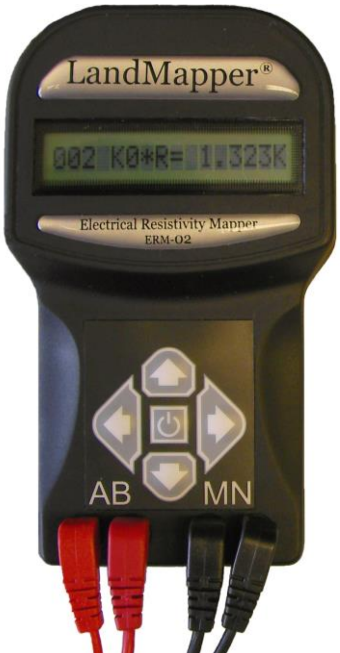
Measuring Electrical Resistivity and Conductivity of Natural Systems with



LandMapper® ERM-01

USER MANUAL
THEORY
CASE STUDIES

Before using the device read the instructions

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2004-2016

WARNING:

- The LandMapper geophysical resistivity meter is internally powered equipment (1x9V)
- Equipment utilizes a variety of probes (electrodes) for use in the field and in laboratory.
- Some of those probes have sharp parts.
- Equipment type is continuous operation.
- If the equipment is receiving or causing interference, the equipment should be relocated away from the other equipment.
- There is no preventive inspection or maintenance required on the system or on parts of the system.
- Remove the battery if the equipment is not going to be used for prolonged time.
- Environmental requirements for storage and transport:
  Ambient temperature:-40C to +70C
  Relative humidity: 10% to 100%
  Atmospheric pressure: 500hPa to 1060hPa

Follow local governing requirements when disposing of equipment or batteries

CAUTION: General Warning – refer to accompanying documents

MADE IN RUSSIA
exclusively for Landviser LLC, USA
Technical documentation on file at Landviser, LLC
828 Davis Rd., League City, TX 77573

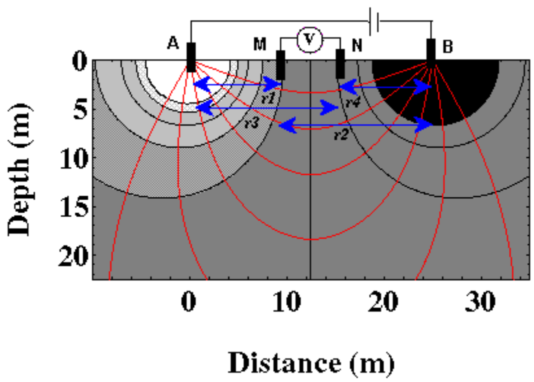
TABLE OF CONTENTS

The geophysical device LandMapper ERM-01 can be used to measure **electrical resistivity** or **conductivity** of soils and plants for fast non-destructive mapping of agricultural fields, construction and remediation sites, and similar applications.

Our device is **very versatile** and can be applied on soil surface, in wells/pits, or in soil and other semisolid laboratory samples. In a typical setting for resistivity or conductivity (ER or EC) the **four-electrode probe** is placed on the soil surface and ER value is read from the digital display. Device allows to measure electrical resistivity of the surface soil layer of the depth set by varying the size of the four-electrode probe.

The equipment is developed in Russia by IP GeoPro for Landviser, LLC, USA and based on more than 30 years of scientific research of Russian and American soil physicists. Prototypes of the LandMapper ERM-01 and ERM-02 were developed and used for soil studies in Russia, USA, Canada, Western Europe, Philippines, Chili, China and even Antarctica (Pozdnyakov et al., 1996; Pozdnyakova et al., 1996; Pozdnyakov, 2001; Pozdnyakova, 1999; Pozdnyakova et al., 2001; Golovko and Pozdnyakov, 2009-2012).

OPERATING PRINCIPLES OF RESISTIVITY/CONDUCTIVITY MEASUREMENTS



Our equipment utilizes well-known four-electrode principle to measure electrical resistivity or conductivity, as shown in the figure.

LandMapper measures potential difference (Δφ), which arises between the two electrodes (M and N), when electrical current (*I*) is applied to the other two electrodes (A and B).

In theory, electrical resistivity (*ER*) of a material is defined as follows:

$$ER = \frac{A\Delta\varphi}{LI} \quad [1]$$

where L is the length of a uniform conductor with a cross-sectional area *A*. A/L is a geometrical coefficient (K), which is easily calculated for different in-situ electrode arrangements or calibrated with test solutions for laboratory conductivity cells.

LandMapper ERM-01 calculates electrical resistivity (*ER*) using formula:

$$ER = K\frac{\Delta\varphi}{I} \quad [2]$$

electrical conductivity (*EC*) can be derived (post-processed) data via reciprocal of the measured resistivity:

$$EC = \frac{1}{ER} \quad [3]$$

Coefficient K in Eq. [2] is geometrical factor depending on the distances among the electrodes AMNB. The vast majority of the 4-electrode arrangements (arrays) employed in geological and soil exploration is linear central-symmetric arrays similar to one shown in the figure above. In such arrays the potential-measuring MN electrodes are placed between A and B electrodes and AM=NB. The coefficient K for such arrays is calculated with formula:

$$K = \pi\frac{[AM]\cdot[AN]}{[MN]} \quad [4]$$

where AM, AN, and MN are respective distances between electrodes measured in meters.

The depth of the measurement depends on the electrical resistivity of the soil as well as on the geometry of the four-electrode probe. For the probes in Wenner configuration (central symmetric, AM=MN=NB=*a*), which are supplied with the LandMapper ERM-01, the depth of the investigation is approximately equal to electrode spacing (***a***) for most soils (Barker, 1989). Any size and shape four-electrode probes can be used with LandMapper ERM-01, the calculation equations for geometric coefficients K are provided in Table 1.

DESCRIPTION of LandMapper ERM-01

Technical Specifications

- Range of measurements……………………………………….………ER= 0.1-1 10^6 Ohm m
- Automatically adjusts electrical resistivity range to provide best measurement accuracy.
- Precision and error of measurements is typically less than 1%.
- User-defined K (geometrical coefficient)……………………….………..…...0.01 up to 99.99
- Quantity of changeable K-coefficients..……………………………………………………...9
- Quantity of data storage locations…………………………………………………..…….999
- Range of operation temperatures…………………..from - 10 up to + 40 C^0 or 14 to 100 F
- Air humidity no more than……………………….……………………….………………65 %
- Weight of the device no more…………………….…………………………….. 250 g or 8 oz
- Current of consumption no more……………………..…………………..……………..7.0 mA
- Output voltage, no more………………………………………………… ………….………5 V
- Measurements comparable with DC methods, frequency…..............………………1.25 Hz
- Computer connection…………………………………………………….……………serial port

Controls

⏻ - ON/OFF key

► - FUNCTION key. The multifunction key for operation mode selection (ER/EC/EP) and storage of data

◄ - INPUT key. The multifunction key for taking measurements, correction of a K coefficient, recording or erasing data or contrast values

▲ - UP key. The multifunction key for scrolling through operation modes, K coefficients, storage cells, or contrast values

▼ - DOWN key. The multifunction key for scrolling through operation modes, K coefficients, storage cells, or contrast values

AB - Socket for connection of current-inducing AB electrodes

MN - Socket for connection of voltage-measuring electrodes (plug non-polarizing electrodes here for electrical potential measurements)

Serial port for data transfer to a computer is on the top side panel of the device.

CARE AND MAINTENANCE

Measuring unit

The measuring unit, LandMapper ERM-01, is made of rigid plastic which is adequate in protecting inside electronics during regular field use. It is designed to withstand everyday knocks and scrapes. However, the case is not designed for heavy impact such as being crushed by large objects or falling from too high above.

The LandMapper ERM-01 is not fully protected against the water penetration. If the device is partially or wholly immersed in water or used in heavy rain, the water might ingress inside the unit and cause non-repairable damage with the loss of all saved data. If immersion occurred, disconnect battery and allow unit to completely dry out several days and then try to turn device on again. Although some cases were reported that device worked fine after submergence and subsequent dry-out, LandMapper is not designed to operate in wet conditions and is not warranted for such damage.

The keys and LCD display are designed for routine use over many years. The LCD has a plastic screen to prevent some damage, but a direct hit from a sharp or heavy object may penetrate and damage the display.

The unit, keys, and display can be cleaned with a soft damp cloth. Do not use an abrasive material or chemical cleaner to clean unit or display. They may damage the plastic and make display difficult to read.

The serial port on the top of the measuring unit is a female connector into which a male connector is inserted. It is advised to close the rubber protective shield over the serial port when the unit is used for the field measurements. The appropriate serial cable with 9-pin male/female connector is supplied with the unit for the data transfer from the LandMapper to a personal computer. The pins in the connector/ports can break if a damaged or dirty female serial port in the unit or personal computer is being used for the connection.

> **Important:** you can use the **supplied** serial cable with any standard USB-to-Serial connector. Do not use other brands of serial cables unless you lost/damaged original cable. If you cannot re-connect LandMapper with PC using generic serial cable, please, order spare cable directly from Landviser, LLC.

The LandMapper device should be stored at a room temperature when not in use. Remove the battery from the device for prolonged (> 1 month) storage. Use only 9V PP3 type battery – do not use any other type of battery or power supply. The meter may be damaged by a power source not recommended by Landviser, LLC. When replacing the battery in the battery compartment, do not pull the battery leads, because they may disconnect inside the meter and cause malfunctioning that can only be repaired by the manufacturer.

The LandMapper has been designed for use only with Landviser's supplied, specified or recommended four-electrode probes, cables, laboratory cells, or non-polarizing electrodes. The Landviser, LLC is not responsible for any damage to the measuring unit caused by using non-authorized accessories.

Four-electrode probe

The four-electrode probe is rigid enough for routine field mapping, but should not be forced into extremely stony or cemented soil. In most conditions a single push on the handle is enough to sufficiently ground all four electrodes. Sometimes, in case of very long probes, the outer A and B electrodes will not penetrate soil to provide a good contact for the measurements. In this case they can be grounded by a slight press on the probe directly above an electrode with a foot. Remove probe from the soil by a slight pull on the handle.

The plastic parts of the four-electrode probe are joined in a T-socket and can be reinforced with metal screws. To prevent the screws from becoming loose limit unnecessary assemble/ disassemble of a probe.

It is not necessary to clean the electrodes between measurements or after a field work, but it is a good practice to clean the electrodes with soapy water and completely dry them prior to prolonged storage. The probe can be stored in any compartment protected from a harsh weather conditions. It is advised to store electrodes away from excess moisture to prevent metal corrosion.

OPERATION

Quick menu

◄ - **read** value of resistivity, move from digit to digit when changing K or cell numbers

◄and► - **save** value of resistivity in memory, values of the K or contrast, clear memory

▲ or ▼- **change** the number of K, number of cell, and contrast values

► and ▲ or ▼- move through different **operational modes** (see below)

► and ▼ - exit the mode

Operational modes

▲ Erase content of the RAM

▲ View data stored in the RAM cell (#000 through #999)

▲ Check and Change values of K coefficients (K1 through K9; K0=1 - *constant*)

► **Measurement of electrical resistivity with an entry into RAM (default on startup)**

▼Voltage indication of the battery

▼Change Contrast of Display

▼Data transfer to computer (A PC com wait)

Setting up the K coefficient on the device

LandMapper ERM-01 is usually supplied with one four-electrode probe in Wenner configuration (optional) and the probe-specific coefficient K is preset in the device memory (K1). If you ordered or build multiple probes/cable arrays, you can change K1-K9 coefficients in the device. **Note:** K0=1 always and is not changeable by user!

1. Press the ⏻ button to turn the device on. As the device is turned on the brief message "ASTRO-LANDVISER" is displayed on the screen of the device.
2. Press and hold the FUNCTION key (►) and press the UP key (▲) to enter the coefficient changing mode.
3. Scroll through K coefficients with the keys (▲) or (▼). Change the value of the coefficient with the keys (◄) and (▲) or (▼). The digit to be changed is selected with the INPUT key (◄), the digit starts blinking and can be changed with the keys (▲) or (▼). The value of K0=01.00 is constant and cannot be changed by the user. If a measurement is taken using K0, the resulting output is resistance, not resistivity, and can be useful when the geometry of the array is constantly changing, as in 2D imaging or electrical tomography. In this case the resistance values can be multiplied by corresponding K coefficients according to the arrays used to obtain the resistivity.

   Note: You can calculate and enter the K-coefficients easily following instructions at the end of this manual.

4. To store the new value of the K coefficient press and hold the (►) key, then press the (◄) key. The new value of K coefficient is stored in the device's memory and the value is not blinking.

<u>*Display listing:*</u>

KN = --,--

KN is an ID of the K coefficient (from K0 to K9)
--, -- is the value of the K coefficient from 00.01 up to 99.99

Conductivity (µS/cm)	Resistivity (Ω-cm)	Dissolved Solids (ppm)
.056	18,000,000	.0277
.084	12,000,000	0.417
.167	6,000,000	0.833
1.00	1,000,000	.500
2.50	400,000	1.25
20.0	50,000	10.0
200	5000	100
2000	500	1,000
20,000	50	10,000

Note: K coefficients depend on probe/cell size. You can build probes suitable to different media. Solutions/soils with an extremely high conductivity require a sensor with a probe constant greater than 1.0. Solutions/soils with extremely low conductivity require a sensor with a probe constant less than 1.0. The greater the distance between the electrodes, the smaller the current signal (www.omega.com).

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Typical Values of Electrical Conductivity and Resistivity of Soils and Waters measured with LandMapper

LandMapper is the only device you will need to reliably measure electrical properties in wide range of conductivities: from ultra-pure water and rocks to salty brines and ocean waters!

Hand-held and portable, LandMapper utilizes the most accurate 4-electrode contact method, uses one 9-volt battery and can measure down to 10 m (30 ft).

