to the Geonics EM31, EM38 and EM31s can be purchased from GF Instruments of Czechoslovakia - www.gfinstruments.cz but at a cheaper price. It has been suggested that rigidity of these devices is less than that of Geonics devices. They use a HP calculator as a data logger. No mention of simultaneous GPS logging was found on the GF Instruments web site.

Figure 21 GF Instruments CM-031

Figure 22 GF Instruments CM-032

Figure 23 GF Instruments CM-138

LR Scintrex

Scintrex have reportedly developed a multi-frequency FDEM device similar to the Geophex GEM2 but with a more limited range of operating frequencies. The device, EM4 Genie HLEM, is not yet publicly marketed.

EC Imaging using Geo-electric devices – Terrestrial and Waterborne

Geo-electric devices have an advantage over FDEM devices in that they use simple electric fields rather than complicated electromagnetic phenomenon. This means that they can produce much less ambiguous data in some situations. They also have a severe disadvantage in that they must make good electrical contact with the ground. This is fine on water but difficult to achieve on land without use of electrodes hammered into the ground. Some devices use capacitive coupling to overcome this problem while others use weight, ploughing devices and innovative electronics.

The following geo-electric devices were compared:

- Geometrics Ohm-mapper TR4
- Veris Technologies Mobile Sensor Platform
- Terraohm Instruments AB RIP 924 Mk2
- Aarhus University Hydrogeophysics Group PACES
- MUCEP
- Iris Instruments Corim
- ABEM Terrameter and Lund Imaging system.
- AGI Sting Swift Instrument series
- Iris Instruments Syscal Pro
- Zonge GDP32-2
- Radic Research SIP256
- DMT's RESECS
- Oyo Handy-Arm

Continuous Terrestrial EC Imaging - Geometrics Ohm-mapper

The new Geometrics OhmMapper is a capacitively-coupled resistivity meter that measures the electrical properties of rock and soil without cumbersome galvanic electrodes used in traditional resistivity surveys. A simple coaxial-cable array with transmitter and receiver sections is pulled along the ground either by a single person or attached to a small all-terrain vehicle. Thus, data collection is many times faster than systems using conventional DC resistivity.

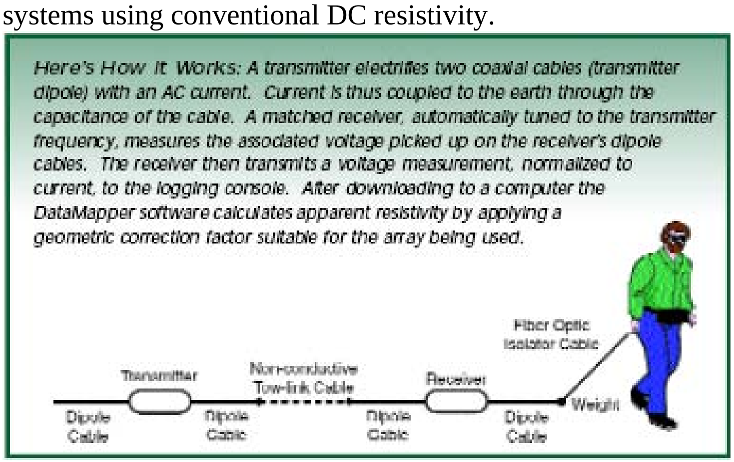

Figure 24 The Ohm-mapper with 2 transmitter and 2 receiver electrodes. A full system has 6 receiver electrodes.

The first introduction of this device to Australia did not make much impact but the instrument has since been greatly enhanced. A single dipole version of this device has been trialed in Australia by Monash University but it failed to gain a market because it collected basically the same data as Geonics EM31 instruments, already popular in Australia, but at a higher cost. The device now can be operated with 5 receiver dipoles which allow it to sample 5 different depths simultaneously. It easily samples to a depth of 20 metres at most locations. It can be towed efficiently behind a quadbike using a safety coupling and disposable sleeves that cover protrusions on the electrode array that drag along the ground. The electrode array needs to be about 5 times as long as the focus of the depth of investigation of the instrument so there is a limit to how sharply the device can be dragged around corners without the assistance of somebody lifting and dragging the array. This means that, when used to survey paddocks in a grid pattern, every 2nd or third line would be surveyed first and then the other lines would be infilled on a second pass.

Figure 25 A capacitively coupled resistivity meter towed behind an all-terrain vehicle in Nebraska. The capacitively coupled resistivity meter (the cable and white tubes) consists of a

coaxial-cable array with transmitter and receiver sections. (Source – USGS OGW Branch of Geophysics website)

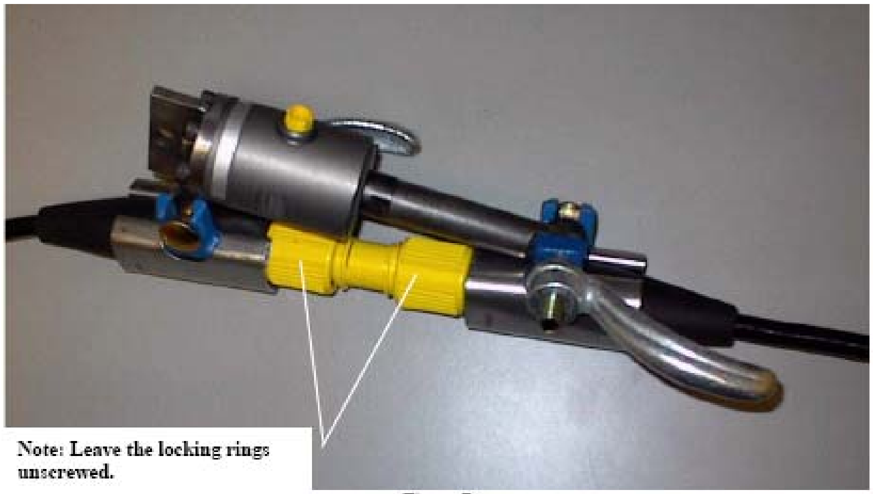

Figure 26 The limited strain coupler used to save the Ohm-mapper cables in case they get caught when being towed behind a quad bike.

Continuous Terrestrial EC Imaging - PACES

Aarhus University Hydrogeophysics Group have developed a geo-electric system that they call 'Pulled array continuous electric sounding – PACES'. A 300kg geo-electric array is towed behind a tractor of design similar to the Australian 'Dingo' excavator. The array is so heavy that it makes sufficient ground contact to operate continuously, with production efficiency, on the moist Danish soil. It images in detail down to about 30m deep. The device has been used to image for 10's of thousands of kilometers over various aquifers of interest in Denmark. PACES uses special controlled impedance electronics and selective stacking to cope with poor ground contact. Use of this or a similar device in Australia would be more difficult because our climate results in drier topsoil usually. We would probably need to plough the cable deeper. Trials by the author have suggested that it is plausible. It is the authors opinion that recent invention of the Geometrics Ohm-mapper multi-dipole system is, however, likely to make the PACES system uncompetitive. PACES main advantages are that it can image deeper than the Ohm-mapper and it is not affected by skin depth issues in conductive soils like the Ohm-mapper.

Figure 27 The PACES device being towed along near Aarhus, Denmark. The 300kg 90m long geo-electric cable is being towed behind a tracked vehicle similar to the Australian 'Dingo' mini-earthmover. The system images to a depth of about 30m provided that the ground is moist.

Figure 28 A PACES system electrode making contact with moist soil in a groove ploughed by the towing tractor.

Continuous Shallow Terrestrial EC Imaging - Veris Technologies

Veris technologies have produced a geo-electric array mounted perpendicularly behind a tractor or 4wd and made up of coulter disks. It senses two depth intervals: 0-0.3m and 0-1m deep. It also senses pH at 0.1m depth every 12 seconds using a hydraulically controlled sampler, ion sensing electrodes and a water reservoir that cleans the electrodes and sampler. In recently cultivated, dry or cloddy soil the device may not maintain good ground contact resulting in inferior measurements to EM devices such as the Geonics EM38DD. This instrument has been intensively marketed for precision soils management and is discussed much in the United States Salinity Laboratory research documents.

Figure 29 The Veris mobile sensor platform with electrodes sensing EC at 0.0-0.3m and 0.0 to 1.0m and pH at 0.1m depth every 12 seconds.

Continuous Shallow Terrestrial EC Imaging - Iris Instruments Corim

This instrument is available from http://www.iris-instruments.com . The Corim is a capacitively coupled resistivity imaging device for detailed imaging of the rootzone. Data produced and a photo of the instrument provided here indicate its capabilities. Coupling to the ground when the instrument is towed across uneven ploughed ground may result in noisy data. The author suspects that the linear electrodes of the Geometrics Ohm-mapper have greater coupling capability than the small plate electrodes of this device. Intending buyers should therefore discuss this limitation with both suppliers before purchase. This device is designed to image the rootzone in much more detail than the Ohm-mapper.

Figure 30 The Iris Instruments Corim.

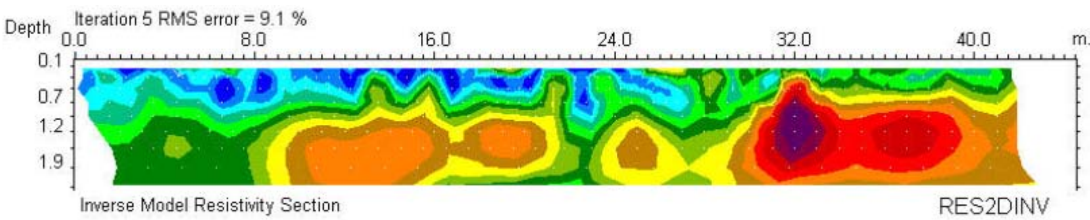

Figure 31 A sample of processed Corim data showing detailed variation in EC of a soil profile.

Continuous Shallow Terrestrial EC Imaging – MUCEP and RATEAU

Geo-electric arrays that use wheels with prongs that penetrate the soil and capacitive electrodes inside the tyres of wheels have been created by the Univertite Pierre et Marie Curie Department de Geophysique Appliquee and the Centre de Recherches Geophysiques. A shallow penetrating quadripole geo-electric array was designed for an operator to tow while walking and a vol-de-canards geo-electric array was designed for towing behind a tractor or car. Observation of the photos below will explain the device configurations. The devices sample at <0.01s in order to selectively reject bad quality data. The devices have been called RATEAU (Resistivimetre ATtele a Enresistremente AUtomatique) and MUCEP (Multi-pole Continuous Electrical Profiling).

Figure 32 A Capacitive MUCEP

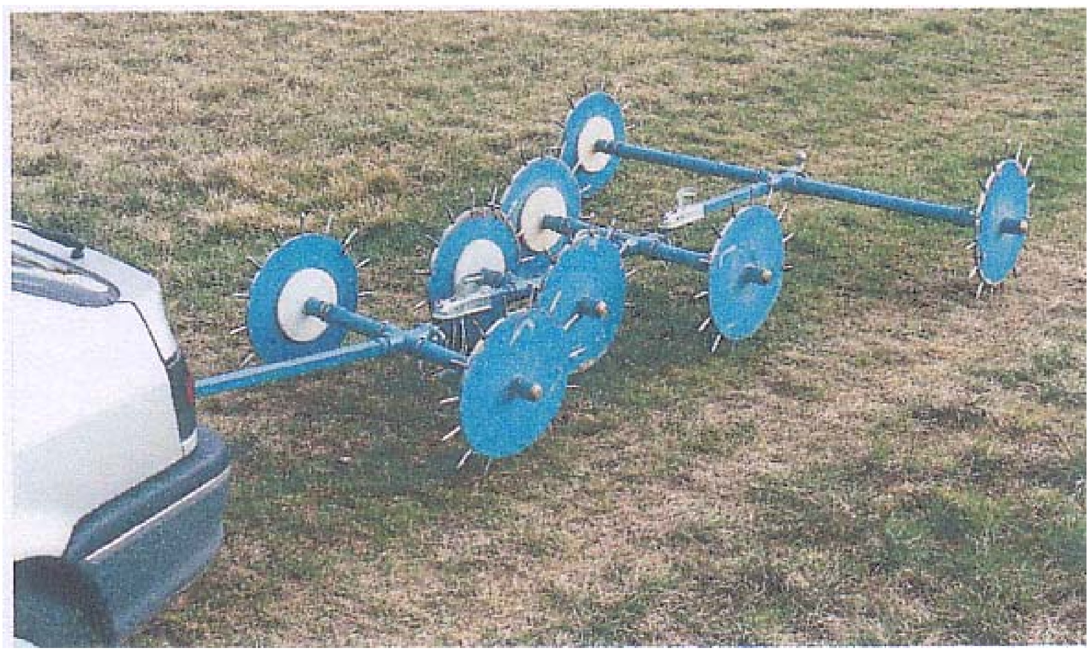

Figure 33 A Spiked wheel MUCEP

Waterborne and Terrestrial EC and IP Imaging - ABEM Terrameter and Lund Imaging System and the Terraohm Instruments AB RIP924.

ABEM marketed what was probably the first automated geo-electric EC imaging system and have upgraded that system progressively over the years. Electrodes are laid out and sequentially utilized by an automated switchbox – the Lund Imaging System developed by Torleif Dahlin of Lund University. The system has 4 isolated receiver channels and is compact. ABEM argue that 4 channels is enough to enable the instrument to collect data as fast as cables can be connected to electrodes when used with the automated switchbox.

Competing receivers have 1, 8, 10 or more channels. Common competing receivers do not however have isolated inputs.

For aquifer imaging, it can be used in production mode if only a few transects are needed to resolve an aquifer ready for siting a bore. Timms and Acworth (Timms, 2002 and Charlesworth, 2005), have used it for spatially detailed soil moisture imaging in the Liverpool Plains, NSW, but due to survey speed, it is not appropriate for production soil surveying such as is typically conducted with the Geonics EM31 and EM38. Acworth is continuing to develop a means of using this instrument for efficient bulk soil moisture sampling in cracking soils.

Figure 34 The ABEM Lund Resistivity Imaging System

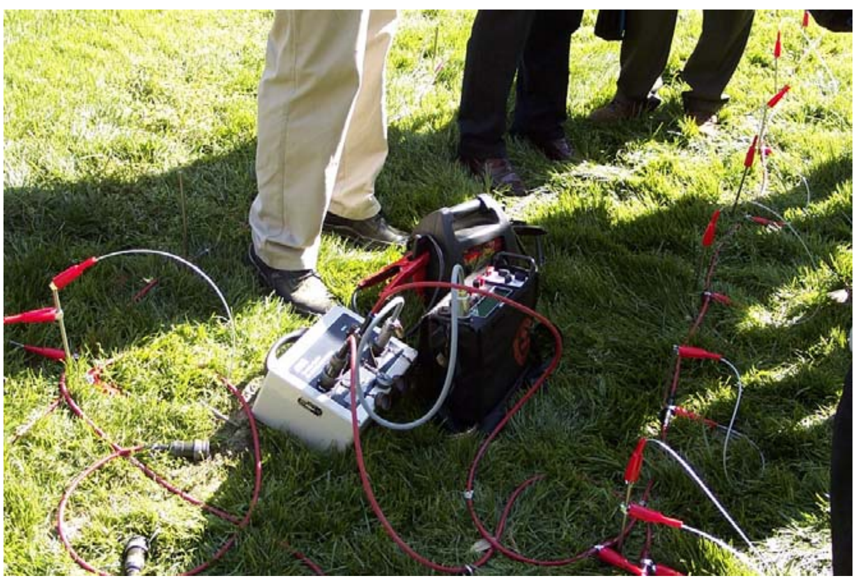

Figure 35 The ABEM SAS 4000 Terrameter and Lund Imaging System with electrodes laid out in a miniature array for demonstration purposes.

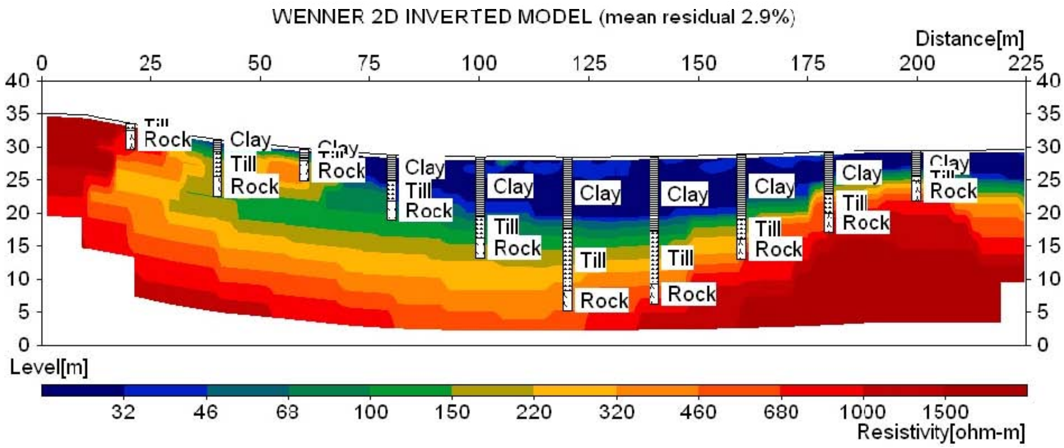

Figure 36 Multi-depth EC data, collected with a ABEM SAS4000, accompanied by drill hole ground truthing.

Combination of the TerraOhm RIP 924 Mk2 and ABEM ET 200 with a compact computer running MS Windows 2000 or XP results in a compact continuous geo-electric imaging system for use in waterborne mode with a floating or submerged cable or in cultivated ground with a towed ripped in cable or hammered in stakes. This device, which was initially developed for marine cable routing surveys, has fully isolated inputs that permit large voltages to be measured from some electrodes without compromising measurement of small voltages received from other electrodes. Further information is available from torleif.dahlin@tg.lth.se . This instrument collects both EC and induced polarization (a property related to clay content) data on 8 channels with 24 bit resolution continuously.

Figure 37 The RIP924 from Terraohm Instruments AB

Waterborne and Terrestrial EC, IP and SIP Imaging - Zonge Engineering and Research Organization

Zonge have produced a multipurpose geophysical data processor, the GDP32, that can be used for all types of geo-electric surveying. It is used with a battery powered transmitter and voltage booster for this purpose. The system can be used for any type of waterborne or terrestrial geo-electric survey, as well as most types of electromagnetic survey and magnetotellurics. It is therefore more expensive and cumbersome than equipment dedicated to geo-electric surveying. Individual inputs can be attenuated in order to measure voltages up to 40V without compromising measurement of other lower voltages received on other electrodes. The author has used Zonge equipment for many surveys without any major problems. Both EC and induced polarization (a property related to clay content) data was successfully collected on 8 dipoles using this instrument by the author.

The GDP-32 can collect induced polarization and spectral induced polarization data in frequency domain rather than time domain. This enables it to image hydraulic permeability in some types of geology. See Zonge – NanoTEM for equipment photo.

Terrestrial EC and SIP imaging - SIP-256 from Radic Research.

Radic Research have very recently released a high performance geo-electric imaging system specifically designed for spectral induced polarization imaging that can be used as a hydraulic permeability indicator in some types of geology. On each dipole, it has a box that digitizes signal for noise reduction.