Typical Water or Soil* Salinity	Electrical Conductivity, ECw (dS/m)	Electrical Resistivity, ER (Ohm m)	Total dissolved solids, TDS (ppm)	**Measuring Mode:** Display reads: **Base unit** Measuring limits: Unit modifiers displayed	**EC (conductivity)** 000 K1*C= **S/m** **10^{-6} – 10 S/m** **n, mk, m**	**ER (resistivity)** 000 K1*R= **Ohm m** **0.1-10^{6} Ohm m** **K**	
Air	- reading of non-connected Landmapper =>			**K** - kilo Ohm m = 10^{3} Ohm m	~390n	~2560K	
Dry Granite/Gabbro	10^{-5}	10^{6}	N/A	**n** - nano S/m = 10^{-9} S/m	1000n	1000K	range of reliable measurements with LandMapper ERM-02
Ultra-pure Water	$5.6 * 10^{-6}$	178,571	$3.6 * 10^{-2}$	**mk** - micro S/m = 10^{-6} S/m	5.6mk	178.5K	
Distilled Water	0.02	500	12.8	**m** - milli S/m = 10^{-3} S/m	2m	500	
Non-saline Sandy Soil	0.01 - $1*10^{-5}$	100-10,000	N/A		1m-1mk	100 - 10K	
Non-saline Silt Soil	0.05-0.5	20-200	N/A		5m-50m	20-200	
Non-saline Clay Soil	0.1 - 2	5-100	N/A		10m - 200m	5-100	
Nonsaline water	<0.7	>143	<500		< 70m	143	
Saline water	0.7-47	0.24-143	500-30,000				
Slightly saline	0.7-3	3.33	500-2,000		300m	3.33	
Medium saline	3-6	1.67	2,000-4,000		600m	1.67	
Highly saline	6-14	0.71	4,000-9,000		1.4	0.71	
Very highly saline	14-47	0.21	9,000-30,000		4.2	0.21	
Brine	>47	<0.24	>30,000		>4.7	<0.24	
Atlantic Ocean	43	0.23	27,520		4.3	0.23	
Great Salt Lake	158	0.06	101,120		15.8	0.06	
Dead Sea	~516	$2 * 10^{-2}$	330,000		51.6	$2 * 10^{-4}$	

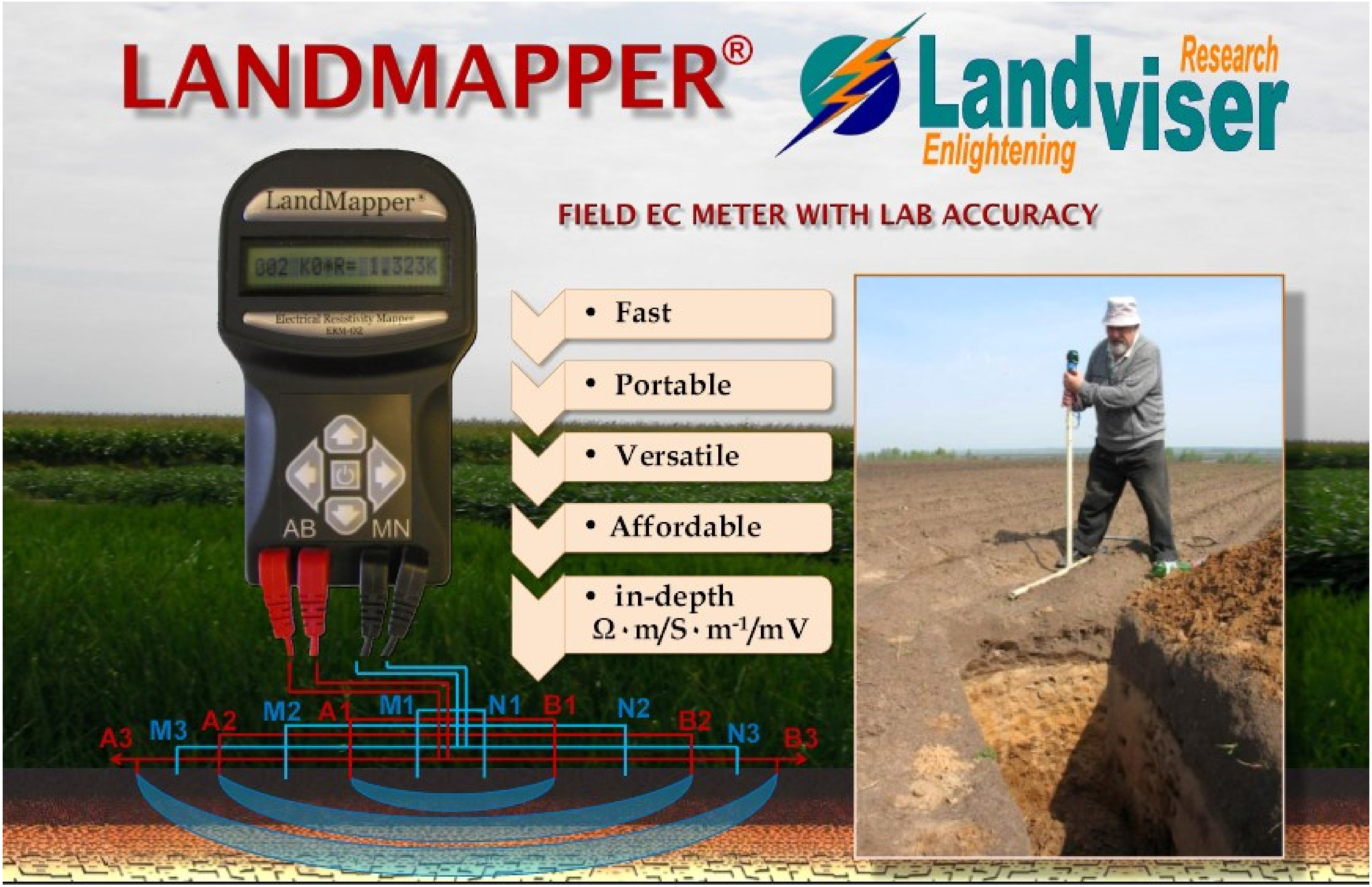
$$EC = \frac{1}{ER} \qquad ER = \frac{1}{EC}$$

EC <=> ER conversions only valid for base units S/m <=> Ohm m!

Salinity of Lakes is taken from http://www.duluthstreams.org/understanding/param_ec.html

Soil salinity is routinely evaluated in the labs from electrical conductivity of liquid soil saturation extract (ECe). The resulted total salinity is reported either directly in conductivity units (dS/m) or converted to TDS (total dissolved solids) concentration in ppm (parts per million) using formula:

1 dS/m = 640 ppm = 640 mg/L = 0.64 g/L = 0.064% = 45.7 grains per gallon


LANDMAPPER®
Research
Landviser
Enlightening
LandMapper®
FIELD EC METER WITH LAB ACCURACY
• Fast
• Portable
• Versatile
• Affordable
• in-depth
Ω·m/S·m-1/mV
AB
MN
A3 M3 A2 M2 A1 M1 N1 B1 N2 B2 N3 B3

Measuring electrical resistivity

1. Connect the A, B, M, and N electrodes from the four-electrode probe to the corresponding sockets on the front panel of the device

   (red wires to the AB socket and black wires to the MN socket).

2. Ground all the electrodes of the four-electrode probe at a desired location.

3. Press the ⏻ button to turn the device on. Device is ready for measurements. To save the battery, the device will automatically turn off after 5 min of standing idle.

4. Press the INPUT key (◄) and take electrical resistivity reading from the digital output on the screen.

   Note: If the resistivity is larger than 1000 Ohm m, the device displays a number followed by letter K, indicating that the resistivity value is in kilo Ohm m. Multiply the number displayed by 1000 to get value in Ohm m. LandMapper can measure ER in wide range of resistivities/conductivities, see table on the next page or at http://landviser.net/webfm_send/15

5. To store the value of electrical resistivity in the device memory press and hold the FUNCTION key (►) and then press the INPUT key (◄) again. The value of resistivity is stored in the memory, the number of the storage cell is advanced, and device is ready to read and store next measurement.

<u>*Display listing:*</u>

$$\underbrace{001}_{1}\ \sqcup\ \underbrace{K}_{2}\underbrace{0}_{3}\underbrace{*}_{4}\underbrace{R}_{5}\underbrace{0000}_{6}$$

1 – Storage cell ID (000 to 999)
2 - Coefficient K
3 - ID of a K-coefficient (0 to 9)
4 – Sign of multiplication
5 – Indication for resistivity (R)
6 – Value of electrical resistivity

Accessing RAM and saving a measurement in a specific memory cell

1. Holding down the FUNCTION key (►), press key (▲) twice to switch to the memory content mode.
2. Scroll through the RAM cells using UP (▲) and DOWN (▼) keys to view the content of the cells

<u>*Display listing:*</u>

$$\underbrace{\text{001}}_{1}\quad \underbrace{\text{--,--}}_{2}\quad \underbrace{\text{KN}}_{3}$$

1 – Cell ID number
2 – Value of the electrical resistivity (--,-- if no entry)
3 – Number of the K-coefficient

3. To select a specific cell to store the recent measurement, press the INPUT key (◄) - the first digit starts blinking - and change it with the keys ▲ or ▼.
4. Press and hold down the FUNCTION key (►) and then press INPUT key (◄) to save the selected cell ID number – the digit stops blinking
5. Exit the memory content mode by holding down the ► key and pressing the ▼ key twice.
6. Press and hold the FUNCTION key (►) and then press the INPUT key (◄) to save the measurement.

Clearing the memory

1. Press and hold the FUCTION key (►) and choose the mode “Clearing RAM” by pressing the UP (▲) key three times.
2. Holding down the FUNCTION key (►) press the INPUT key (◄). Indicator will show the progress of erasing RAM cells:

<u>*Display listing:*</u>

" >>> ______ <<< "
001

001 – memory cell ID number changing from 000 to 999

At the end of the erasing cycle the display will read:

" 000 --,-- K0 "

Test the battery voltage

Press and hold the FUNCTION key (►) and choose the mode “Battery voltage” by pressing the DOWN (▼) key twice.

Display listing:

Ubat = -.- V
1

1 - Battery voltage

If the voltage of the battery is less than 7V, the following message will appear:

Ubat < min

In this case it is necessary to replace the battery.

Change the contrast of the LCD display

Press and hold FUNCTION key (►) and choose the mode “Contrast” by pressing DOWN (▼) key three times.

Display listing: Contrast = --

1 - Value of the contrast from 1 to 27.

Using keys (▲) or (▼) select the optimal contrast value.

To save the contrast value press and hold FUNCTION key (►), then press INPUT key (◄).

Transfer the stored values of resistivity to a computer

1. Connect the included serial cable to the socket on the side panel of LandMapper and to the serial port of your personal computer.

   Note: Use serial cable supplied with LandMapper, not the generic cable from an electronics store! If your computer does not have serial RS-232 port, use standard USB to RS-232 convertor, which can be purchased from us or any electronics supply store. Make sure that you are purchasing USB-to-Serial converter which supports your operation system. Supplied serial cable was tested to work with many brands of USB-to Serial converters and WinME-Win7 operation systems.

2. Copy driver “**connectERM01.exe**” from the root directory of the enclosed CD to the hard disk of your PC. You can also download fresh version of the program from our website http://landviser.net/webfm_send/182 (login/registration required). The program was tested only on the IBM-compatible computers with different versions of Windows, up to Win7.

3. Double click the file "**connectERM01.exe**" to start the program for data transfer.

4. Choose the serial port (com1 to com4) to which the device is connected (usually com1).
5. On the device: holding FUNCTION key (►) select the data transfer mode by pressing DOWN (▼) key four times.

Display listing:

A PC com Wait

6. In the program click the button “Press when unit screen reads “A PC com Wait””. The device will sequentially list the cells being transferred.

Display listing:

PC com N

N - Memory cell ID number from 000 up to 999

7. The transferred data are listed on the right hand side of the program window. The data can be stored as a file in ASCII format (.txt) or copied to the Window clipboard and pasted into any suitable spreadsheet program. The data file format is:

N of cell **N of K** **Value of resistivity/conductivity**

TROUBLESHOOTING

Problem	Solution
Device will not turn on or display is fading	Change the battery. Use only 9-V PP3 battery. It is a good habit to check the battery voltage before each field measuring session and always have spare batteries available.
The memory is full (display shows the memory cell ID number 999)	Transfer data to PC. Perform the “Cleaning RAM” procedure.
Low visibility of the display	Increase contrast in the “Contrast” mode.
Unusually low or high values of the measured resistivity (highly different from the same or nearby location)	Indicates interrupted connectivity (device/wire/electrode/soil). In most cases re-grounding of the electrodes will solve the problem. If the problem persists, check the connections at the device interface. Check and tighten the nuts where the wires connect to the electrodes on the probe.
Problems with connection to PC	Change the com port in the transfer program. Try to free COM1 port on your PC if you set up connection with other devices before. DO NOT run **connectERM01.exe** and **com.exe** simultaneously – they use the same COM port. Note: **com.exe** can only be used with LandMapper ERM-02!

GUARANTEE, REPAIRS AND SPARES

Instruments supplied by Landviser are guaranteed for one year against defects in manufacture or materials used. The guarantee does not cover damage through misuse, inexpert servicing, or other circumstances beyond our control.

For the US this means that no charges are made for labor, materials, or return shipment for guarantee repairs.

For other countries, the guarantee covers free exchange of faulty parts during the guarantee period.

Alternatively, if the equipment is returned to us for guarantee repair, we make no charge for labor or materials but we do charge for shipping and handling and US customs clearance.

We strongly prefer to have such repairs discussed with us first, and if we agree that the equipment does need to be returned, we may at our discretion waive these charges.

Service and spares

We recognize that some users of our instruments may not have easy access to technically specialized backup. Please refer to the Care and Maintenance section of this Manual for specific information on this product.

Spare parts for repairable instruments manufactured by Landviser can be supplied directly from us. These can normally be sent within 3 working days of receiving an order.

Spare parts and accessories for sensors not manufactured by Landviser, but supplied by us individually or as a part of a system, may be obtained from the original manufacturer. We will try our best to obtain the requested parts as quickly as we can, but an additional delay is possible.

Should it prove necessary, instruments may be returned to us for servicing. We normally expect to complete repairs of our instruments (such as four-electrode probes) within 2 days of receiving the equipment. The faulty measuring unit will be returned to the manufacturer, IP GeoPro in Russia and may be subject to an additional delay of two to four months.

Users in countries that have a Landviser Agent or Technical Representative should contact them first.

Protocols for Laboratory / Field measurements with LandMapper ERM-01

Resistivity or conductivity measurements in laboratory cell

The four-electrode principle is best illustrated in the laboratory conductivity cell (Fig. 1). The cell is a rectangular plastic box with the current electrodes A and B as brass plates on the smaller sides. The potential electrodes M and N are the brass rods in the middle of the long side of the cell. A constant current (*I*) is applied to the two outer electrodes (A and B) and the arising potential difference (*ΔU*) is measured between the two inner electrodes (M and N).

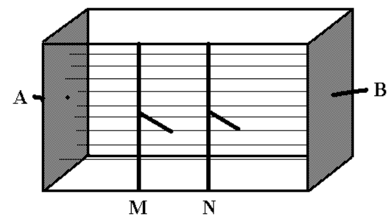


Fig. 1. Scheme of the four-electrode laboratory conductivity cell. Electrical field lines are shown with thin straight lines (uniform electrical field).

The geometrical factor for a cell is obtained from the calibration solutions of a known resistivity (conductivity). The laboratory cells supplied by Landviser, LLC have K-geometrical coefficient printed on the respective cell (Fig. 2).

The sample of soil paste or suspension is placed in a cell to measure electrical resistivity. The cell construction shown in the figure ensures the induction of static uniform electrical field in the cell. The field is imposed on the homogeneous soil sample to measure an accurate electrical resistivity of a sample. The time variation and the difference in electrical resistivity are less than 0.5 % when measured in the same soil sample by the cells with different geometry.

You can input the K-coefficient for the cell you using into device memory, f.e. Kcell=0.029; then input K1=0.03. Press left arrow button to take ER. Read and record value of ER from the display. In the situation you want more precision, make measurements at K0=1, download data to computer and them multiply on Kcell=0.029.

If you wish to make your own cells or want to recalibrate K-coefficient for an old cell, follow instructions at the end of this manual.

The measurements in four-electrode laboratory cell can be utilized to measure precise amount of total dissolved solids in soil, calibrate field measurements and develop the relationships between various soil properties and electrical resistivity. See our eLibrary at http://www.landviser.net/content/soil-electrical-geophysics-public-library-zotero

Four-electrode profiling and mapping

The uniform static electrical field can be created in field conditions to measure soil electrical resistivity or conductivity in situ (Zdanov and Keller, 1994), but it is rather difficult to achieve in practice. Therefore, most modern geophysical methods, such as four-electrode profiling and vertical electrical sounding apply non-uniform electrical field to soils through the point electrodes grounded on soil surface.

The electrical resistivity measured with these methods is termed apparent or bulk electrical resistivity, to distinguish it from the resistivity measured in laboratory in homogeneous samples with uniform electrical field. The electrical profiling method is based on the same four-electrode principle as the conductivity cell. The electrical field is distributed in a soil volume, which size can be estimated from the distance among AMNB electrodes. The geometric coefficient (*K*) can be precisely derived from the array geometry based on the law of electrical field distribution. The practical formulas to calculate K-geometric coefficients for different arrays are provided in DO-IT-YOUSELF probes, cables,

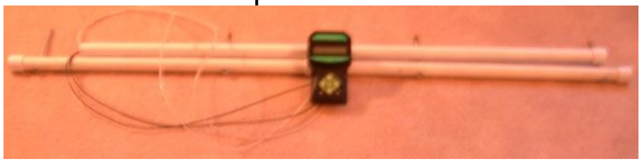
The arrays of different geometries are suitable for various applications. Equally spaced arrays (*AM=MN=NB=a*) in the Wenner configuration with small *a* distances from 2 to 6 cm were used for measurement of electrical resistivity on the walls of open soil pits. Arrays with *a* from 15 to 80 cm were applied for mapping of lateral changes in electrical resistivity on the soil surface. The electrode array is moved along a surveyed line and the electrical measurements result in a horizontal profile of apparent resistivity. The final results include subsurface apparent resistivity values from the measured locations. Results may be plotted as profile lines or contour maps (isopleth resistivity map), or in other presentations according to the specific needs. The method is more accurate than electromagnetic profiling although slower and more labor-intensive.

Setting up LandMapper ERM-01 for ER soil mapping

Convenient, one person operation for mapping top soil down to 0.5 m depth. Use the supplied medium soil mapping probe or order custom probes at http://landviser.net/webfm_send/29 . You can even build your own probes.

1. Remove the device and parts of four-electrode probe from the shipping box. Electrodes are sharpened for better penetration into soil, use precaution to avoid the injury as with any sharp objects.

2. Electrode probe is folded for compact shipping (see figure), i.e. handle is removed from the T-socket in the center of the probe with electrodes.



Large probes are shipped so that one shoulder of the probe with electrodes is removed from the T-socket. In that case, insert the shoulder all the way back into the

T-socket. You may want to use a rubber mullet to hammer the tube into the socket. The tubes can be further secured in the socket with included screws.

3. Take the handle and push four wires all the way through the tube until the banana plugs appear at the other end of the handle. Install handle into the open socket of the T-shaped tube connector located on the tube with electrodes. Hammer the handle into the T-socket with a rubber mullet.

4. Push the wires through the spare T-shaped tube connector with a Velcro fastener, two at the each side. Mount T-connector on the top of the handle tube.

5. Insert banana plugs into the respective sockets on the front panel of the device: red for AB socket (AB) and black for MN socket (MN).

6. Attach the LandMapper ERM-01 measuring unit to the Velcro fastener on the top of the handle or just hold it in a hand. Ground the electrodes. It is not necessary to insert the electrodes all the way into soil, just slight contact will be sufficient.

7. Select or set up the coefficient K specific to your probe. See Calculate K coefficient for any four-electrode probe on how to calculate K.

8. The device is ready for measuring electrical resistivity with four-electrode probe.

9. Walk around the area where you want to conduct ER mapping. Stick probe to the ground and press measuring button (left arrow). Value of ER/EC is output on display. You can store values in LandMapper memory or record it on paper. You can walk in any pattern and GPS your measuring locations simultaneously. Then back in the office you can use any GIS software to develop EC maps. See f.e. this webpage http://www.landviser.net/content/how-use-landmapper-and-consumer-grade-gps-data-logger-quickly-map-salinity-farm-fields

Quick Estimation of SALINITY in Field Soils and Irrigation Water with LANDMAPPER® ERM-02

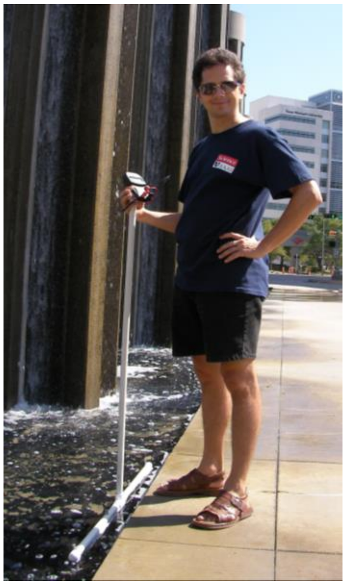
(the same principle apply for ERM-01, but you will have to recalculate: EC=1/ER back in the office, ERM-02 output EC directly in the field as described below)

Soil salinity is routinely evaluated in the labs from electrical conductivity of liquid soil saturation extract (ECe). The resulted total salinity is reported either directly in conductivity units (dS/m) or converted to TDS (total dissolved solids) concentration in ppm (parts per million) using formula:

1 dS/m = 640 ppm = 640 mg/L= 0.64 g/L=0.064%

But **now EC of soil and waters can be measured directly in the field** using highly accurate method of four-electrode probe and Landmapper ERM-02 measuring device. Best of all, probes can be build to sense different soil layers down to 30 ft! Probes are simple and inexpensive to make from common materials available at any hardware store.

For irrigation water and soil solutions: To measure ECw just put 4-electrode probe of LandMapper used for mapping into a ditch, canal, or other water source. Make sure that all 4-electrodes are in contact with water. Take a reading in EC (conductivity) mode. Display will read (example):



K0*C= 150m - which indicates milli Siemens (mS/m)

To convert to dS/m, divide display number by 100, i.e.

150 mS/m=1.5 dS/m.

Use the table below to quickly evaluate salinity of irrigation or surface water:

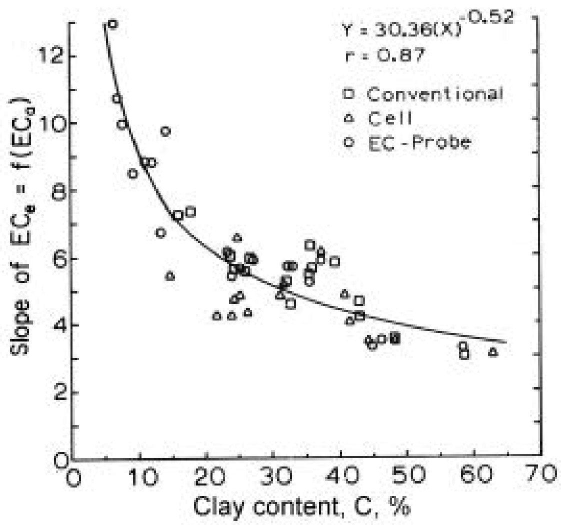
Salinity Class	Electrical Conductivity, ECw (dS/m)	Total dissolved solids, TDS (ppm)
Nonsaline water	<0.7	<500
Saline water	0.7-42	500-30,000
Slightly saline	0.7-3	500-2000
Medium saline	3-6	2000-4000
Highly saline	6-14	4000-9000
Very highly saline	14-42	9000-30,000
Brine	>42	>30,0000

For field soils: Conventional analysis of soil salinity is cumbersome, since it requires collecting big soil samples, preparing soil paste and using vacuum extract apparatus to collect soil solution extract for measuring ECe. Farmer usually had to wait up to 10 days to get back results from the lab. Also salinity is highly variable across the fields and with soil depth. Soil salinity is also highly dynamic and can drastically change during growing season depending on rain, irrigation and other management practices.

LandMapper ERM-02 can be used to check for dangerous salinity levels at different locations and soil layers directly in the field very quickly – one EC reading takes only 4 sec! Few samples can be collected from areas with extreme min-max levels of EC and salinity values can be double-checked at the laboratory using LandMapper ERM-02, optional laboratory 4-electrode box and simple and accurate procedure described in separate flyer. Scale for weighting soil and distilled water is the only additional equipment needed.

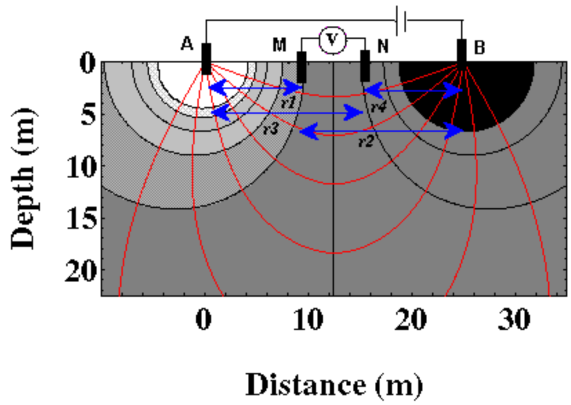
However, **usually ECa measured directly in the field is enough to delineate spots of dangerous salinity** within the field and design management/remediation plan.

ECa or apparent (bulk) electrical resistivity measured with LandMapper in the field can be related back to ECe by multiplying ECa*$K_{texture}$. The $K_{texture}$ varies from 3 to 6 for typical loam and clay loam soils, and can be estimated from soil clay content and a graph at the left. However, those $K_{texture}$ for recalculation of ECa to ECe were derived for relatively dry California soils and if one is measuring ECa in wet situations like after heavy rain in saturated or flooded soil (also possible with LandMapper ERM-02!), $K_{texture}$ multiplication is not necessary. Recent measurements on rice paddies in TX have shown that at ECa=1.5 dS/m at 6" and 16" depth rice is thriving under full flood.



Remember, ECe or electrical conductivity of soil saturation extract is MAXIMUM soil salinity, and one should not be alarmed of high ECe values, especially if growing relatively salt-tolerant crops without excess water. ECa or bulk soil electrical conductivity is much more valuable as its shows amount of ACTIVE or MOBILE salts in soil profile under field soil moisture conditions.

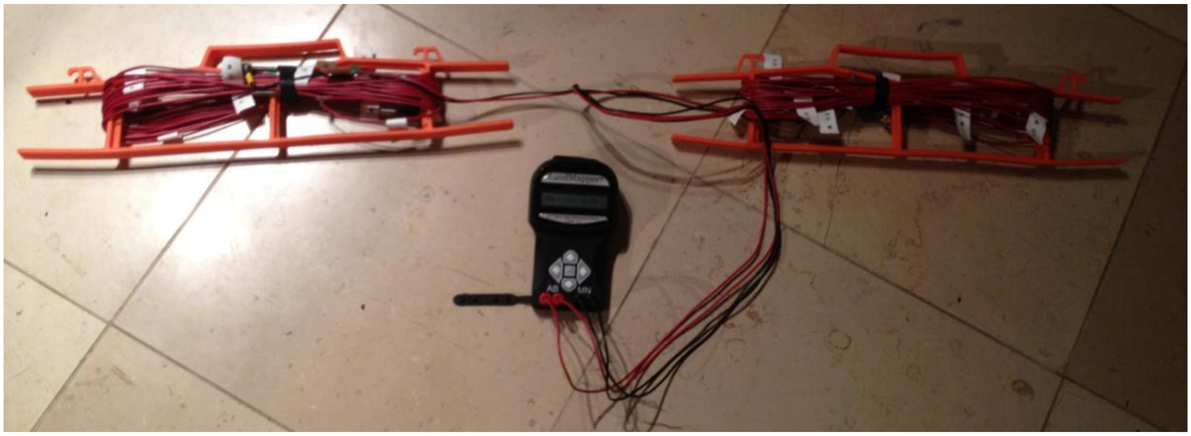
Bulk soil electrical conductivity (ECa) is measured from soil surface to the depth in the big soil volume determined by the distance among four electrodes (ABMN) and therefore is more representative of field conditions than measurements in small soil sample or soil ECa insertion probe. The depth and volume of measurement may be varied by changing the spacing between electrodes. When the distance between the outside pair of electrodes (the current electrodes, AB) is small, the flow of electricity is shallower. The effective depth of measurement is about one-third of the distance between AB electrodes. The calculation of ECa from field measurements done with different size probes will be done automatically by LandMapper ERM-02 if geometrical coefficient Kg is imputed into device for specific probe. Kg can be calculated from distances among ABMN electrodes using formula below (input distances in meters):



$$K_g = \pi \frac{[AM]\cdot[AN]}{[MN]} \qquad \pi = 3.1416$$

Four-electrode probes supplied by us will have Kg printed on the probe and imputed into LandMapper ERM-02. Device can store nine Kg (K1-K9) coefficients to facilitate quick changes in the field for up to 10 probes for different depths. Default K0=1 and cannot be changed. K0 is used with a probe to the depth ~6" where AM=MN=NB=a=16 cm or for resistance/conductance measurements.

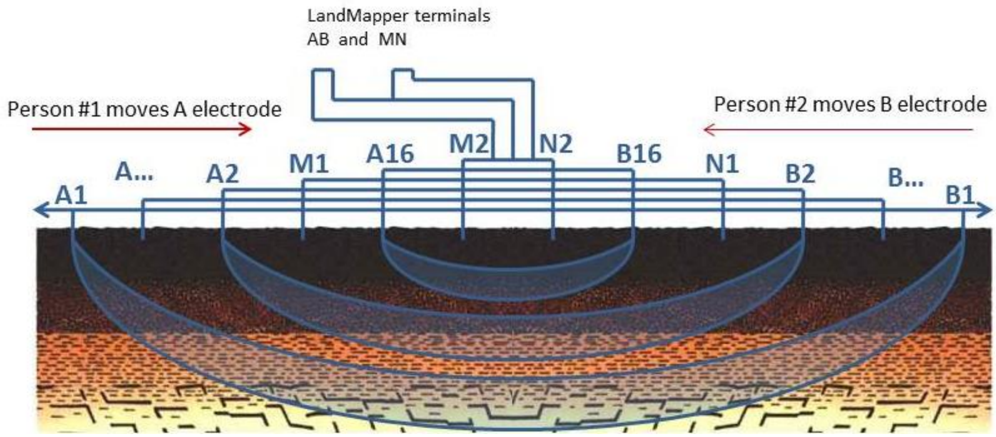
1D Vertical Electrical Sounding (VES) with LandMapper



This manual VES technique is described to use with Landviser's supplied manual VES cable. It is most convenient to use with three people. The worksheet in Excel format can be downloaded from http://www.landviser.net/webfm_send/185

[M1N1] = 2.0 m

[M2N2] = 1.0 m



1. Establish the center location for the VES profile. It is a center point between M2 and N2. Here the person with LandMapper will conduct measurements.
2. Send two persons outward in a straight line from the center to unwind both red wires from the probe up to 14 m mark and insert electrodes in soil => A1 and B1.
3. Measuring person grounds central black M1N1 electrodes at MN/2=1.0 m (green label, black wires). Connect black wires (MN) to MN- terminals of LandMapper.
4. Connect red wires (AB) to AB- terminals of LandMapper.
5. Take ER-reading at K0=1 and AB electrodes at 14 m.
6. Move A and B electrodes to 12 m marks at both sides - take ER-reading.
7. Continue until AB/2=6.0.
8. Move MN electrodes to 0.5 m mark (black wire, green label) and AB to 5.0 m mark.
9. Continue taken measurements until last AB/2=1.0 m.
10. Field ER-readings can be stored in LandMapper memory or recorded manually.
11. The recorded ER-values needs to be multiplied on appropriate K-coefficients.