Figure 38 Radic Research SIP-256

Waterborne and Terrestrial EC Imaging - Iris Instruments Syscal Pro (Marine and Switch)

This instrument is available from http://www.iris-instruments.com . It can measure 10 channels of geo-electric data from waterborne or terrestrial arrays (using an automated switchbox and multicore roll-along cable. It has a +/-15 volt range with reference to its second electrode which limits its ability to measure data from arrays with very large differences in input voltages. It does however have 1000V input protection. The transmitter, controller and some memory are all boxed with the receiver in a very compact way (see photo). For waterborne surveys it should be used with a computer and GPS/Sounder. Software sold separately allows the operator to see imagery as it arrives and log it with GPS and sonar data. The author collected waterborne data on two occasions with a Syscal Pro rented from www.Geoforce.com.au in Perth but used internal storage rather than purchasing a computer and software for external logging as shown in figure below. Without the external computer, it was very difficult to use the Syscal Pro to collect waterborne data due to lack of facility to check data as it was collected – nevertheless, a lot of data was successfully collected and the compactness of the instrument was greatly appreciated. In waterborne mode the instrument cannot collect induced polarization data.

Figure 39 The Iris Instruments Syscal Pro geoelectric imaging device.

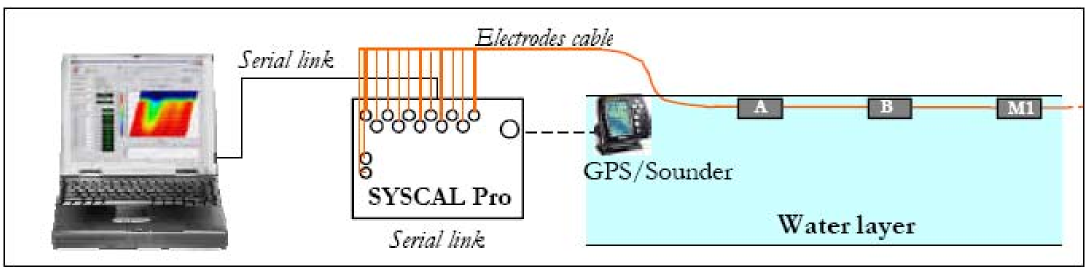

Figure 40 The Iris Instruments Syscal Pro and a Garmin GPS/Sounder 188 setup with a computer running Sysmar software for waterborne geo-electric imaging.

Waterborne and Terrestrial EC Imaging - Advanced Geosciences Incorporated

AGI (www.AGIUSA.com) have produced instrumentation very similar to that of ABEM. They produce 1 and 8 channel instruments and an instrument for waterborne surveying. They also produce automated electrode switching systems and multi-core arrays. They have gained much of the USA market. Currently their system is limited to 5V input which makes it difficult to use with optimized waterborne arrays but they wish to increase this limit to 15V like the Syscal Pro. Like the Syscal Pro, their instruments do not have isolated inputs but rather a ground on channel 2.

Figure 41 The AGI Super Sting R8 IP Earth Resistivity/IP Meter.

Figure 42 The AGI Marine Resistivity Imaging System

AGI have created extensive software resources for their instruments. They have also created telemetry support to permit their equipment to continuously monitor changes occurring in aquifer salinity in the vicinity of geo-electric arrays permanently set up in drill holes.

Detailed Terrestrial EC Imaging - RESECS

Deutshe Montan Technologie GmbH have produced a geo-electric system which can handle up to 960 electrodes using addressable electronics packages on top of each electrode. The system is good for focused high value imaging such as for archaeology but its features are not needed for soil imaging. Being a terrestrial system that requires stakes to be hammered into the ground, it is not efficient for soil surveying.

Terrestrial EC Imaging - Handy-Arm

A Japanese company – Oyo – has recently entered the geo-electric equipment manufacture market. They have produced a basic roll-along cable style of instrument for terrestrial use called Handy-Arm.

EC Imaging using Time Domain (Transient) Electromagnetic Devices - Terrestrial and Waterborne

Time domain devices are good at efficiently imaging deeply but struggle to resolve the first 5 metres of the earth. When towed behind a vehicle on a non-conductive trailer, they prove to be very efficient aquifer imaging devices. They require a large transmitter coil to be set up and a receiver coil placed nearby. They have been used for years in mineral exploration but in mineral exploration the loops are laid out by hand. For groundwater exploration, manual loop laying rarely can be justified and loops small enough to be towed need to be used. There is little difference between towed TEM systems and many airborne systems except for technological appeal, speed of coverage and cost of dealing with aircraft. The following TEM devices are discussed below:

- Zonge NanoTEM
- Geonics Protem47
- Geonics Protem57
- PATEM
- TerraTEM
- SMARTem

With most of these devices, it is not principally the device that will result in success or failure of a survey but the way in which it is set up and operated.

Zonge NanoTEM

Zonge have produced the NanoTEM system for shallow TEM exploration - 5 to 100m deep. They used it with a floating loop towed behind a houseboat to image salinity beneath the Murray River in South Australia. The author has a comparison of this data with waterborne geo-electric data in his thesis and which will be published at the IAH conference proceedings in December 2005. The NanoTEM system is robust and incorporated channels as soon as 2 microseconds after turn-off so that it can see as shallowly as possible.

The author has successfully used the NanoTEM with a towed 8 x 8 m loop to find and resolve depths of prior streams in the Murrumbidgee Irrigation Area. 25 kilometers could be surveyed in one day.

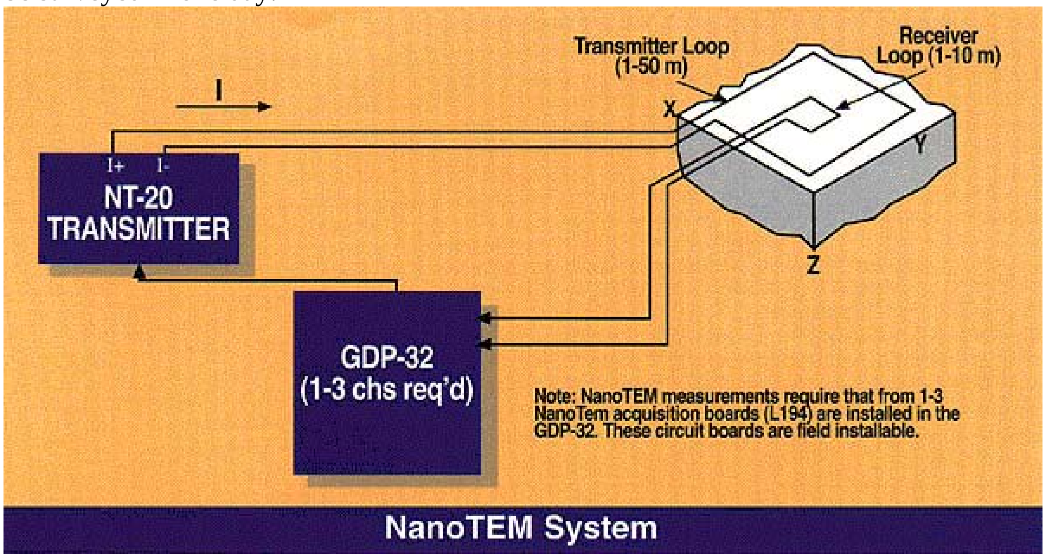

Figure 43 A schematic of the NanoTEM system in operation.

Figure 44 The Zonge GDP32-2 with an embedded NanoTEM Transmitter.

Geonics PROTEM 47 and 57

The Geonics PROTEM 47 system is designed with fast response like the NanoTEM so that it can be used to image shallow aquifers. Geonics however only have supported continuous acquisition only by special order rather than routinely in their PROTEM so PROTEMs currently in Australia are probably not currently equipped for towed TEM surveying. They are however ideal for moving loop surveys over deeper aquifers where loops must be laid out manually. In Denmark, 45000 such 40 x 40m loops were laid out in order to image shallow aquifers before the SkyTEM system was put into production there.

PROTEMs have a very clear real time display of data that saves a great deal of time in field data acquisition due to the ability to detect noise levels, anomalies and unwanted effects of metallic objects very clearly. Comparitive tests of noise levels of various instruments have proved that the PROTEM can collect low noise data. Protem 57 is a more powerful version of Protem 47 and can image to depths of hundreds of meters.

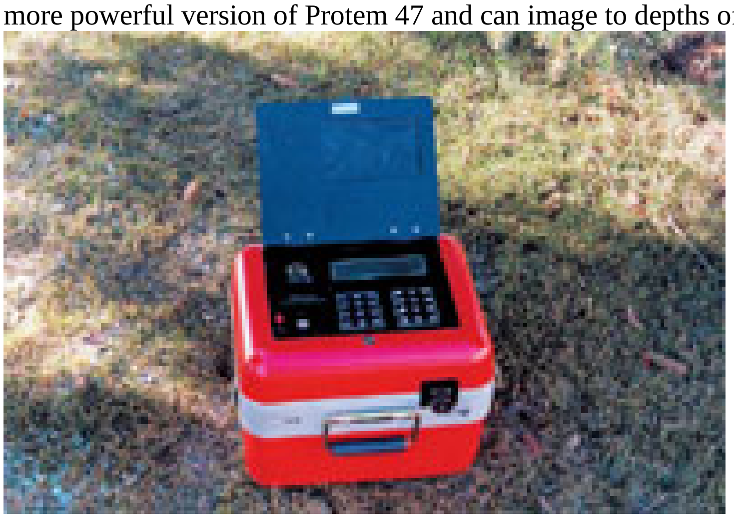

Figure 45 Geonics Protem.

PATEM

Aarhus University Hydrogeophysics Group have been towing a large TEM device across the ground for some years. The device can image over 100 meters deep with multiple layer resolution. They have now moved all their PATEM technology into their airborne TEM system – SkyTEM. In Denmark, numerous fences and land access issues make PATEM surveying less efficient than SkyTEM. The scenario in Australia is very different and so PATEM, or similar devices, has potential here for aquifer imaging. It was found that the PATEM system, which has its receiver coil towed behind the transmitter coil, coped poorly with lateral inhomogeneities. PATEM has a low and high moment transmission that allows both shallow and deep data to be imaged.