Note: if ER values measured on deep AB/2 (#1-5) are too small, switch to K1=10, or even K2=100 (99.99), don't forget to record which K-taken you used in the table, then the table on second page in the Excel workbook will re-calculate ER automatically and plot VES profile.

Field data recording table

AB distances, m	MN m	Measurement from deep to shallow #	AB/2, m	K-set	K-taken	ER-1	ER-2	ER-3	ER-4
[A1B1] = 28	2.0	1	**14.0**	K0=1	1	10.41			
[A2B2] = 24	2.0	2	**12.0**	K0=1	1	27.47			
[A3B3] = 20	2.0	3	**10.0**	K0=1	1	102.8			
[A4B4] = 18	2.0	4	**9.0**	K0=1	1	15.75			
[A5B5] = 16	2.0	5	**8.0**	K0=1	1	13.49			
[A6B6] = 14	2.0	6	**7.0**	K0=1	1	10.26			
[A7B7] = 12	2.0	7	**6.0**	K0=1	1	21.28			
[A8B8] = 10	1.0	8	**5.0**	K0=1	1	30.07			
[A9B9] = 9	1.0	9	**4.5**	K0=1	1	12.29			
[A10B10] = 8	1.0	10	**4.0**	K0=1	1	13.73			
[A11B11] = 7	1.0	11	**3.5**	K0=1	1	15.37			
[A12B12] = 6	1.0	12	**3.0**	K0=1	1	62.18			
[A13B13] = 5	1.0	13	**2.5**	K0=1	1	16.02			
[A14B14] = 4	1.0	14	**2.0**	K0=1	1	26.04			
[A15B15] = 3	1.0	15	**1.5**	K0=1	1	18.18			
[A16B16] = 2	1.0	16	**1.0**	K0=1	1	18.18			

Recalculation table

AB distances, m	MN m	Measurement from deep to shallow #	AB/2, m	K-multiply	K-taken	Recalculate ER for VES interpretation ER-1	ER-2	ER-3	ER-4
[A1B1] = 28	2.0	1	**14.0**	306.3	1	3188.6			
[A2B2] = 24	2.0	2	**12.0**	224.6	1	6170.4			
[A3B3] = 20	2.0	3	**10.0**	155.5	1	15986			
[A4B4] = 18	2.0	4	**9.0**	125.7	1	1979.2			
[A5B5] = 16	2.0	5	**8.0**	99.0	1	1335			
[A6B6] = 14	2.0	6	**7.0**	75.4	1	773.59			
[A7B7] = 12	2.0	7	**6.0**	55.0	1	1169.9			
[A8B8] = 10	1.0	8	**5.0**	77.8	1	2338.1			
[A9B9] = 9	1.0	9	**4.5**	62.8	1	772.21			
[A10B10] = 8	1.0	10	**4.0**	49.5	1	679.36			
[A11B11] = 7	1.0	11	**3.5**	37.7	1	579.44			
[A12B12] = 6	1.0	12	**3.0**	27.5	1	1709.3			
[A13B13] = 5	1.0	13	**2.5**	18.8	1	301.97			
[A14B14] = 4	1.0	14	**2.0**	11.8	1	306.78			
[A15B15] = 3	1.0	15	**1.5**	6.3	1	114.23			
[A16B16] = 2	1.0	16	**1.0**	2.4	1	42.836			

Instead of writing ER values on the paper in the provided tables, you can store ER in LandMapper's memory. You still need to keep track of what cell # starts new VES profile and which K values had you used (this K values are stored indefinitely, but don't change K in the middle of field trip).
Good Field Practice: If you wish to relay on stored ER data, make sure to set up data connection to your computer BEFORE you head to the field! You can store some mock data and do download and memory clean up before you go out and start collecting real data! Also clean up ERM-01 memory from all mock data before actual field session, so you don’t get confused which data are those!

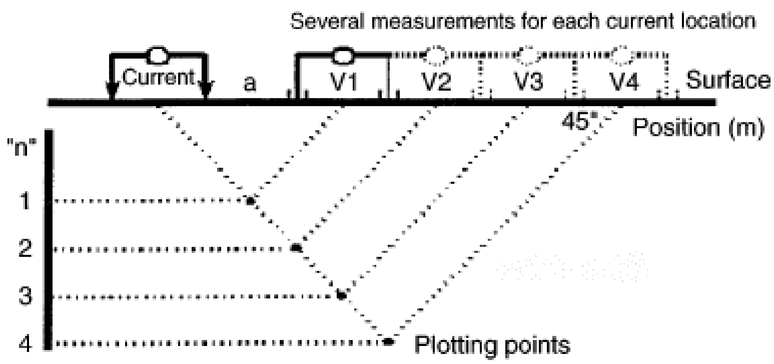
2D Dipole-Dipole Electrical Tomography with LandMapper

Manual measuring of electrical resistivity 2D cross-section is possible with LandMapper with supplied (optional) or made by user cable set.
There are two modifications of 2D cable set offered and tested by Landviser, LLC:

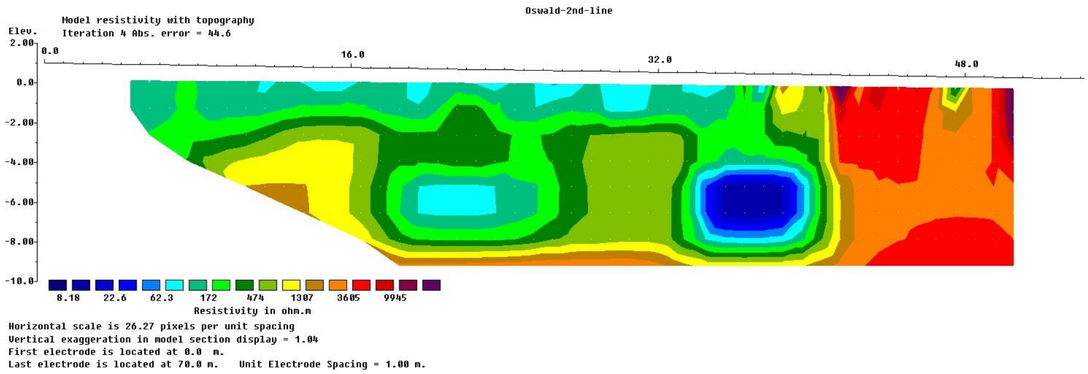
1. Mobile shallow (~2 m depth) set consisted of two T-style probes (AB and MN dipoles) similar to mapping probes. The dipoles are set at 1 m size with possible separation between dipoles (wire length) no more than 5 meters (n=5).
2. Stationary set (~ 14 m depth) where electrodes are hammered on the soil surface along the straight line at one meter distance. Electrodes are simple metal spikes/nails and is sourced locally (are NOT provided by Landviser, LLC). We supply wires with banana-plug connections to LandMapper terminals on one end and alligator clips on the other end to connect with electrodes.

Principle of measurements with both sets is the same for both cable sets and is illustrated by figure below. You can also watch instructional videos on our YouTube Channel - **LandviserLLC**

AB MN



The complete scheme of dipole-dipole manual protocol is provided as Excel workbook on USB drive to all our customers. You can also download that Excel file from our website http://landviser.net/webfm_send/258 (need to register). The detail description below covers step-by-step protocol to conduct dense (~0.5 m resolution) measurements down to ~14 m depth and 50 m long. The profile can continue indefinitely to the right, as shown in Excel file. Different depths and resolutions are possible by modification of this basic protocol, per request we can develop custom protocols for you (info@landviser.net). This protocol is designed that whole set can be saved into LandMapper's memory (stores 1000 data points), downloaded to PC, recalculated in Excel workbook and re-formatted for Interpretation of data in RES2DINV software (see DIY for demo version of software http://www.landviser.net/node/232). This protocol was tested by several groups of archeologists and is most suitable for detecting relatively large burial places and shallow caves. The method can help to pinpoint areas of very low resistivity (i.e. metal objects) of rectangular shape, for example as on the figure below.



Field procedure

Hammer electrodes (nails) in a straight line one meter apart. You will be making series of measurements with AB (current) electrodes planted at the beginning of the line and moving MN farther apart to reach deeper.

We refer to size of dipoles (distance between AB or MN electrodes) as “a” and during measurement protocol we will move dipole MN farther to the right from dipole AB “n” times. In this setup there will be three levels of the measurements, for different sizes of dipoles:

Level 1 - AB=MN= 1 m (measure at each electrode)
Level 2 - AB=MN= 3 m (skipping some electrodes)
Level 3 - AB=MN= 6 m (skipping some electrodes)

Level 1

Electrodes are numbered from left to right starting with “0”. For the first measurement connect electrodes #0 and #1 with alligator clips on the red wires and push banana plugs on the AB terminals of LandMapper. In the same way connect electrodes #2 and #3 to MN terminals of LandMapper using black wires. Take first measurement of electrical resistivity with LandMapper. For the next measurement (marked by “1” diagonally) move MN electrodes to #3 and #4. Note, that you can just move one alligator clip, from electrode #2 to #4, i.e. you can flip-flop M and N electrodes in dipole, this will not affect measurements. Refer to the picture below:

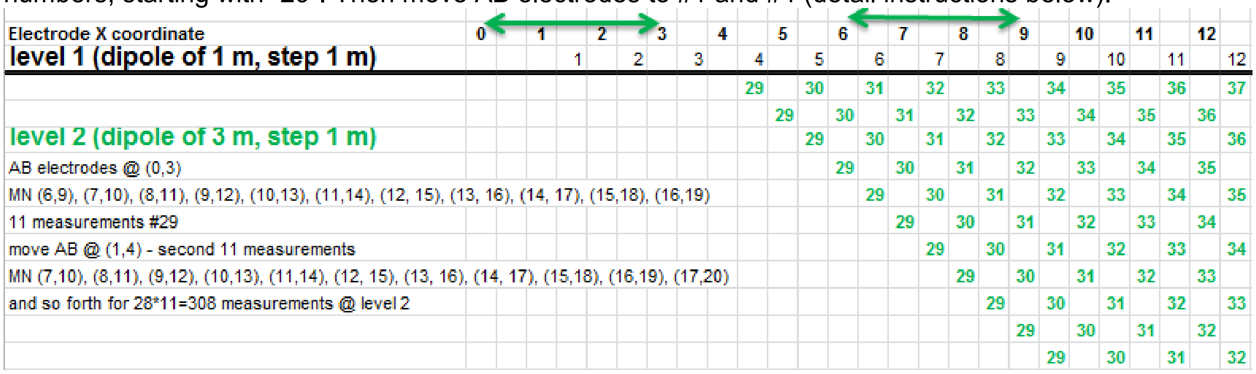
	Electrode layout pseudo-section																								
Electrode X coordinate	**0**	↔	**1**		**2**	↔	**3**		**4**		**5**		**6**		**7**		**8**		**9**		**10**		**11**		**12**
level 1 (dipole of 1 m, step 1 m)				1		2		3		4		5		6		7		8		9		10		11		12
AB electrodes @ (0,1)					1		2		3		4		5		6		7		8		9		10		11	
MN (2,3), (3,4), (4,5), (5,6), (6,7), (7,8)						1		2		3		4		5		6		7		8		9		10		11
move AB @ (1,2) - second 6 measurements	first 6 measurements						1		2		3		4		5		6		7		8		9		10	
MN (3,4), (4,5), (5,6), (6,7), (7,8), (8,9)								1		2		3		4		5		6		7		8		9		10
and so forth for 28*6=168 measurements @ level 1									1		2		3		4		5		6		7		8		9	

You should not exceed total length in any combination (from A to N electrode) to more than 7*a in order to keep good signal-to-noise ratio of the system. Therefore, after completing six moves of MN dipole, move AB dipole to electrodes #1 and #2 and repeat six measurements moving MN electrodes in the similar manner (six measurements marked “2” on the picture above). Twenty eight sets of six measurements complete Level 1 set of measurements.

Level 1 measurements cover approximately 2.5 meter depth.

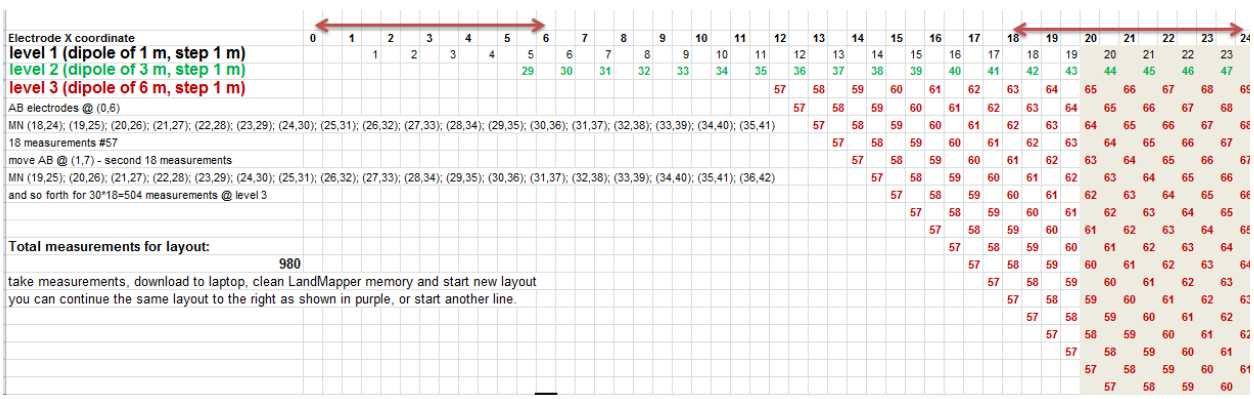
Level 2

In order to go deeper, we will increase the size of dipole to AB=MN=3 m. Connect AB electrodes to #0 and #3 nails. Connect MN to electrodes to #6 and #9. Continue in the same way as for Level 1, moving MN electrodes at one meter steps to the rights (eleven diagonal measurements marked by green numbers, starting with "29". Then move AB electrodes to #1 and #4 (detail instructions below).



Level 3

Increase dipole size one more time to AB=MN=6 m. Connect AB electrodes to #0 and #6 nails. Connect MN to electrodes to #18 and #24. Continue in the same way as for Levels 1 and 2, moving MN electrodes at one meter steps to the right (eighteen diagonal measurements marked by red numbers, starting with "57". Then move AB electrodes to #1 and #7 and MN electrodes to #19 and #25 (detail instructions below).



After completing all measurements listed in Excel file for levels 1, 2 and 3 you will have 980 data points stored in LandMapper's memory and about to reach a limit of the memory. Download data to laptop and paste them into ***ERM-data_in*** worksheet in first three columns (separate data from cell number and K0 indicators using Excel Data function "Text to Columns"). Make sure the resistivity values correspond to the four-electrode combinations (electrode distances from the origin in meters) they were taken on in the next four columns. For example, if you took several measurements at the same combination or skipped a, adjust worksheet accordingly.

From LandMapper			A	B	M	N	K
0	K0=	3.73	0	1	2	3	18.84
1	K0=	0.88	0	1	3	4	75.36
2	K0=	0.68	0	1	4	5	188.4

The worksheet will recalculate respective geometric coefficient and resistivity values as well as put data in last four columns to be copied then into the last worksheet – ***RES2DINV_data***. Before you do that, check Min/Max statistics on top of ***ERM-data*** sheet to check for typos (zero resistivity) or very high resistivities (bad connection with electrodes). Those bad data can be eliminated before importing into RES2DINV for interpretation, or cleaned directly in the software.

Copy "data-only" to the RES2DINV-file			
1st_el	a	n	ER_a
0.00	1.00	1.00000	70.27
0.00	1.00	2.00000	66.32

Refer to the RES2DINV file format description and to website:

- Input data format for any array - http://www.landviser.net/node/265
- Running resistivity inversion modeling in RES2DINV software - http://www.landviser.net/node/457

After downloading data into Excel file, clean LandMapper memory and start new profile or continue the same profile in the right direction indefinitely, see detail instructions in Excel file.

History of four-electrode probe method of electrical resistivity/conductivity

The first attempt to measure electrical resistivity of soils was made at the end of the nineteenth century with the two-electrode technique. Whitney et al., Gardner, and Briggs developed relationships between soil electrical resistivity and soil water content, temperature, and salt content. The two-electrode method measures the sum of both soil resistivity and the contact resistivity between the electrode and soil. The latter is very erratic and unpredictable.

Simultaneously researchers in deep geophysical exploration continued experimenting with electrode arrangements and different applications. The earliest record – patent #17844 was issued to Frank S. Chapman "Method for Detecting Presence and Approximate Location of Metallic Masses"; no date given. Through the 1880's, 90's and into the twentieth century, numerous others filed patents on similar systems. Conrad Schlumberger was issued patent #1,163,469 on December 7, 1915 for his "Method of location of ores in the subsoil and 14 years later another patent (#1,719,786) on July 2, 1929 for his "Method for location of Oil-Bearing Formation."

Wenner, based on the work of Schlumberger, suggested that a linear array of four equally spaced electrodes would minimize soil-electrode contact problems if potential-measuring and current-induced electrodes are separated in space. Since then all the electrical resistivity methods applied in geophysics and soil science are still based on the standard four-electrode principle.

Method of four-electrode probe has been used in soil practices since 1931 for evaluating soil water content and salinity under field conditions. Halvorson and Rhoades applied a four-electrode probe in the Wenner configuration to locate saline seeps on croplands in USA and Canada. Austin and Rhoades developed and introduced a compact four-electrode salinity sensor into routine agricultural practices. A special soil salinity probe, which utilized the same four-electrode principle, was also designed for bore-hole measurements and/or for permanent installations in soils for infiltration and salinity monitoring. An electrical cell used to measure electrical conductivity of soil samples, pastes, and suspensions, was also developed based on four-electrode principle. The advantages of electrical conductivity measurements for evaluation of soil salinity led to development of soil salinity classifications using electrical conductivities of soil pastes and suspensions. Relationships between electrical conductivity measured in-situ with four-electrode probe and conductivity of soil solution or saturated soil paste were developed [4, 38]. The method of four-electrode probe was also used for evaluation of some other soil properties, such as soil water content; structure; bulk density, porosity, and texture; stone content and pollution by oil-mining facilities, locations of the burial places in archaeology and criminology, etc. Recently measurements of soil electrical resistivity were coupled with geostatistical methods to develop accurate soil maps.

Modern electrical geophysical technologies of EC/ER

The method of measuring electrical resistivity or conductivity using four-electrode probe has been applied in geology and soil science for almost a century and the theory of the method is well developed. It should be noted that Schlumberger, Sundberg, Wenner and many others were participants in the early development of electrical methods. Electrical methods increased in popularity, sophistication and sensitivity as technology improved. Modern deep geophysical devices measure several other electrical parameters of the subsurface and have automatic commutation of the different electrode combinations (SYSKAL, IRIS, ABEM LUND System). It is customary to calculate induced polarization (IP) and metal conductivity factor (MCF) using data collected in both time domain and frequency domain.

Using data collected from different four-electrode combinations, a resistivity/IP pseudosection of the subsurface is produced. 2D inversion software is used to create a two dimensional view of real geometry. Combining 2D views gives a 3D view of areas having contrasting electrical properties. The recent advancement in deep geophysics were in developing inversion software (GEOTOMO Software)

Methods of electrical exploration have been used to find formation faults, formation bedding, water saturated aquifers, mineral deposits, and hydrocarbons including coal. Vertical electrical sounding and geoelectrical imaging methods work well in applications having good resistivity contrast.

Recently, electrical geophysical methods become increasingly popular in soil and environment studies. The methods have been adapted to soil studies through hardware modification (smaller electrodes, array spacing, low-capacity batteries) which increased devices portability. This modification was essential since depth of interest for soil investigations is much smaller than for geological exploration. Besides, soils usually have lower contrast in electrical parameters between horizons. Usually, many factors simultaneously influence electrical parameters measured in soils in-situ.

Methods of field soil electrophysics include direct current (DC) and auxiliary current (AC) methods. Parameters of stationary electrical fields are measured by contact (DC) methods. Predominantly in soil studies, electrical conductivity or resistivity is measured by DC methods of four-electrode probe such as EC-mapping and vertical electrical sounding (VES) (Veris Technologies, Inc; LandMapper ERM-01 by Landviser, LLC). However, natural electrical potentials exist in soils between soil horizons, between soils and plants, and in a direction of predominant water and solution transport. Method of self-potential can be used to outline water fluxes. Currently, the only soil-adapted equipment on the market capable of measuring natural electrical potentials in soils and plants is LandMapper ERM-02 by Landviser, LLC.

Parameters of non-stationary (electromagnetic) fields are measured by non-contact (AC) methods, which measure parameters of secondary electrical fields induced in soils and do not require physical contact with soil - EM-devices: AEMP-14, DualEM, various EM sensors by Geonics, Ltd, PulseEKKO 1000 Ground Penetrating Radar (GPR)). These AC methods are fast on-the-go non-destructive devices, but they measure EC somewhat less accurately than DC contact methods and also are severely depth-limited especially on conductive clay, saline and nutrient-rich soils. Time-domain reflectometry (TDR) technique has been evolved into fast and reliable method of measuring soil water content using contact high-frequency AC current. Advances in TDR technology have brought cost of such devices to the affordable range and they can be used to map and monitor soil water content in topsoil of agricultural fields (Dynamax Theta Probe).

Laboratory and lysimeter soil electrophysics utilizes TDR water-sensors and small EC four-electrode probes to study water and solution transport, soil water properties , colloid and aggregate formation and soil-plant energetic balance.

Still EC-mapping is a predominant electrical geophysical technique widely used in agriculture. All of the field EC-sensing methods have different advantages and limitations.

Methods of EM cannot directly measure different resistivities or conductivities of soil horizons and provide only average or bulk electrical conductivity of the soil profile. Besides, not a single modification of EM method can evaluate soil layers shallower than 0.5 m. GPR evaluates profile differentiation of soil electrical conductivity in shallow subsurface soils, but its performance is often poor in electrically conductive environments, such as salty and clay soils. NRCS has published Ground-Penetrating Radar Soil Suitability Maps derived from the soil attribute data contained in the State Soil Geographic (STATSGO) and the Soil Survey Geographic (SSURGO) databases (http://soils.usda.gov/survey/geography/maps/GPR/index.html) for whole continental USA.

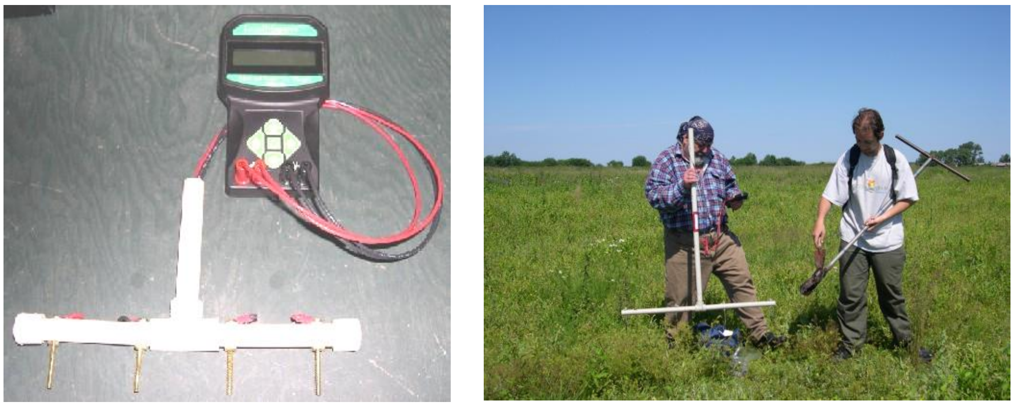


Fig. LandMapper ERM-01 device. (a) LandMapper with a soil pit probe, (b) typical setting for soil mapping application.

Although EM-31 and EM-38 devices of Geonics are virtually non-destructive and potentially can be applied on perennial crops, the electromagnetic techniques provide low depth resolution and generally cannot measure EC in the top soil layer shallower than 0.5 m. Besides, both technologies are quite expensive, which limits their adoption on small and mid-sized farms.

DC electrical geophysical methods, such as electrical profiling (EP) and vertical electrical sounding (VES), implied in Veris' and Landviser' instruments, are more accurate and applicable over a wide range of electrical conductivities and can be easily scaled down to measure differences in electrical parameters on a smaller scale, i.e. between soil horizons in the vadose zone. However, the Veris's device is bulky and measurements are semi-destructive, i.e. cannot be conducted during plant growth and/or on perennial horticultural crops.

A new digital devices, LandMapper ERM-01 and ERM-02, were developed by Landviser LLC to be used within a broad range of agricultural applications (Fig. 1). This device is portable, fast, accurate, compact, safe, and affordable. It uses fully customized, interchangeable, and easily constructed four-electrode probes, which make it highly versatile for many applications, ranging from ER measurements in the laboratory and soil pits to non-destructive field mapping of soil layers at 0-30 ft depth. Thus, the new LandMapper can be a valuable tool for fast and economical soil mapping and response monitoring in precision agriculture.

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Electrical fields and soil properties

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(an abridged version of the paper presented on 17th World Congress of Soil Science, Bangkok, Tailand, 14-20 August 2002)

Abstract

Many kinds of electrical fields appear in soils and their parameters, such as electrical resistivity, conductivity, and potential, can be measured with electrical geophysical methods. Methods of self-potential (SP), electrical profiling (EP), vertical electrical sounding (VES), and non-contact electromagnetic profiling (NEP) were used to measure electrical properties of basic soil types, such as Spodosols, Alfisols, Histosols, Mollisols, and Aridisols (USA Soil Classification) of Russia *in-situ*.

The density of mobile electrical changes, reflected in measured electrical properties, was related to many soil physical and chemical properties. Soil chemical properties (humus content, base saturation, cation exchange capacity (CEC), soil mineral composition, and amount of soluble salts) are related with the total amount of charges in soils. Soil physical properties, such as water content and temperature, influence the mobility of electrical charges in soils. The electrical parameters were related with soil properties influencing the density of mobile electrical charges in soils by exponential relationships based on Boltzmann's distribution law of statistical thermodynamics (r=0.657-0.990).

Generally, the electrical methods can be used for in-situ soil mapping and monitoring when the studied property alone highly influences the distribution of mobile electrical charges in the soil. The electrical properties were used to improve soil characterization for soil morphology and genesis studies; to develop accurate soil maps for precision agriculture practices; and to evaluate soil pollution, disturbance, and physical properties for engineering, forensic, and environmental applications.

Introduction

Soil surveys require quick and, when possible, non-destructive estimations of numerous soil properties, such as salinity, texture, stone content, groundwater depth, and horizon sequence in soil profiles; however, conducting soil measurements with a high sampling density is costly and time-consuming. Conventional methods of soil analysis mostly require disturbing soil, removing soil samples, and analyzing them in a laboratory.

Electrical geophysical methods, on the contrary, allow rapid measurement of soil electrical properties, such as electrical conductivity, resistivity, and potential, directly from soil surface to any depth without soil disturbance. The *in-situ* methods of electrical conductivity (e.g. four-electrode probe and electromagnetic induction) are routinely used to evaluate soil salinity (Halvorson and Rhoades, 1976; Chang et al., 1983; Rhoades et al., 1989). Some electrical geophysical methods were used to map groundwater tables (Arcone et al., 1998), preferential water flow paths (Freeland, 1997a), and perched water locations (Freeland, 1997b); to outline locations of landfills (Barker, 1990); and to evaluate water content (Edlefsen and Anderson, 1941), temperature (Briggs, 1899), texture (Banton et al., 1997), and structure (Nadler, 1991) of soils. However, the relationships between electrical properties and other soil chemical and physical properties are very complex because many soil properties may simultaneously influence in-situ measured electrical parameters (Rhoades et al., 1976; Banton et al., 1997).

Despite the advantages of electrical geophysical methods, their applications to soil science problems are not straightforward and require thorough study. First, the theory about nature of development and distribution of soil electrical fields, whose parameters are measured with the electrical geophysical methods, is still being developed (Pozdnyakov et al., 1996; Pozdnyakova, 1999; Pozdnyakov, 2001). Second, the equipment for geophysical methods of vertical electrical sounding, four-electrode profiling, ground-penetrating radar, etc. manufactured and readily available is not suited for measuring electrical properties in shallow (0-5 m) soil profiles. Finally, the in-situ measurements of electrical parameters need a specific calibration in every study to be reliable for monitoring and mapping different soil properties. To address the discussed problems, the objectives of this study were: (i) to study the basic law of electrophysics governing the electromagnetic fields in soils; (ii) to modify conventional electrical geophysical methods for measuring various electrical properties in soil studies; (iii) to establish relationships between measured electrical properties and other soil physical and chemical properties; (iv) to evaluate the influence of soil-forming processes on distributions of electrical properties in soil profiles; (v) to apply the modified electrical geophysical methods and the developed relationships for estimating spatial distributions of soil properties essential in soil surveys, precision agriculture practices, and environmental engineering.

Materials and Methods

Electrical geophysical methods used in this study can be broadly classified as methods measuring natural electrical potentials of the ground without introducing additional electrical field and methods utilizing artificial electrical or electromagnetic fields to measure soil electrical parameters. Method of self-potential (SP) measures the naturally existed stationary electrical potentials in the soil. Vertical electrical sounding (VES) and electrical profiling (EP) methods measure electrical resistivity or conductivity of soil to any depth when a constant electrical field is artificially created on the surface. VES and EP methods as well as laboratory method of measuring electrical resistivity in soil samples are based on four-electrode principle, but vary considerably in electrode array lengths and arrangements, which makes the methods suitable for different applications. The VES, EP, and SP methods evaluate parameters of the stationary electrical fields in soils. All the methods of stationary electrical fields require grounding electrodes on the soil surface; therefore, measurements with these methods can be made only at agricultural fields, rural areas, or in laboratory in soil samples. At the moment only equipment for four-electrode profiling or mapping, LandMapper ERM-01, and equipment measuring electrical resistivity/conductivity/potential, LandMapper ERM-02, is distributed by Landviser, LLC. We are developing equipment for vertical electrical sounding, LandVisor ERI-01, which is specifically designed for soil shallow studies.

Electromagnetic induction methods (EM), non-contact electromagnetic profiling (NEP), and ground penetrating radar (GPR) introduce electromagnetic waves of different frequencies into soils. The EM, NEP, and GPR evaluate properties of the non-stationary electromagnetic fields in soils. All the methods of non-stationary electromagnetic fields are mobile. The methods do not require a physical contact with the soil surface and can measure electrical resistivity or conductivity in soils covered with firm pavement. The NEP method, which we used in this study, has been specifically designed in Russia for shallow-subsurface environmental studies and now in prototype stage (Pozdnyakova et al., 1996). Landviser, LLC. is planning to introduce a device for non-contact electromagnetic profiling to the market soon.