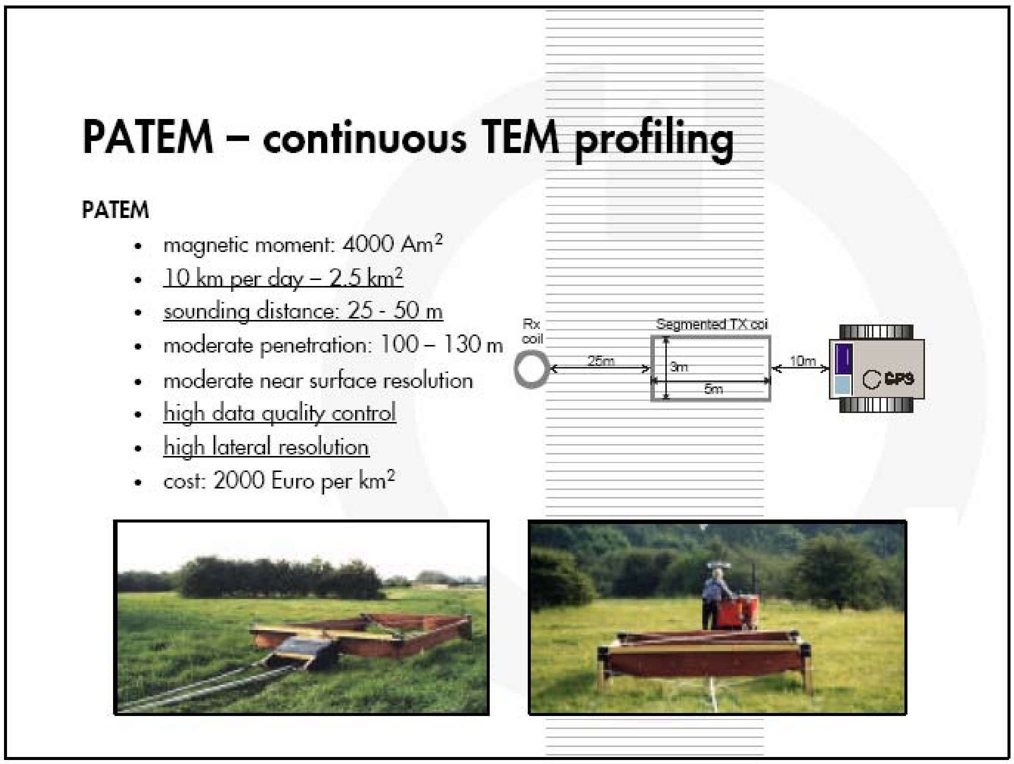

Figure 46 The Aarhus Hydrogeophysics Group PATEM device.

TerraTEM

TerraTEM is a new instrument being produced from Monash University and marketed by Alpha Geoscience. It has capabilities very similar to the Zonge NanoTEM. It is a suitable instrument for towed TEM surveying.

SMARTem

SMARTem developed by EMIT in Western Australia is a receiver only device that can mimic many other TEM receivers. It must be used in conjunction with a transmitter made by Geonics, Iris Instruments or Zonge. It has not been marketed for hydrogeological and environmental purposes. Geoforce of Western Australia set up a very small towed loop system with this device and called it TinyTEM.

EC Imaging using Magnetotellurics - Terrestrial

Magnetotellurics, including CSAMT, CSAET and other techniques with similar acronyms are useful for deep detection of inclined low EC features influencing groundwater flow. Zonge have successfully used the technique to site deep expensive drill holes in deep fractured rock aquifers. Both theory and practice of magnetotelluric imaging are complicated but images produced by reputable operators usually are suitable for the layman to interpret.

EC Imaging using Airborne EM

EC imaging using airborne EM systems is good for large aquifer or aquitard definition surveys but not for soil imaging. Such devices must strip out the effect of instrument altitude from the data. This makes it impossible to accurately image topsoil. Usually data is only reliable 10 meters or more beneath the ground but thickness x conductivity of shallower conductive surface layers can also be resolved. Some airborne systems can see hundreds of metres into the ground but most cannot simultaneously resolve shallow and deep features.

The following airborne EM systems have been reviewed:

- SkyTEM
- Dighem Resolve
- GeoTech VTEM
- GeoTech Hummingbird
- GPX HoistEM
- Aeroquest TEM
- Aeroquest Impulse
- Geophex GEM 2A Broadband
- Towed bird fixed wing TEM such as SaltTEM, GeoTEM and MegaTEM.

SkyTEM

SkyTEM is an airborne EC imaging system designed specifically for imaging aquifers. It has a combination of numerous technological advances not present in other airborne EC imaging systems. This combination gives it the ability to resolve shallow aquifers just as well as ground based TEM systems, such as the PROTEM47, while also resolving deep aquifers – typically as deep as 250m. It transmits alternately through low and high moment loops. Its X and Z component receiver coils is situated in a null-coupling arrangement and the transmitter loop is rigid resulting in very low noise levels. The X component data improves resolution of upper layers if correctly processed. Footprint is small. Kevlar and timber 3D truss construction have resulted in weight of 300-350kg, low enough for the equipment to be operated beneath a Eurocopter EC120 Colibri (sling load limit of 700kg) or Bell Jetranger (A$900 per operating hour), or, in hot climates, a Bell Longranger helicopter (A$1200 per operating hour). All equipment apart from a laptop used to guide the pilot are outside of the helicopter so no special certification of installation is required – any suitable helicopter can, therefore, be used for survey as soon as it is available. The instrument is operated from the ground so that the weight of an operator is not included in the helicopter payload. Software for processing allows users to interactively reject data affected by metal items such as fences and transmission lines before presenting data to users.

Compared to the Dighem Resolve system, SkyTEM can see deeper, resolve layers just as well, use smaller helicopters with no installation hassles and does not require extensive dataset calibration. If SkyTEM can gain a market share similar to that of Dighem, then the author believes that it will cost less per kilometer than Dighem. The author believes that SkyTEM and airborne FDEM devices such as Dighem are the most suited devices for airborne imaging of aquifers – other airborne devices will therefore not be directly compared here. For shallow aquifer definition, a significant difference between SkyTEM and Dighem is calibration. The SkyTEM system itself is calibrated and stable and thus produces data that is absolutely calibrated while Dighem data surveys conducted in

Australia have required lots of complicated calibration involving EM39 borehole logging before shallow features could be resolved.

Figure 47 SkyTEM rigid helicopter-borne transient electromagnetic system with null coupled receiver coil.

Mobilization of the bulky SkyTEM frame segments may be conducted long before a survey begins and electronics may be hand carried to the survey site when the frame has arrived so that mobilization costs are minimal. Shipping to Australia is planned for the end of 2005.

The Aarhus Hydrogeophysics Group have an extensive and highly refined interactive processing system developed for processing SkyTEM data. This system allows trained operators to selectively remove interference from fences and transmission lines from datasets so that they only reflect aquifer properties. Processed SkyTEM data then appears as shown below.

Technical specifications: SkyTEM has dual moment transmission which means that, with other advances, it can transmit a 100000Am^2 moment (higher if a larger generator is used) with a 34 microsecond turnoff and then transmit a low moment signal with a 3 microsecond turnoff. Survey speeds of 100km/hour have been achieved. Speed is determined by helicopter power and desired flying height which both affect resolution. SkyTEM has multiple altimeters and tilt meters on it. Data is processed to remove altitude effects as well as tilt effects. Although helicopter power can be used to operate SkyTEM, it is best to supply power to it using a sling loaded generator. A thorough appraisal of SkyTEM features is given in Sorenen and Auken (2004). Be aware that numerous major advances have been made in SkyTEM development since the article was written.

Figure 48 SkyTEM being lauched.

Figure 49 SkyTEM interactive processing. Fences and powerlines are identified on a map showing flightlines and data at the intersections is manually observed and removed if it appears as if it could be affected.

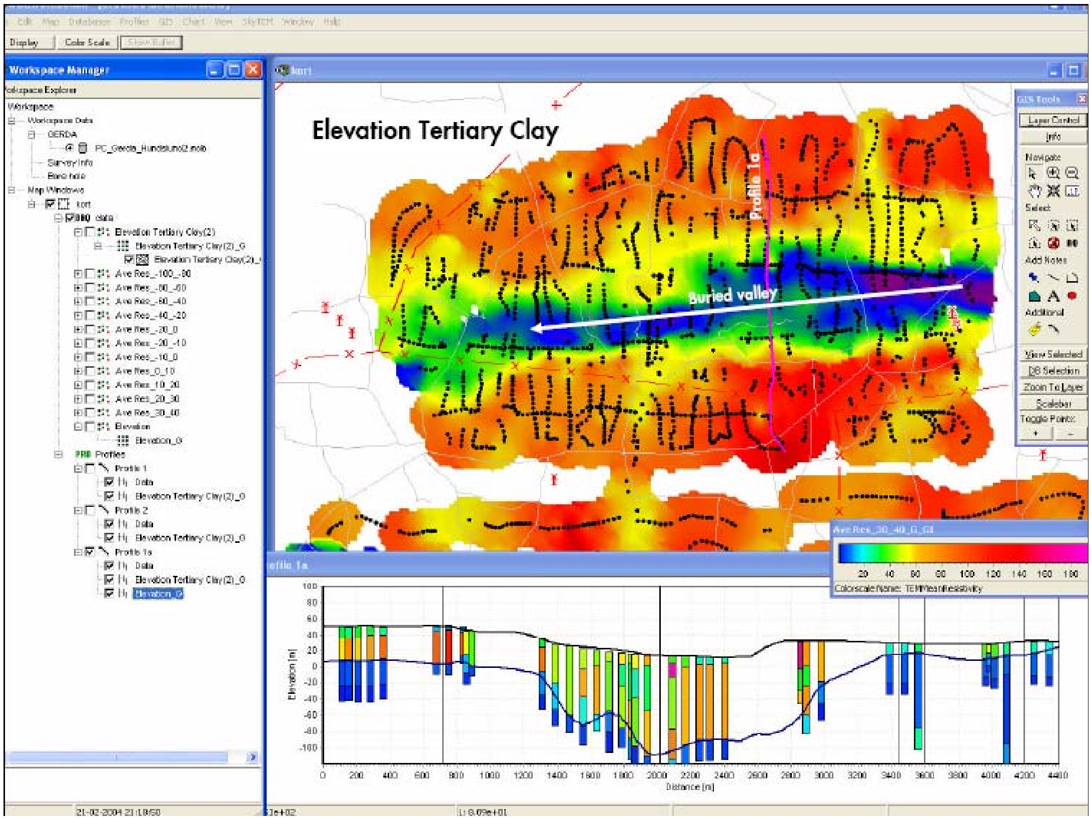

Figure 50 An example of processed SkyTEM data presented in the 'Workbench' package.