The geophysical methods do not measure individual charges in soils, but rather outline places with different densities of electrical charges. Thus, the measured with the geophysical methods electrical parameters provide information about volume density of mobile electrical charges in soils. Volume density of electrical charges is proportional to the number of electrically charged particles in an elementary volume of media. Volume density of mobile electrical charges designates the content of ions, which neutralize charges on a free surface (Schuffelen, 1972). As surface charge in soils is formed by sorbed (exchange) cations and anions (Sparks, 1997), the ion exchange capacity is equivalent to the density of exchange surface charges. The ion exchange capacity of the soil is the product of the soil specific surface and surface charge density (Uehara and Gillman, 1981).

Soil charge is determined by an ion exchange, which in turn depends on three factors: isomorphic substitutions in clay minerals, breakage of ionic bonds in organo-mineral complexes, and alteration of charge distribution in macromolecules of soil organic matter. Therefore, soil chemical properties, such as humus content, base saturation, cation exchange capacity (CEC), soil mineral composition, and the amount of soluble salts influence the ion exchange in soils. These soil properties are related with the volume density of mobile electrical charges in soils and, in turn, with the soil electrical parameters. Soil chemical properties, responsible for the formation of soil ion exchange capacity, are related with the total amount of available charges in soils.

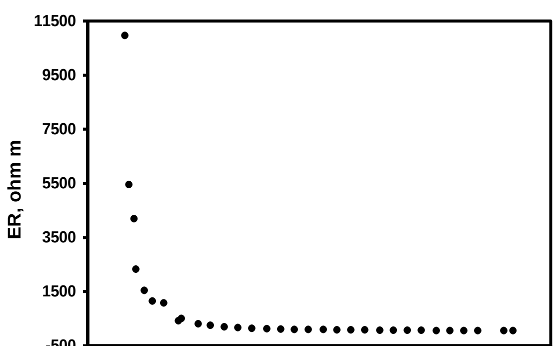

Fig. 2. An example of experimental relationship between electrical resistivity and water content of a peat soil.

Soil physical properties, such as water content and temperature, influence the mobility of electrical charges in soils. From our studies of the relationships between electrical resistivity and soil bulk density or soil water content (Fig. 2) in laboratory conditions the mobility of electrical charges exponentially increases with the increase in those properties causing electrical resistivity decrease (Pozdnyakova, 1999). Other soil physical properties, such as soil structure, texture, and bulk density, alter the distribution of mobile electrical charges in soils. Thus, the volume density of mobile electrical changes is related to many soil physical and chemical properties.

Electrical parameters, such as resistivity and potential are exponentially related with the volume density of mobile electrical charges based on Boltzmann's distribution law (Bolt and Peech, 1953):

$$\sum_{i=1}^{i=m} N_i \Big/ N_{io} = \exp\left(-\varphi \sum_{i=1}^{i=m} \nu_i e \Big/ kT \right) \qquad [1]$$

here $\sum_{i=1}^{i=m} N_i / N_{i0}$ is the ratio of the density of mobile electrical charges in the local volume vs. standard conditions, ν_i is the valence of the *i*-th ion, *e* is the electronic charge, *k* is the universal gas constant, and *T* is the absolute temperature. Therefore, from Eq. [1] the volume density of the mobile electrical charges is exponentially related to the electrical potential. According to Ohm's law the electrical potential is in direct proportion to the electrical resistivity. If the change of a soil property, such as water content, bulk density, or salt content causes a proportional change in the volume density of the mobile electrical charges, a relationship between electrical parameters and soil property (*SP*) can be expressed as

$$SP = a_1 \exp(-b_1 \varphi) = a_2 \exp(-b_2 ER) \qquad [2]$$

where a_1, a_2, b_1, and b_2 are empirical parameters; φ is the electrical potential, and *ER* is the bulk electrical resistivity of the soil. Some relationships between soil properties and volume density of mobile electrical charges may not obey a single exponential equation on the whole range of property variation. For example, the relationship between soil water content and electrical resistivity was approximated with different exponents at different ranges of soil water content due to the influence of soil-water retention (Pozdnyakova, 1999).

While measuring electrical parameters *in situ*, it is difficult to study separately the relationship between a soil property and electrical parameters. Therefore, the relationship of Eq. [2] may be less strong when measured under the simultaneous variations of many soil properties. Nevertheless, the general exponential relationships were obtained for many soil properties, such as total soluble salts, CEC, base saturation, humus content, etc. both in laboratory and under field conditions (Pozdnyakov et al., 1996; Pozdnyakova, 1999, Pozdnyakova et al., 2001).

Considering the qualitative structure of mobile electrical charges, soils can be broadly subdivided into two groups. The first group is soils with low soluble salts and CEC filled by Ca^{+2}, Mg^{+2}, Al^{+3}, and H^{+}. These soils are formed by the processes of podzolization, lessivage, eluviation-illuviation, humification, mineralization, and gleization in humid areas (Wilding et al., 1983). Spodosols, Alfisols, Gelisols, Histosols, Ultisols, and Mollisols can be considered as soils of the first group. The processes of calcification, salinization, alkanization, pedoturbation, humification, and mineralization are dominant in arid and semiarid areas in the second group of soils with CEC filled by Ca^{+2}, Mg^{+2}, and Na^{+} and, in some soils, with high salinity. Soils of the second group represented by Aridosols, Vertisols, and some Mollisols. Inseptosols and Entisols can be assigned to either the first or second group depending on the primarily soil processes dominating in a soil.

For the soils of first group the strongest exponential relationships were obtained for the exchange capacity and base saturation. The correlation coefficients for the relationships with base saturation were as high as 0.90 and 0.88 for soil and colloid suspensions, respectively. The correlation coefficients of the relationships between cation exchange capacity and electrical resistivity were 0.89 for soil suspension and 0.87 for colloid suspension. These two properties characterize the amount of exchange cations in soils. Since soils in humid areas have a low amount of soluble salts, the exchange cations play an important role in soil electrical conductivity. The soil base exchange cations are relatively mobile and primarily conduct electricity in soils of humid areas. Humus content also increases the cation exchange ability of the soils. Therefore, the relatively strong relationship (r = -0.78) was found for the total humus content and electrical resistivity of the colloid suspension. A high correlation coefficient (r = -0.78) was also obtained for the field water content and electrical resistivity of the colloid suspension. The water content in the soils of humid areas is not limited by precipitation and usually determined by the water retention ability of soils. Therefore, soils with high clay and humus contents tend to have high base saturation and high field water content. Thus, for soils in humid areas the basic source of mobile electrical charges is from soil exchange and retention capacity. Electrical resistivity has strong exponential relationships with soil properties characterizing soil exchange capacity, such as base saturation, water and humus contents, and cation exchange capacity. Similar relationships were obtained for the electrical resistivity measured in-situ in open soil pits and on the soil surface with the four-electrode probe and VES

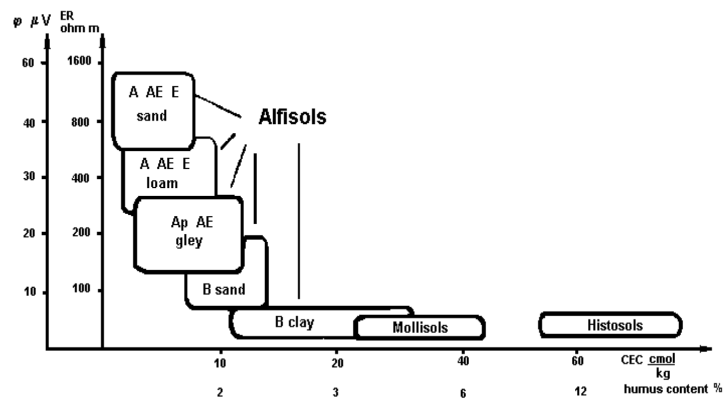

Fig. 3. Schematic relationship between electrical parameters and soil properties showing approximate distribution of data for soils in humid areas.

methods. The relationships were not as strong as those, measured in soil and colloid suspensions, but nevertheless appeared exponential. Since CEC and organic matter are the predominant sources of mobile electrical charges in soils of the first group, there is general exponential relationship between those properties and electrical parameters, measured *in situ* (Fig. 3).

The exchange capacity of soils in arid areas (second group) is filled with calcium, magnesium, and sodium cations and the same cations dominate in the soil solution. Therefore, the electrical parameters show strong relationships with these cations. A strong exponential relationship was obtained between electrical potential, measured on soil surface with the self-potential method and the sum of Ca, Mg, and Na (r = 0.810). For the sodium content alone and electrical potential, the relationship is also exponential with r = 0.599. The Na/(Ca+Mg+Na) ratio is related with the electrical potential by the linear relationship with r = 0.543. Electrical potential decreases with the increase of relative amount of sodium in Aridosols. The same type of linear relationship with r = 0.356 was obtained for Al/(Ca+Mg+Al) ratio and the electrical potential in Alfisols of humid areas. Such ratios are important for soil genesis studies, since they indicate the degree of sodicity in Aridisols, and the degree of eluviation (podzolization) in Alfisols and Spodosols. The obtained relationships can be used to study the soil-forming processes in these soils. Since soil salinity in soils of the second group is the summary characteristics of the available electrical charges, the electrical parameters are strongly related with the total soil salinity. Figure 4 shows the schematic curvilinear relationship between electrical resistivity or potential and soil salinity for the soils of second group.

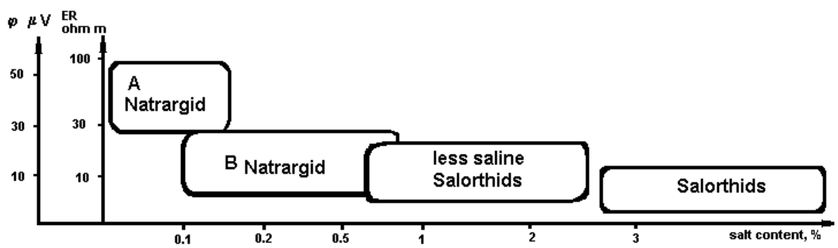

Fig. 4. Schematic relationship between electrical parameters and soil properties in arid soils.

Electrical parameters measured with geophysical methods *in situ* are related with different soil properties, easily measured, and can be used in many soil studies. Different principles of applications should be considered for the three types of problems.

The first-type problems are the monitoring of a soil property, which is only one to vary during the measurements. In such problems the measured electrical resistivity or potential can directly indicate the change in the soil property *in situ*. Such principle was utilized for measuring differences in peat soil compaction under seasonal road and monitoring soil defrosting in spring (Pozdnyakova, 1999).

The second-type problems include investigations of soil properties, which predominantly influence the measured electrical parameters. Therefore, the measured electrical parameters usually show strong relationships with such properties even in field conditions. For example, since the variation in stone content influences the soil electrical resistivity much stronger than variation of any other properties in soils of Crimea Peninsula, the VES method was able to accurately outline the layers with different stone contents in these soils and estimate the volumetric content of stones (Pozdnyakov et al., 1996; Pozdnyakova, 1999). Pollution by petroleum products highly increases the electrical resistivity of Gelisols in northwest Siberia, while salty mining solutions decrease resistivity of the soils. Therefore, methods of EP, VES, and NEP could be used to map pollution in these soils (Pozdnyakov et al., 1996; Pozdnyakova, 1999). Extreme dryness of Histosol in some seasons highly increases the electrical resistivity at the top of the profile, whereas variation of soil water content around field capacity usually does not alter the typical profile distributions of electrical resistivity in the soils (Pozdnyakova et al., 1996; Pozdnyakova, 1999). Disturbance of soils changes the measured electrical resistivity in the soils of humid area significantly enough to detect hidden burial places for forensic and archeological applications (Pitruk et al., 1997).

The third-type problems require careful considerations of the relationships between many soil properties and electrical parameters measured *in situ*. Although soil electrical parameters depend simultaneously on many soil properties, such as salt, water, humus or stone content, CEC, texture, and temperature, in many situations the influence of some soil properties can be considered negligible if they vary around their maximum, based on Boltzmann's distribution law). For example, soil water content close to the field capacity does not practically influence the change in electrical resistivity (Fig. 2). Therefore, in-situ measurements of the electrical parameters of soils in humid areas is not influenced by water content variation and can be used to evaluate elluvial-illuvial horizons in soil profile and more stable soil properties, such as CEC, soil texture, and humus content (Fig. 3). On the other hand, the high variation of soil water content within the whole possible range in the profiles of alluvial soils in Astrakhan' area allows locating the groundwater table (Pozdnyakova et al., 2001).

Thus, the basic laws of soil formation and electrical field distribution govern the relationships between electrical parameters and soil properties. Easy measured *in-situ* electrical resistivity, conductivity, and potential can be applied in non-destructive mapping and monitoring of many soil properties.

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Case-Studies

Despite numerous EC-mapping case studies conducted in many countries by numerous researchers, only a few studies demonstrated a complex approach to electrical geophysical site survey. In most studies only one technique of EC-mapping, either EM or four-electrode method was employed. We have developed a complex methodology of ER-mapping and vertical electrical sounding to aid in agro-reclamation mapping. This approach was tested in humid areas near Moscow and arid areas near Astrakhan. In specific situations when study requested outlining the subsurface fluxes, the technique of self-potential was employed in addition to methods of electrical resistivity/conductivity.

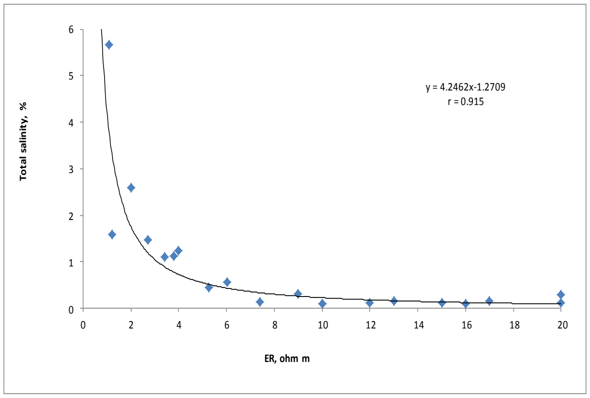
Electrical geophysical methods for soil surveys, environmental and agricultural soil mapping

In the situations when one or two soil properties highly influences measured electrical properties, EC methods can be used for evaluation of such properties in-situ. Our recent results have shown good correlations with various soil properties including but not limited to pH, resistance to penetration, soil water content, and stone content. The technology can be used to enhance existing data from soil series maps using the measured electrical resistivity maps.

The applications of the methods included studying soil texture, compaction, and soil morphology; mapping soil spatial variability within agricultural fields, catenas, or landscapes; locating genetic horizons, hardpans, compacted or disturbed layers, stones, and groundwater tables in soil profiles; and monitoring soil drying or soil solution transport. Our previous research has shown that ER measurements can also be used to outline soil salinity and stone content, to detect and map impermeable layers, and to monitor water and fertilizer states in soil.

Vertical Electrical Sounding to detect soil salinity in arid areas

Water and salt content distributions within the soil profile are the main properties causing considerable variations in electrical resistivity. Since the evaporation in the arid areas (Astrakhan', Russia) is about five times higher than the precipitation, the water content and salt distributions are determined mainly by the saline groundwater.