Fugro Dighem

Dighem Resolve has been used in Australia, Europe and Namibia for investigation of aquifers and aquitards. In South Australia it resolved, after extensive calibration using EC logs of drill holes, thickness of the Blanchtown Clay, an aquitard. In Namibia, it resolved locations of paleochannels suitable for extraction of fresh water. In Germany it identified salty aquifers adjacent to aquifers filled with fresh water from melted snow.

The Dighem system is a frequency domain electromagnetic instrument with separate transmitter coils for separate frequencies. The DighemVRES has five coplanar horizontal coils operating at frequencies ranging from 380 Hz to 10100 Hz and is specifically designed for layered earth geology resolution. Other airborne FDEM systems use both co-axial and coplanar coils. This means that they are more suited to finding vertical conductors rather than aquifers which are usually layered. It is claimed to be capable of imaging up to depths of 150m in some terrains. It must be lifted with a moderately large payload helicopter (eg. Eurocopter AS350B Squirrel) and components housed in and on the helicopter must be certified in each helicopter they are installed in. The instrument itself has a 50 to 100m footprint but smoothing conducted when using tie lines to extrapolate calibration data through Dighem datasets also affects footprint.

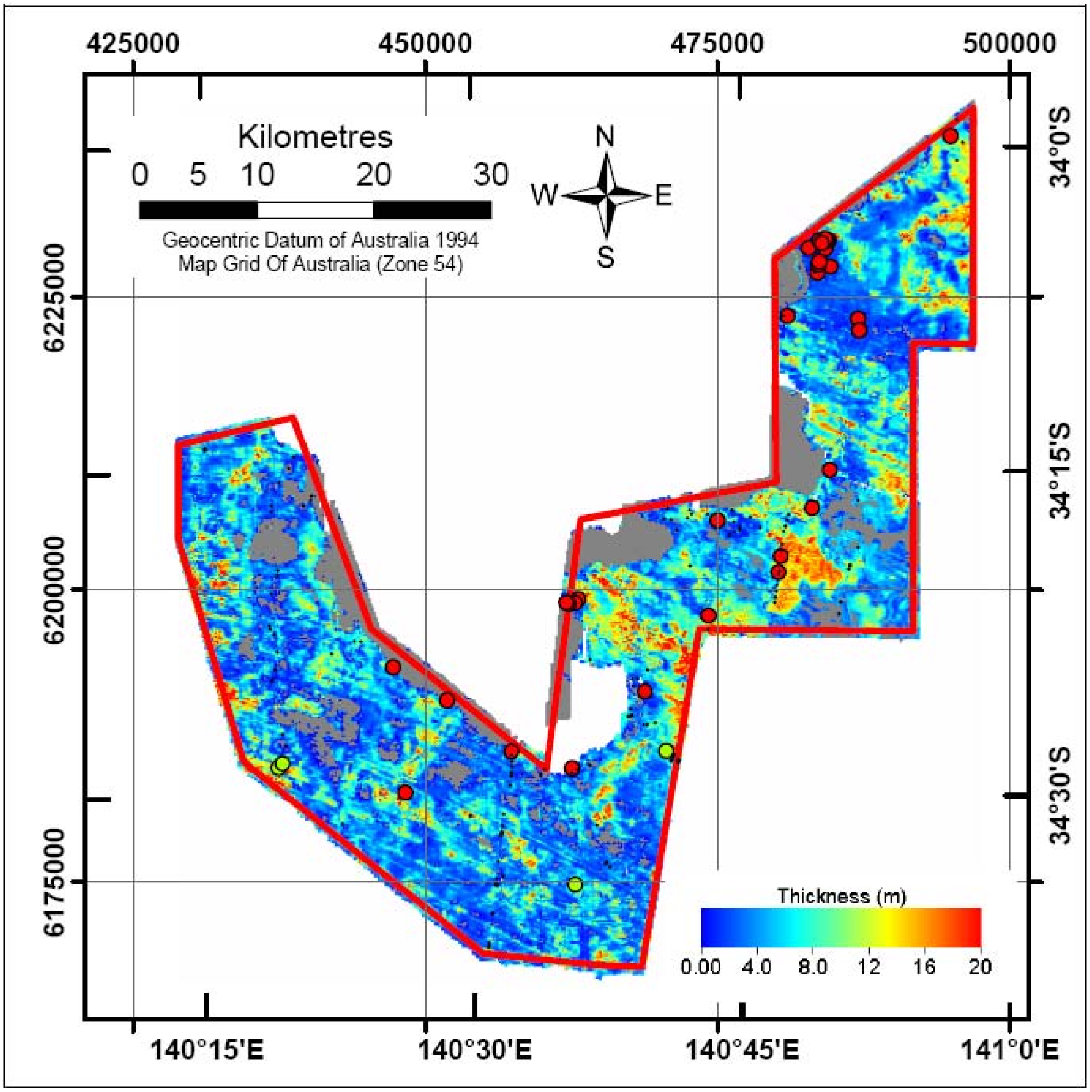

Figure 51 Thickness of the Blanchtown Clay (Berri-Loxton – South Australia) as inferred by Dighem data using Geonics EM39 borehole logs. (from Brodie 2004)

Figure 52 A Dighem 'bird'.

Geotech Airborne

Geotech airborne have produced two airborne instruments – the transienty VTEM device in which a 30m wide loop is suspended from a helicopter and a FDEM system called Hummingbird. Neither devices have been designed mainly for groundwater exploration however they may occasionally be applied in this way. Geoscience Australia are currently applying VTEM to groundwater investigation. Because the VTEM is not a rigid system and because it lacks other advances that exist in the SkyTEM system, it has less ability to resolve important changes in aquifers than the SkyTEM system.

The Hummingbird has coil orientations designed for vertical conductor identification rather than layered geology resolution and therefore is probably not as suited to groundwater exploration as the Dighem Resolve system.

VTEM specifications (from their web site) are as follows – note that they do not mention turn off time which is critical for shallow aquifer definition and that NIA is assumed by the author to be equal to Am^2:

Transmitter:	
Transmitter coil	Vertical axis
Pulse:	Trapezoid
Pulse width	1 – 10 msec (selectable)
Base frequency	25 – 200 Hz (selectable)
Peak dipole moment	up to 500,000 NIA
Max Loop area	500 Square Meters
Max current	250 amperes
Receiver:	
RX coils	Single Vertical axis
Sample rate	up to 200 kHz (selectable)
Interval recorded;	Total signal or up to 800 channels

Band width	up to 20 kHz
Spherical noise rejection	Digital, 3 levels
Industrial noise rejection	Digital, 50/60 Hz
Data recording	PCMCIA Flash Card

EM System Noise at 30 hz:
± 0.01 pico volts per Amp meter4
± 1.3 nanoteslas per second
Mechanical:

Maximum airspeed	120 km per hour
Flying height	30 meters AGL
Temperature	-40 °C to + 45 °C
Power requirement;	50 Amps at 28 VDC
Shipping length	2.5 Meters
Weight	350 kg
Installation/Assembly time	4Hours

Figure 53 VTEM

Figure 54 Hummingbird

GPX HoistEM

GPX, situated in Western Australia, have developed the lightweight high moment HoistEM system. It has some similarities in design to the VTEM system. It has been used for a groundwater related project around Esperance in WA.

Figure 55 GPX HoistEM

Aeroquest

Aeroquest have designed airborne FDEM and TEM systems but have optimized their designs for the mineral exploration and un-exploded ordinance detection market. Their devices are displayed below.

Figure 56 Impuse helicopter-borne frequency domain electromagnetic system.

Figure 57 UFO discovered in Toronto – no. AeroTEM helicopter-borne rigid transient electromagnetic system.

Geophex GEM 2A Broadband

Geophex have produced a multi-frequency broadband helicopter-borne FDEM device in which all frequencies are transmitted from one coil and received by two(?) others, thus simplifying design and drift correction but compromising analog electronics optimization. It uses 7 frequencies from 270 to 47970 Hz. Transmitter receiver separation is 5.1 metres – less than Dighem which means that primary field rejection is limited. The GEM 2A has one significant advantage over the Dighem Resolve, that of weight and therefore survey coverage cost.

Figure 58 The GEM 2A broadband FDEM device weighing only 110 kg.

Towed bird fixed wing TEM such as SaltTEM, GeoTEM and MegaTEM.

Early TEM devices had the transmitter loop suspended around fixed wing aircraft extremities and the receiver in a bird about 60m below the aircraft. In recent years it has been realized that these large heavy systems suffer so much from various errors that they have no advantage over the better newer helicopter borne systems. Fixed wing systems such as SaltTEM have however been used in Australia in the past with mixed results. They resolved deeper features but were expected to resolve shallow salinity related features – something they could only do indirectly by inference from deeper features. Usefulness of the old SaltTEM data is beginning to become realized by soil scientists that are applying it at farm scale rather than regional scale as was done by the federal government who managed the surveys.

Software for data resolution enhancement, calibration and imaging.

Software for processing and presentation of EC image data is just as important as the instruments that collect the data. Various packages offer different refinements that speed up, automate and/or enhance resolution of EC data. Different visualization solutions also are available. Some of the software operates in real time or near real time during data collection.

Providers include the following:

Real time mapping - Geomar Software

Geomar software Incorporated Trackmaker series offer software for navigation and data logging using the tough Allegro field pocket computer and Geonics instruments. For use with the EM31 or EM38, the software costs US$750.00. For use with the proposed EM31-multi coil spacing instrument it costs US$2500. An Allegro costs approximately US$3000.

Real time mapping - Geophex

Geophex offer PDA software for navigation and real time EC mapping (EC map generation as you survey) for use with the GEM2. It runs on Microsoft Pocket PC devices. As an operator drives or walks along, EM data comes up as points on the screen coloured to represent their conductivity value. At any time the operator may stop and execute gridding to transform the existing colored points into a background gridded image.

Real time imaging - TerraOhm Instruments AB

TerraOhm offer real time imaging software for use with the RIP 924 waterborne acquisition device. They have facilitated simultaneous logging of extra devices such as pressure and water property sensors. They also offer the Lund Imaging System software for ground surveys using the same device with a switchbox.

Real time imaging – Iris Instruments

Iris instruments offer real time imaging software (Geomar) for use with the Syscal Pro waterborne acquisition option. This software logs the geo-electric data, GPS data and sonar depth data and plots it in real time on a computer running Microsoft Windows XP.

Visualization software - Golden Software

Golden software offer ‘Surfer’. An affordable gridding and mapping package.

Visualization and archiving software - ESRI

ESRI offer ArcView. The package used by most agencies in Australia to work on EM31 imagery. It offers excellent archiving and data organization support for about A$4400 but the gridding algorithm only comes with an extension that costs about $7000.00. Using some scripting, Surfer8 can be used to perform gridding from ESRI but there is no documentation to show how to do this.

Visualization software – other

Other gridding and imaging packages exist. GStat is free but requires C++ programming skills to use. Manifold is affordable as is Kilimanjaro (Idrisi) which is based on GStat.

Geosoft Montaj is very capable, offers masses of features and has good macro recording support. The Australian company – ENCOM – make products for complex 3D imaging.

Multi-depth EC processing and visualization - Aarhus University Hydrogeophysics Group

The Aarhus University Hydrogeophysics Group write custom software for all their instruments as well as web sites and databases for distributing their data. Their TEM processing software possibly is the most efficient and thorough on the market – there are too many features in their software to mention here. They also have written many of the most effective tools for continuous geo-electric survey processing.

Multi-depth EC geo-electric processing - AGI

AGI offer planning and inversion software for use with their instruments. It is called EarthImager 2D & 3D.

Multi-depth geo-electric EC processing - Loke

www.geoelectric.com. Loke offers Res2dInv and Res3DInv. Packages for 2D inversion of data from geo-electric devices. Geometrics, ABEM and Iris Instruments device data generally is processed using Res2DInv.

Multi-depth EC processing - Interpex

Interpex offer inversion software with good interactivity and some automation. Their principle package is called IX1D. It can invert FDEM, geo-electric and TEM data from numerous instruments. It can greatly enhance the vertical resolution of EC data. An example is given below in which almost meaningless GEM2 data was transformed into useable information with some smart user applied constraint and IX1D.

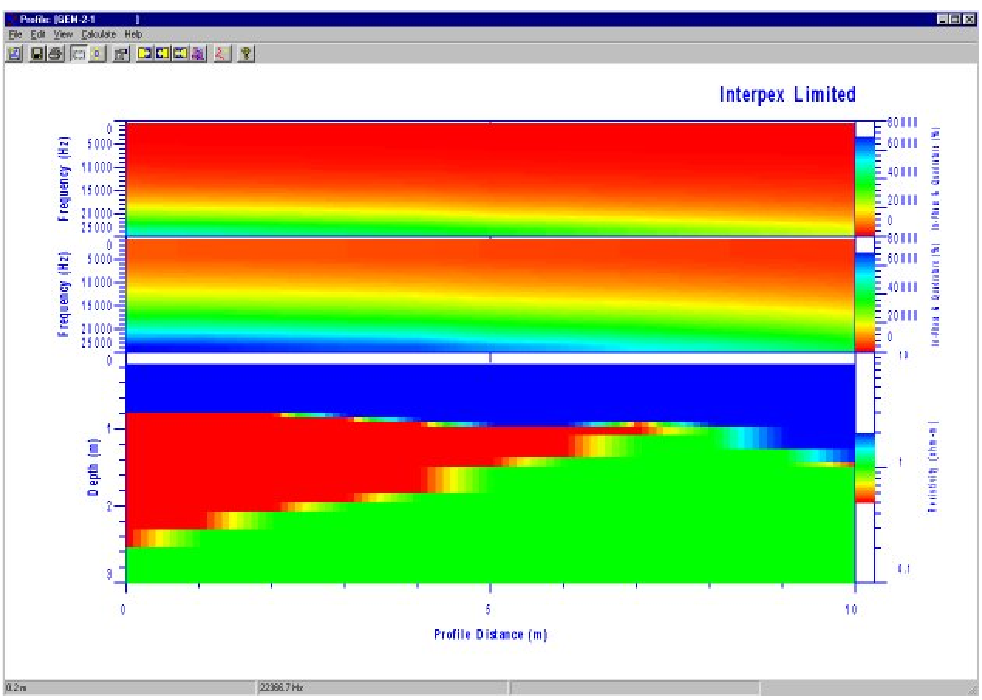

Figure 59 IX1D GEM-2 data interpreted with 3 layers; layered resistivities are fixed and only thicknesses are allowed to vary.

Multi-depth EC processing and visualization – Enigma V7.5

PetRos EiKon Inc. (www.PetRosEiKon.com) offer a package for processing and 3D visualization of data from many FDEM, TEM, geo-electric and magnetic devices. The 3D visualization requires that data is collected across an entire grid.

Allen Hydrogeophysics

The author of this article offers HydroGeoImager for inversion of waterborne or other continuously acquired geo-electric data. The software also offers visualization of that data and TEM data in three dimensions using EC ribbons, as shown below, or as sets of depth slices. HydroGeoImager's EC ribbon imaging facility permits almost instant 3D presentation of datasets collected along irregular tracks, logged using GPS.

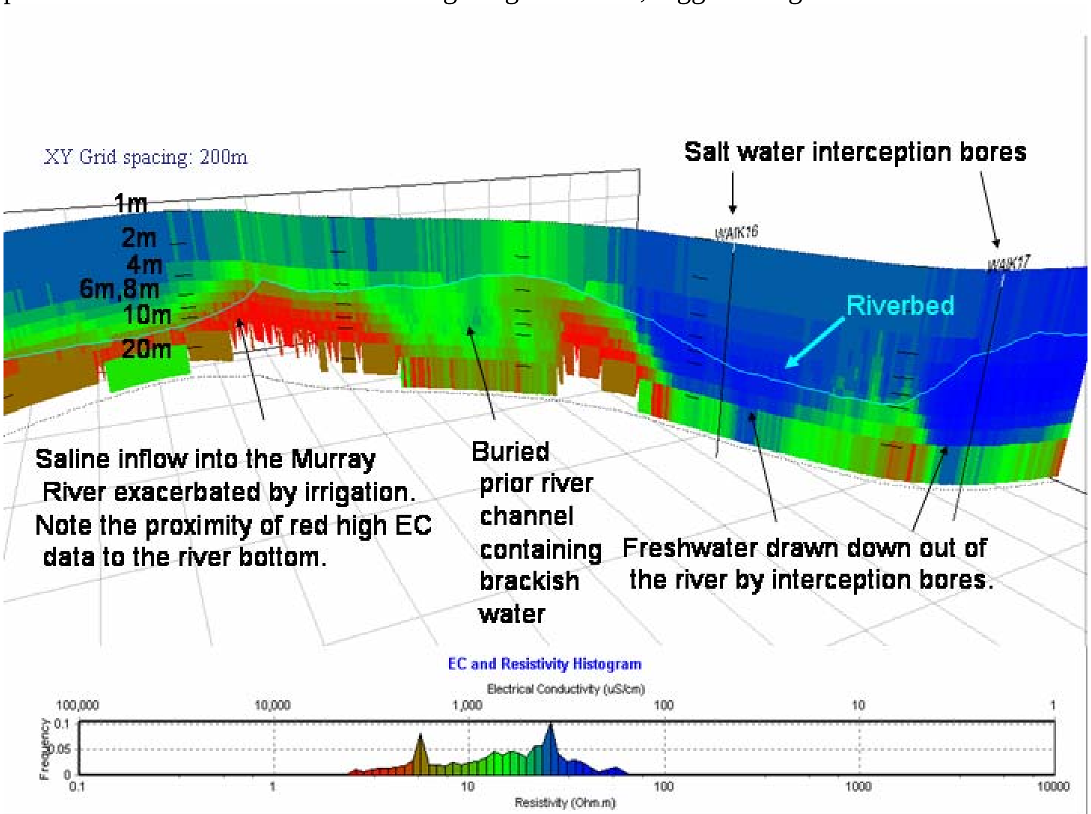

Figure 60 An EC ribbon produced of geo-electric data collected along a river by HydroGeoImager.