The differentiation of salinity in the unsaturated zone of the soil profiles was revealed by small fluctuations of electrical resistivity in upper part of the VES profiles. We thoroughly interpreted the VES results to estimate the layers with different resistivities for 12 soil profiles. The total salt content was measured in soil samples collected from the layers of soil profiles as shown in Table (columns 1 and 2) for one example profile.

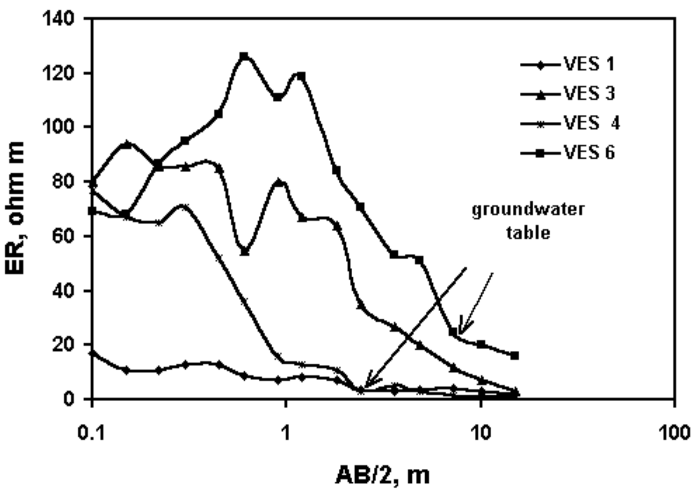
The VES method outlined three layers with different resistivity for the same soil profile (Table, columns 3 and 4). In the column 5 a weighted averages for the outlined soil layers were recalculated from the total salt contents in column 2. Data of recalculated total soil salinity and VES electrical resistivity were combined from the layers of all 12 soil profiles to obtain a relationship between electrical resistivity and total salt content shown in the figure above.

Depth	**Total salinity**	**Results of interpretation**		**Recalculated salinity for interpretation layers**
		Layer depth	ER	
— m —	**—% —**	**— m —**	**ohm m**	**——— % ———**
0-0.02	**0.092**	**0-0.17**	**98**	**0.074**
0.02-0.05	**0.087**			
0.05-0.20	**0.068**	**0.17-0.74**	**15**	**0.095**
0.20-0.40	**0.07**			
0.40-0.70	**0.112**			
0.70-1	**0.117**	**0.74-2.55**	**12**	**0.117**

For quick delineation and estimation of salinity in a soil profile we can consider that a resistivity of 10-20 ohm m corresponds to a total salt content between 0.3 and 0.5% and a resistivity less than 3 ohm m indicate that the total salt content in soil is >1%. Note, that for different soils/areas those values can be different, but general relationship should remain the same: low resistivity (i.e. high conductivity) corresponds to high soil salinity.

Vertical Electrical Sounding to detect groundwater levels in arid areas

Water and salt content distributions within the soil profile are the main properties causing considerable variations in electrical resistivity. Since the evaporation in the arid areas (Astrakhan', Russia) is about five times higher than the precipitation, the water content and salt distributions are determined mainly by the saline groundwater.



The soil profile is divided into a top unsaturated layer with high resistivity and a bottom layer saturated by saline groundwater with low resistivity. Considering large differences in electrical resistivity between the unsaturated and saturated zones, the VES method was applied to detect the saline groundwater level. The approximate location of the groundwater table was estimated by a visual inspection of the VES curve. The AB/2 value with the sharp change to the low resistivity (3-20 ohm m) was selected from each VES profile and multiplied by an empirical coefficient (0.32 for the investigated soils). These coefficients vary from 0.28 to 0.34 for other soil types (Barker, 1989). For example, for VES 6 the AB/2 with such sharp change is 7.2 m and the groundwater table is estimated as 7.2x0.32=2.3 m. In some cases (VES 3) it was difficult to visually determinate where the VES curve has a sharp change in electrical resistivity. Nevertheless, with the computer interpretation of the VES data we could determine the changes more accurately. The results of the computer interpretation of the VES data were compared with the real groundwater tables measured in bore-holes and the relative errors of the VES estimation varied from 3 to 11% as shown in Table.

Case number	Groundwater table		Relative estimation error
	Real (bore hole)	Estimated (VES)	
	m		%
1	2.19	2.37	7
2	1.15	1.29	11
3	2.47	2.55	3
4	2.38	2.25	5
5	1.60	1.53	5
6	1.17	1.34	8
7	1.32	1.22	8
8	1.38	1.24	10
Mean			8

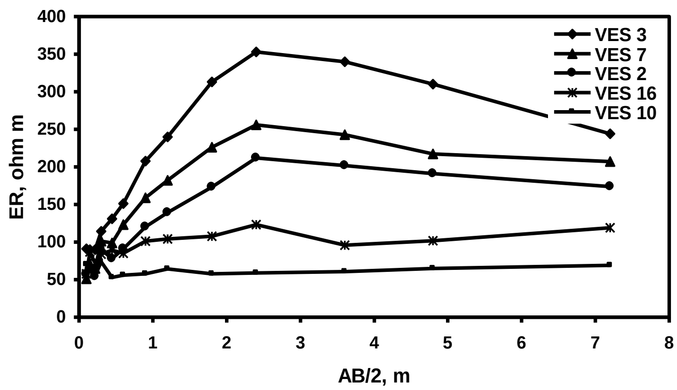
Reference: Barker, R.D. 1989. Depth of investigation of collinear symmetrical four-electrode arrays. Geophysics. 54:1031-1037.

Evaluation of soil stone content with electrical geophysical methods to aid orchard planning

Establishments of orchards and vineyards are long-term and money-intensive, but highly pay-off projects. This study allowed developing procedure for incorporating geophysical survey data into recommendations of usage skeletal soils under orchards. Geophysical methods of electrical resistivity, such as VES and four-electrode mapping provided the information about spatial distributions of stones in skeletal soils. The resistivity of rocks or stones is much higher (about 10^4-10^{12} ohm m) than the resistivity of soil horizons with any texture. Therefore, high resistivity will indicate the presence of stones in soil profiles.

Study was conducted on skeletal soils (Paleoxerolls and Lithic Xerorthents) formed on carbonate-cemented marine deposit, limestone, or pebbles of alluvial origin in western part of Crimea Peninsula, Ukraine. The stone content varied from 2 to 90% of fragments coarse than 2 mm by volume and stony layers occurred in soil profiles at the depth as shallow as 12 cm.

The measured VES profiles were used to approximately evaluate the depth and arrangement of the stony layers in the soils. Most of the soils in the study area were well characterized by a three-layer VES profile. The top layer (I) had the smallest stone content (0.22-0.41 cm^3 cm^{-3}) with electrical resistivity about 80 ohm m. The middle layer (II) had the highest stone content (>50 cm^3 cm^{-3}) and electrical resistivity as high as 450 ohm m. The bottom layer (III) was not always presented in soil profiles. In some profiles layer III was outlined as having lower resistivity (40-200 ohm m) than layer II, which indicates a decrease in stone content in the bottom layer compared with layer II.



The approximate stone content of soil profiles was evaluated by observing VES profiles; thus, the stone content in the soil profiles decreases in a row of VES 3-7-2-16-10. We developed a rough scale for evaluation of stone contents in Crimea soils. Note, that the values may be different for other soils/regions.

Stone content by volume	Electrical resistivity
——— % ———	———— ohm m ————
<5	<50
5-20	50-80
20-40	80-120
40-60	120-150
60-80	150-250
>80 (slightly eroded rocks)	>250 (1000-3000)

During the study and collaboration with scientists from Nikitskij Arboretum, Yalta and Crimea Institution of Irrigated Orchards, Eupatoria, **three soil properties** were found to be essential for estimation of soil potential productivity for usage under orchards. These properties are **stone content** in the **layers of 0-50 cm, 50-100 cm, and >100 cm**; the **depth to impermeable rock**; and the **depth of the A horizon**. We developed a practical guideline for estimation of soil productivity from the stone content and depth to the rock for some typical fruit trees.

Culture	Stone content in layers 0-50 cm	50-100 cm	>100 cm	Depth to rock	Potential productivity
Pear	**<10**	**<20**	**<30**	**>160**	**100**
	10-25	**20-35**	**30-45**	**140-160**	**75-100**
	25-35	**35-40**	**45-60**	**120-140**	**75-50**
Apple	**<15**	**<30**	**<50**	**>145**	**100**
	15-25	**30-45**	**50-60**	**120-145**	**75-100**
	25-40	**45-50**	**60-75**	**100-120**	**75-50**
Peach	**<25**	**<45**	**<55**	**>120**	**100**
	25-35	**45-55**	**55-65**	**100-120**	**75-100**
	35-55	**55-65**	**65-75**	**80-100**	**50-75**
Apricot	**<20**	**<25**	**<40**	**>130**	**100**
	20-30	**25-35**	**40-50**	**110-130**	**75-100**
	30-40	**35-45**	**50-65**	**90-110**	**50-75**
Cherry	**<15**	**<25**	**<40**	**>140**	**100**
	15-25	**24-35**	**40-50**	**120-140**	**75-100**
	25-35	**35-45**	**50-60**	**100-120**	**50-75**
Plum	**<15**	**<25**	**<50**	**>130**	**100**
	15-25	**25-35**	**50-60**	**120-130**	**75-100**
	25-35	**35-45**	**60-70**	**100-120**	**50-75**
Almond	**<25**	**<45**	**<65**	**>110**	**100**
	25-40	**50-60**	**70-80**	**100-110**	**75-100**
	40-50	**60-70**	**80-90**	**80-100**	**50-75**
Walnut	**<20**	**<30**	**<50**	**>100**	**100**
	20-30	**30-40**	**50-70**	**90-100**	**75-100**
	30-40	**40-60**	**70-90**	**80-90**	**50-75**

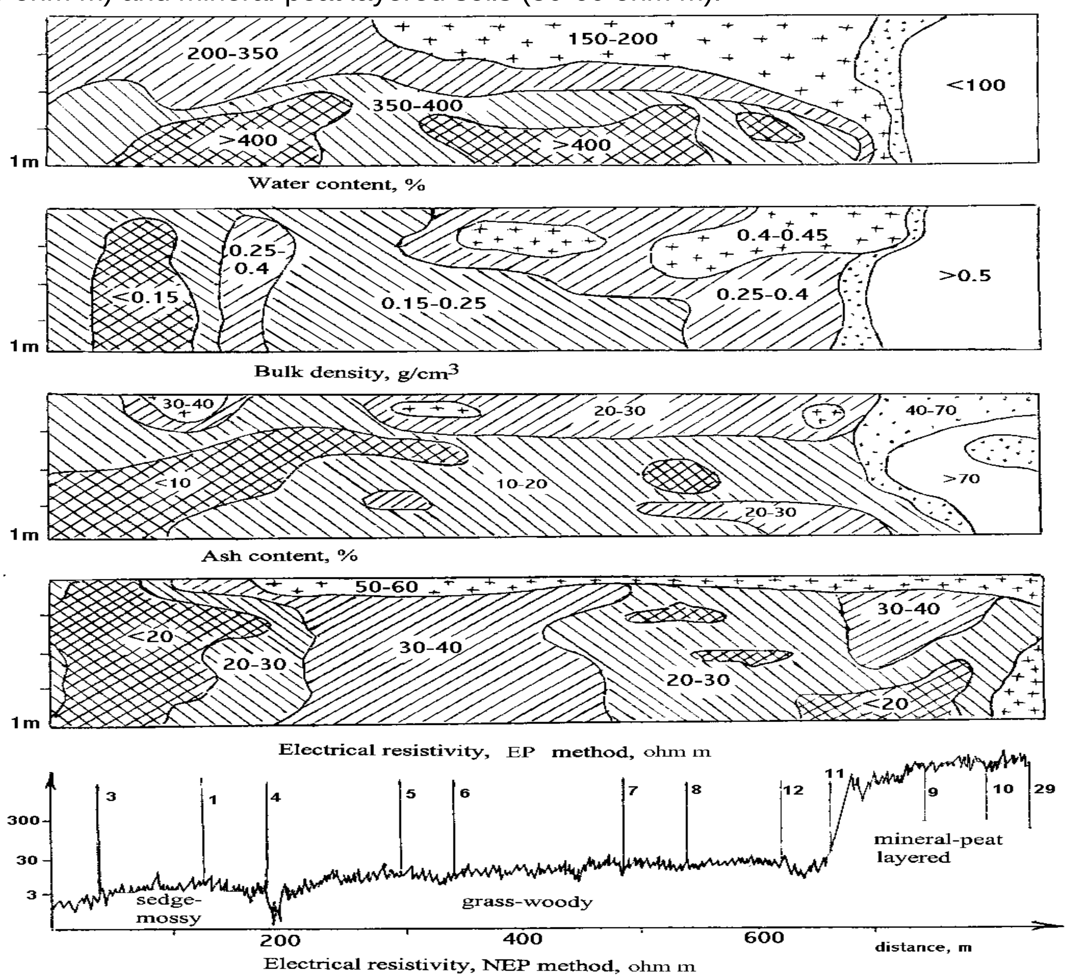
Let us demonstrate how to evaluate the possible productivity of orchard on a particular soil using the VES measurements and Tables. Soils with VES 2, 16, and 10 do not have a contact with an impermeable rock within 240 cm, since the resistivity is less than 250 ohm m for all the AB/2. VES 7 and 3 reach value of 250 ohm m at the AB/2 equal 240 and 90 cm, respectively. Through the VES interpretation or using the recalculation coefficient 0.323 obtained for the studied soils we can estimate that the depth to the rock is 240 x 0.323 = 77.5 cm for VES 7 and 90 x 0.323 = 29.1 cm for VES 3. These two soils are too shallow to be used under any of the orchard cultures. The soils with VES 2, 16, and 10 can be evaluated for the stone content in the characteristic layers of 0-50, 50-100, and >100 cm. These depths can be approximated with AB/2 <180, 180-360, and >360 cm. VES 10 has electrical resistivity of about 50 ohm m through the profile, which represents about 8-10 % of stone content. The soil can be used for growing of any fruit culture. Soil with VES 16 has resistivity about 100 ohm m, therefore, about 20-40% of stones uniformly distributed in the profile. Referencing to Table, this soil can ensure 100% productivity for peach, almond, or walnut orchards.