Borehole logging equipment

Hydro-geophysical imaging is rarely much use on its own. It normally needs to be calibrated with borehole or other data before it can be used to manage aquifers. Lithological logs and water samples are very important, but, in most cases, geophysical logging is required to investigate deep boreholes. Many hydrological properties are only measurable before a drilling rig disturbs aquifers so some geophysical techniques are designed to measure during drilling or penetrating. Other techniques are designed to work once holes have been cased.

For most irrigation related borehole logging, a basic logging suite including a winch, logger, gamma tool, geo-electric EC tool and caliper tool is used. For cased holes, an induction (EM) tool must be used to measure EC. The Gamma tool differentiates clays from sands while the EC tool measures salinity and clay content. The caliper tool find blowouts in the drill holes that disturb the EC and gamma data and suggest friable geology.

Often sonic and neutron tools are added to determine porosity and effective porosity. Gamma-Gamma density probes may measure rock density which helps to identify some sorts of aquifers.

Various water sampling tools are available for water sampling and temperature determination up and down holes but these suffer from movement of groundwater up and down the hole.

To visualize the rock and casing of drillholes, acoustic televiewers and optical televiewers such as those produced by Advanced Logic Technology may be used. Such viewers identify fracture zone locations and orientations. Such zones typically are aquifers.

Various tools and techniques also are available for determining where water enters and leaves boreholes. These tools are important for investigating aquifer cross contamination occurrences such as are common in our Great Artesian Basin bores. Reliable tools/techniques for such logging include heat pulse flowmeters, EM flowmeters and the hydrophysical logging technique. Other tools exist such as the impellor flowmeter (not recommended) and the scanning colloidal borescope flowmeter.

Basic Downhole Logging Equipment Packages

A small basic winch, logger, gamma tool, geo-electric EC tool and caliper tool typically costs about US$25,000 as a package deal in the USA. Companies selling such equipment include GeoVista, Mount Sopris Instruments, Colog and Robertson Geologging. Some modern small systems can be carried as hand luggage on commercial aircraft.

Induction EC loggers

Induction EC loggers are available from Geonics, GeoVista, Robertson Geologging and Mount Sopris Instruments. They are useful for logging EC through PVC casing and have been very popular for groundwater investigation in Australia. Geonics offer the EM39 borehole conductivity probe & console with digital output for US$22625 and an accompanying Gamma Probe for US$18825. Appropriate winch costs need to be added to these prices to create a complete system.

Figure 61 Geonics EM39 downhole electromagnetic induction logger. Gamma is also provided by Geonics

Undisturbed aquifer logging techniques - augers

To identify features such as perched aquifer, logging needs to be conducted before disturbing an aquifer. This may be achieved using an auger, with logging tools inside it, or a penetrometer, again with logging tools inside it.

Århus University Hydrogeophysics group created an auger with a geo-electric array, Gamma sensor and water sampler incorporated into it which they call Ellog. They also have experimented with incorporating a hydraulic conductivity measuring tool into an auger – see the photo below. (Sorensen, 2003). The tool uses a geo-electric analog in which source and sink electrodes are replaced with source and sink water sources on the auger.

Figure 62 An auger tool set up to determine hydraulic permeability in undisturbed aquifers by injecting and withdrawing water through small holes while drilling.

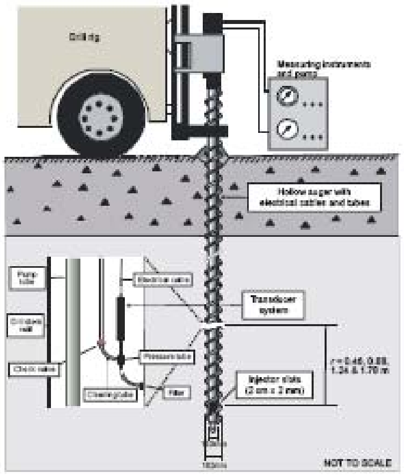

Figure 63 Measuring hydraulic conductivity in an undisturbed aquifer using an auger tool (Sorensen, 2003).

Undisturbed aquifer logging techniques – Penetrometers

Veris Technologies have produced a soil profile penetrometer for determining the variation of EC and soil stiffness with respect to depth through soil profiles.

Other companies have produced penetrometers with sensors that can detect EC and sediment stiffness to as deep as 30m. Douglas Partners provide such a service in Australia. Geoprobe sell penetrometers with geo-electric arrays in their tips.

Figure 64 Veris Penetrometer with EC and pressure sensors.

Crosshole logging equipment

Cross hole logging gives detailed information on aquifers, however, costs confine the use of it to legal disputes over groundwater pollution by factories. It should not be considered for groundwater investigation on the scale required for irrigation.

Soil moisture and water suction sensors

Static (non moving) soil moisture and water suction sensors are already well known to the irrigation and drainage communities. Neutron probes measure soil moisture using radio-active phenomenon. Sentech and others offer devices that use capacitive effects at high frequencies to measure soil moisture. The response is affected by dielectric permittivity and/or EC depending on the frequency. Time domain reflectometry devices use two wires or similar parallel conductors inserted into soil to measure dielectric permittivity and, in turn, soil moisture.

Gypsum block sensors have existed for a long time – electrical conductivity is measured across the gypsum block to measure soil water suction. Other soil water suction devices include tensiometers and WATERMARK (granulated matrix) sensors (http://www.irrometer.com/agcat.htm).

Static sensors will not be considered in detail in this review but moving soil moisture content sensors used to map soil moisture in topsoil across paddock will. Those interested in static soil moisture sensors should see the extensive review by Charleworth, P., 2005, Irrigation Insights No. 1, Second Edition SOIL WATER MONITORING, ISBN 1 920860 56 8 (print) 1 920860 57 6 (online) Product code PR050832 www.npsi.gov.au.

Airborne thermal imagery can give an indication of topsoil water suction due to the effect of evapo-transpiration on soil temperature but such imagery is affected by numerous other factors. Radar is however emerging as a tool for imaging soil moisture content.

Soil moisture content measurement using radar

Radar is promising to become a medium with which soil moisture content will become measurable remotely using a vehicle passing across the land surface. The dependence of radar on soil moisture content is via the property, dielectric permittivity, which is anomalously high for water at radar frequencies. This dependence is the same as utilized by point source moisture meters that utilize time domain reflectrometry (TDR).
Soil Moisture content can be measured by radar, however, presently the techniques involved are probably for researchers only. Soil moisture content can be measured using reflected wave velocity, ground wave velocity, transmitted wave velocity (between boreholes) and surface reflection coefficient. Those with an interest in such methods are referred to Huisman (2003).

Figure 65 An elevated 500-MHz ground penetrating radar (GPR) system being used to measure soil moisture content using surface reflection amplitude (from Huissman, 2003).

Radar equipment is available from Sensors & Software Inc. (www.sensoft.ca), Mala Instruments (www.malags.com) and Geophysical Survey Systems Inc. (http://www.geophysical.com/applications.htm#farming). Radar systems from Mala cost US$32000 to US$43000 (June 2005). Much research on soil moisture content measurement is being conducted using the Sensors and Software Inc. instruments. The high resolution of radar is also being used to sense soil moisture variation around tree roots (see GSSI website).

Remote sensing - aerial photography and satellite imagery

Aerial photography has been used to identify geomorphological features that control groundwater flow for 10's of years. It is still very useful. Various satellite imagery products now also are available but rarely show anything that good aerial photography, properly observed, can show. The differences usually are in ortho-rectification, uniformity and feature enhancement rather than image quality. Remote sensing is very important but will not be discussed further here.

Other types of geophysical instrumentation relevant to soil and groundwater investigation

Radiometrics / Scintilometers / Gamma Ray Spectrometers

Geoexploranium, Scintrex and GF Instruments produce scintilometers. These devices are useful for imaging clay proportion of topsoil by detecting potassium counts. Handheld devices such as the one shown need about 15 seconds to take a measurement. Large crystal packs (15 to 30 litres) may be quadbike or aircraft mounted for broad scale continuous acquisition.

Figure 66 GF Instruments 512 scintilometer also available in a borehole version.

Airborne radiometric data is available from government mineral exploration departments.

Magnetics

Total magnetic intensity (TMI) sensors are occasionally used for water exploration in upland areas where water occurs in rock fractures. They may also define palaeochannels in areas where there is a strong contrast between iron mineral content in the channels and surrounding sediment. TMI sensors have no ability to directly correlate to water presence or salinity but only to iron minerals such as hematite, goethite and magnetite. Australia is relatively well covered by airborne magnetic surveys which are publicly available. Where increased resolution is desired, such as for siting a bore within a narrow water filled fracture zone, a ground based survey is warranted. Ground based instruments now being manufactured tend to be very well designed with gps integration and moving map displays. Instruments manufactured by Geometrics (www.Geometrics.com), LRS Scintrex (www.ScintrexLtd.com) and GEM (www.GEMsys.ca) are displayed below. Magnetic data acquisition is well understood by many mineral exploration geophysicists who could be requested to advise on their use in groundwater exploration. James Cull of Monash University has applied high resolution magnetics to groundwater investigation at various sites in Victoria.

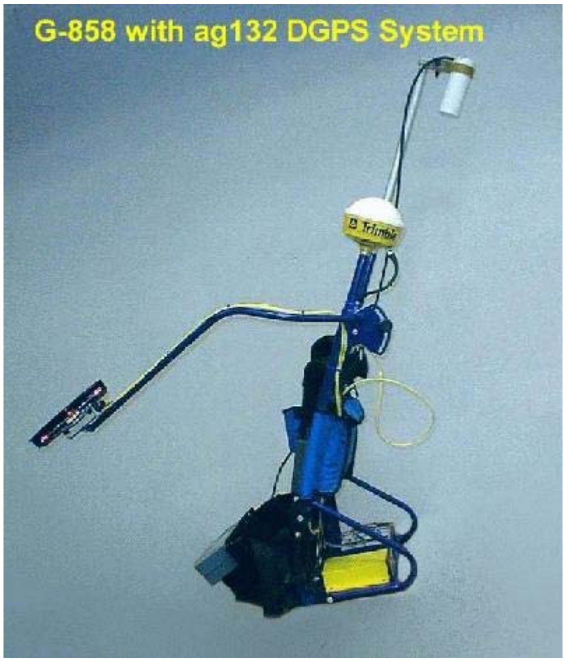

Figure 67 A backpack mounted Geometric magnetometer with a Trimble parallel swathing light bar.

Figure 68 The Geometrics G858 cesium magnetometer

Figure 69 The Scintrex SM-5 Navmag

Figure 70 The GEM GSM-19 Overhauser Magnetometer.

Gravity

Gravity is useful for defining depths of geological basins (with control bores) and faults that control groundwater movement. A national gravity dataset is available from www.ga.gov.au . For identifying faults that confine groundwater flow, detailed gravity transects generally need to be conducted. A gravity meter such as the Scrintrex CG-5 pictured below is often used. It must be set up and leveled like a theodolite at every site it reads gravity. It must be corrected with survey grade GPS altitude data and a great deal of processing is necessary. Airborne gravity now is becoming popular.

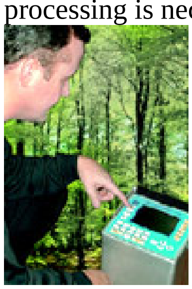

Figure 71 The scintrex CG-5 Autograv gravity meter

Magnetic Resonance Sounding

Magnetic resonance sounding is a direct method of detecting aquifer properties at different depths. It determines water content and estimates permeability. It works in the same way as medical MRI machines by exciting H protons of water molecules however it must use the weak and variable magnetic field of the earth rather than the strong refined fields generated by the enormous magnets of medical MRI machines. Its signal is attenuated by conductive saline groundwater in the same way that transient EM signal is attenuated so it should not be used to investigate deep aquifers under saline cover. It has been used in Australia to define highly valued arid area mine groundwater supplies. At this stage, it seems that the low cost of groundwater in irrigation areas does not warrant use of this technique for irrigation related projects.

An Iris Instruments Numis System designed to penetrate 150m costs 134 000.00 Euros (May 2005) including 5 days training at a buyer selected site.

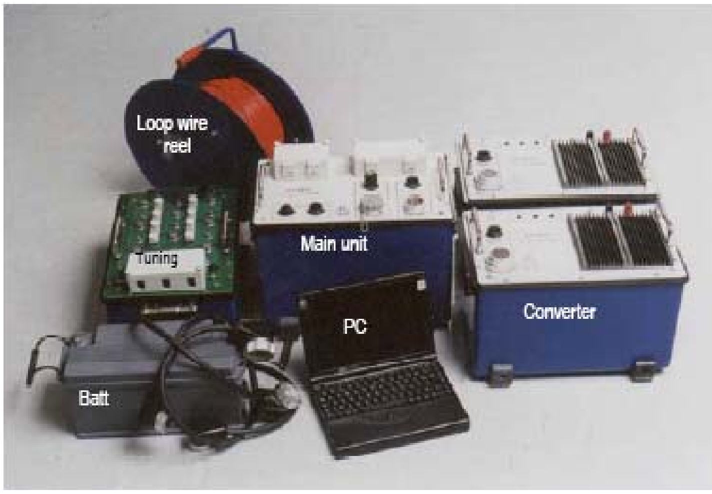

Figure 72 Iris Instruments Numis magnetic resonance sounding system

VLF

ABEM, LRS Scintrex, Iris Instruments and Geonics produce devices suitable for VLF surveying. VLF (very low frequency) exploration uses signals transmitted for submarine navigation to determine vertical or steeply inclined variations in EC in the earth. It can be used for identifying fracture zones in highly resistive rocks that may be suitable as aquifers for bore siting. Its ability to detect features depends on their orientation relative to the direction to the source of the VLF signal.

A Wadi VLF detector costs SEK 63000 from ABEM Instruments AB (Sweden).
An EM16/16R costs US$11850 from Geonics (Canada). Geonics. A Tx27 VLF transmitter is available from Geonics (US$8400) for locally transmitting VLF signal where government supplied signals are weak or directed in an inappropriate direction to detect local geological features and government regulations permit.

Figure 73 ABEM Wadi VLF receiver

Figure 74 LRS Scintrex VLF receiver attachment for their Navmag magnetics receiver.

Figure 75 Geonics EM16/16R and the Tx27

Gisco, www.GiscoGeo.com provide VLF interpretation and presentation software.

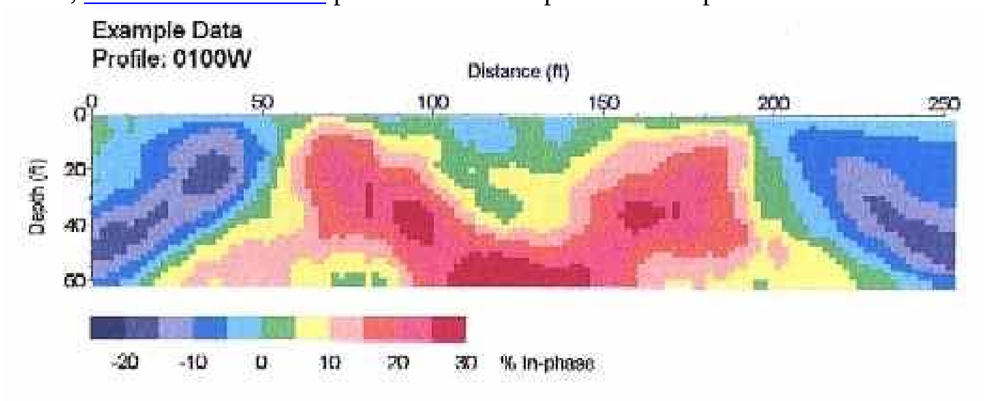

Figure 76 GiscoGeo RAMAG VLF software output.

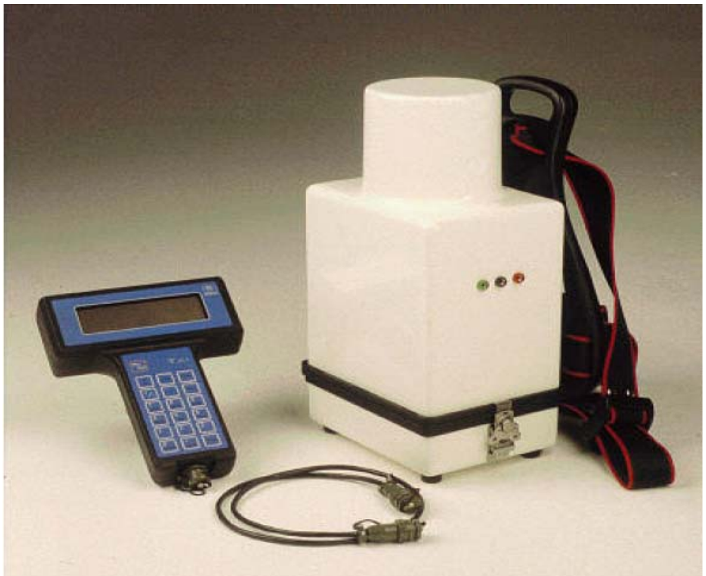

Figure 77 Iris Instrument T-VLF

Seismic

Seismic surveys are used extensively for oil exploration but the author has not found any surveys in which seismic data has been used without R&D funding in hydro-geological surveys. On many occasions, however, seismic data obtained for petroleum exploration is very useful for deep bore siting and groundwater modeling. Much understanding of our deep aquifers extents has come from such data.

Seismic methods for shallow explorations are available and are used in R&D mode for groundwater exploration. Refraction techniques have been investigated by the USGS Office of Groundwater Branch of Geophysics (http://water.usgs.gov/ogw/bgas). Recently surface wave seismic surveys have become a popular R&D topic. These surveys also concentrate on shallow hydro-geological applications.

Figure 78 Conduct of a seismic survey in Nebraska (from USGS, OGW, Branch of Geophysics web site).

Electro-kinetics

Research at ANSTO on the use of electro-kinetics for vertical imaging of hydraulic conductivity is being conducted. The technique has been used near Shepparton and in the South Australian Riverland. Surveys use a seismic source to cause water molecules to generate charges which permeate through sediment creating voltages at the surface that are picked up by a geo-electric array. Chris Waring at ANSTO would greatly appreciate further interest in this technique. Further information is also available from http://snow.stanford.edu/~morf/pride/octupole%20antenna/electro-seismic%20-osmotic%20/artpaperfrm.htm ,
crcleme.org.au/Pubs/Monographs/ regolith2004/Kim_et_al.pdf and
www.zetica.com .

The technical plausibility of electro-kinetic imaging is questioned by many (Acworth 2005, personal communication – see www.wrl.unsw.edu.au/resources/cv/WRL-CV-Ian-Acworth.pdf).

Figure 79 Electrokinetic Imaging (from www.zetica.com)

Water flow monitoring technology

The author, as part of a National Centre for Groundwater Management – University of Technology, Sydney proposal to the Cotton Catchment Communities Cooperative Research Centre will, hopefully be reviewing river flow monitoring technology shortly. The ANCID website, www.ANCID.org.au already hosts many documents on flow measurement in canals.

Seepage measurement technology

The ANCID website, www.ANCID.org.au contains a large review of seepage measurement technology. Since this report was published, the author has developed geophysical technology and techniques, using instrumentation detailed above, for spatial delineation of seepage hot spots – recommendations are encompassed in his PhD thesis (Allen, 2005).

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