Thus, vertical electrical sounding is a useful method for evaluation of stone content in skeletal soils. The measured electrical resistivity profiles were used to estimate stone contents of the different layers in soil profiles. Key soil properties, such as stone contents in characteristic layers of 0-50, 50-100, and >100 cm as well as the depth to rock were estimated. **To further increase the efficacy of the estimation, the extend mapping of an area can be conducted on selected characteristic distances AB/2 equal to 90, 180, and 360 cm with four-electrode probe.**

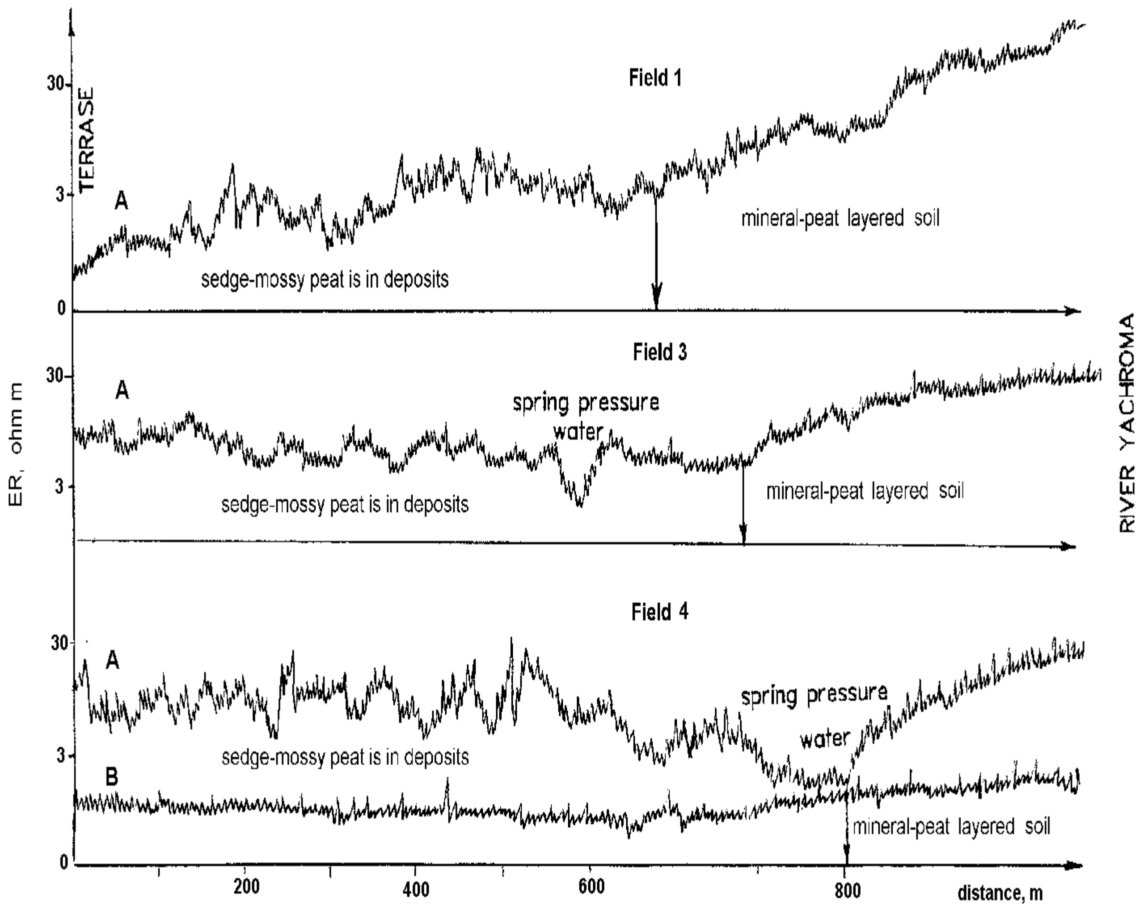
Mapping alluvial soils of humid areas with electrical geophysical methods

Valley soils of humid areas are comprised of various peat and sandy soils of alluvial or lacustrine origins. These soils are located in subordinated positions in a landscape and accumulated high amounts of organic matter and mineral nutrients. Fluctuation of the river bed in space often causes highly complex soil cover in a valley. Studying those soils with conventional methods of soil mapping is very time and resource consuming. Therefore, we tested the electrical geophysical methods of non-contact electrical profiling (NEP) and electrical profiling (EP, with LandMapper ERM-01) for mapping peat and mineral alluvial soils formed in the glacial valley of Yachroma river.

The distinction in botanical structure of peat and hydrology conditions at the different zones of the valley causes distinction in physical and chemical properties of sedge-mossy, grass-woody, and mineral-peat layered soils (Figure). The sedge-mossy peat typically has lower ash content and bulk density, and higher water content, than the grass-woody peat. Electrical resistivity of sedge-mossy peat soil is minimal (<20 ohm m) in comparison with resistivity of grass-woody (30-40 ohm m) and mineral-peat layered soils (50-60 ohm m).



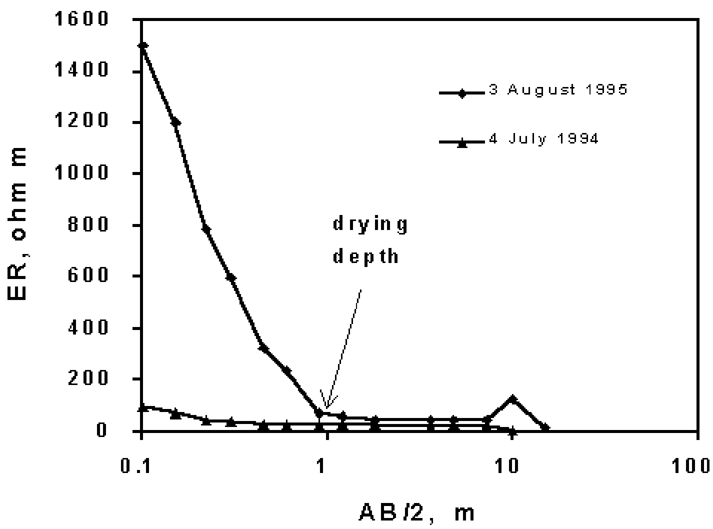
The non-contact electrical profiling method was used for quick mapping of these soils. The area with mineral-peat layered soils is outlined by the highest resistivity (up to 300 ohm m on NEP profile). Resistivity is sharply reduced on peat soils (3 ohm m). Method of NEP provided similar results for the other fields of CPBRS (Fig. 2). From fields 1 to 5 the area of mineral-peat layered and grass-woody soil gradually decreased, whereas the area of sedge-mossy peat soil increased. On the NEP profiles the areas with different genetic types of deposits were characterized by different resistivities. The areas with the resistivity about 3 ohm m characterized presence of sedge-mossy peat in the deposits (Fig. 2). At the transition from mineral-peat layered soils through grass-woody to sedge-mossy peat, the resistivity reduced from 300 to 3 ohm m. The areas with seeping water were possible to detect on NEP profiles as places with the minimum resistivity (Fig. 2). Such extremely low resistivity in spring areas was, probably, because of enrichment of these places with mineral substances (iron and calcium) brought by groundwater.



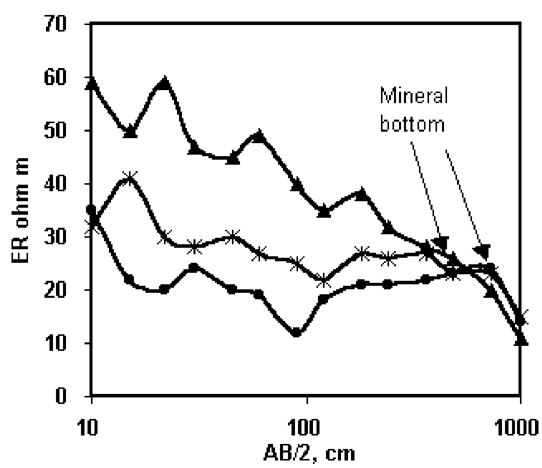
By results of NEP survey we constructed plan of the CPBRS experimental fields, which reflected the basic areas with different peat deposits. The plan agreed with the previous maps of the area developed with conventional geological survey. Based on the distribution of different peat and mineral deposits, an optimal plan of agricultural usage was proposed. Mineral-peat layered soils were recommended to use under intense vegetable production. The rest of the area in fields 1, 2, and 3, especially where seeping groundwater is close to the soil surface, could be used for grass pasture. The whole territory of field 4 and 5 could be used either for pasture or crop rotations of vegetables and grasses. Although such management scheme would reduce usage of soils for high cost vegetable crop, it decreased the cost required for reclamation of these soils and service of drainage systems.

Vertical Electrical Sounding to detect peat deposit thickness and drying depth

The valley landscapes of humid areas are dominated with peat soils of various origins, which become the most productive soils after the proper drainage and cultivation. The high fertility and proximity to water make peat soils the most desirable for vegetable production. However, these soils are also subject to quick degradation during agricultural usage. Excess drainage increases the unproductive decomposition and mineralization of peat and can cause spontaneous ignition of peat soils, whereas little or no drainage can be non-sufficient for normal agricultural practices. Therefore, drainage design and the following agriculture practice on peat soils should be based on careful studies of the peat soil genesis and hydrology of the areas.



Method VES is suitable for detection the resistivity in different soil and geological strata without digging or boring. Usually, peat shows not much difference in electrical properties along the profile. Water content of cultivated peat soils is close to the field capacity during the whole growing season. Other soil properties, such as bulk density, texture, and ash content, that might influence electrical resistivity, are also practically uniform in the soil profile. Therefore, a typical electrical resistivity distribution in the profile of cultivated peat soil (Hemic Haplosaprist) is uniform and about 40 ohm m at the soil surface during the years with average precipitation (Figure, VES for 4 July, 1994). In extremely dry years as in the summer of 1995 in Moscow area, Russia, the upper 50-cm layer of peat soil dried almost to the wilting point, causing an increase of electrical resistivity up to 1,500 ohm m. The drying depth was precisely determined with the VES interpretation. The estimation of drying depth with computer interpretation of VES was verified with direct water content measurements in soil samples collected from the different soil layers.



However, the resistivity of peat soil and an under-laying mineral deposit are shown to be different regardless of the water content conditions of the soil. VES curves of cultivated peat soil on field 8 of CPBRS indicate some decrease of resistivity at AB/2 greater than 1000 m (Figure on the right). This particular area of peat soils is underlined by clay glacial till and lake sediments, which are enriched with colloids and have small electrical resistivity. If peat soils are underlined by a coarse sand material, the difference in electrical resistivity between peat soil and sand deposit might be less pronounced. The interpretation of VES measurements shown, that the depth of peat can be estimated with accuracy about 8.6% if peat is underlined by clay, loam or stony mineral layers (Table).

Table. Estimation of peat soil depth with VES method.

Location	Depth of peat Real (Bore-hole)	Depth of peat Estimated (VES)	Relative estimation error
	cm	cm	%
11	488	432	11.5
7	333	300	9.9
6	173	163	5.8
5	113	102	9.7
4	290	272	6.2
Mean			8.6

Thus, the thickness of the peat and the drying depth of peat soil were measured with VES method. The estimated soil properties are essential for the sustainable management of peat valley soils in intensive vegetable production.

Application of the four-electrode probe method of electrical resistivity in precision farming

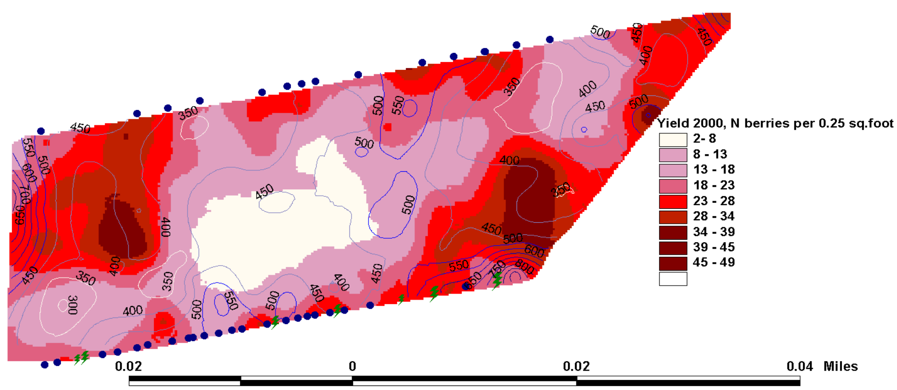
One of the most important issues in precision agriculture is to develop site specific principles of crop management based on variability of soil and hydrological properties. Accessing spatial variability of soil properties often require high-density and repetitious sampling, which is costly, time-consuming, and labor-intensive. One of the challenges facing the adoption of precision agriculture technology is the identification of productivity-related variability of soil properties accurately and cost-effectively.

There is growing evidence that soil EC can be used for characterizing soil productivity and for predicting crop yields. For example, Johnson et al. [23] separated the studied fields in Central Colorado into several classes based on magnitude of EC values. They observed that soil physical and chemical properties, including, bulk density, clay content, soil organic matter content, and biological soil properties, including microbial biomass C and N, and mineralizable N, as well as surface residue mass, were significantly different among the soil EC classes. Kravchenko [24] applied joint multifractal analysis to evaluate spatial aspects of the relationship between corn and soybean grain yields, field EC measurements and topography in an experimental field in Central Illinois. Analysis indicated that the relationship between crop yields and EC differed across the landscape. Variations in EC were shown to be a particularly good predictor of soybean grain yield distributions on higher terrain, i.e. hill tops and shoulders, where EC was successfully used to identify poorly drained areas unfavorable for plant growth.

Kravchenko [24] noted that the strength of the relationship between EC and crop yields in humid regions might be affected by amount of precipitation obtained during growing season. Observed dependency of the crop yield/EC relationship on amounts of precipitation strengthens the need for a compound approach to EC applications for agricultural management in non-arid regions. It is clear that all the factors involved in EC/crop yield correlations, namely, (i) precipitation and (ii) its subsequent horizontal and vertical redistribution determined by field topography, landscape position and hydraulic soil properties, need to be identified. Their contribution to the observed relationships needs to be understood and quantified for EC to become a useful component of agricultural management as a yield predictor.

We tested various techniques to characterize spatial variability of soil properties within a test cranberry bed [70]. Soil and crop analysis were conducted in 1999 and 2000 for samples collected from 216 locations within 6.7 acres cranberry bed planted on Atsion soil in 1993 following removal of blueberries. Data show high variability in topsoil pH (3.8-5.0), water content (0.01-0.62 cm3 cm-3), infiltration rate (0.05-4.3 cm/min), water-soluble Fe (0.1-13.0 mg/L), and electrical resistivity

(124-1,653 Ω m) as well as in yield (0-3,384 berries/sq.m), vine density, berry quality, and PRR (0-95% of roots infested). An in-situ soil moisture sensor (DYNAMAX soil water probe) was used to measure water content at the soil surface (0-5 cm) over the same 216 locations several times during the growing season. Although soil water content changes significantly between precipitation and irrigation events, some areas within the bed tend to experience extreme wetness or dryness, indicating non-uniform drainage in the bed. As was shown [51], the soil water content demonstrated some correlation (exponential or power relationships) with measured electrical resistivity for soils of humid areas (NJ). The presence in topsoil materials with higher water holding capacity, such as clay and silt, and especially water logging conditions can significantly increase the mobility of electrical charges and decrease ER. Those complex conditions are stressful to most crops.



Soil conditions, favorable to PRR, such as soil water logging, higher pH and soluble iron [74] are indicators of reduced environment in soil and all are stressful to plants [75]. As a general outline of soil Red/Ox potential [76], low soil electrical resistivity indicates problem areas on cranberry bed, which correspond to low yield.

Figure shows that lower soil electrical resistivity is generally corresponds to the decrease in cranberry yield. The data were obtained at 216 sampling locations with the prototype of LandMapper ERM-02 and interpolated into the map with commercial software, such as ArcView (ESRI, Inc.) and GS+ (Gamma Design Software, Inc.). Low electrical resistivity outlines the low-lying areas within the field with reduced conditions and prone to Phytophthora root rot disease.

Electrical resistivity vs. soil texture and resistance to penetration

The soil resistance to penetration was measured with the Rimik Cone Penetrometer on two renovated cranberry bogs located on Berryland soil series. The electrical resistivity was measured at the same locations (~200) with the Wenner probe (Landmapper ERM-01) effective to 30 cm depth. The sum of the resistance to penetration to 30 cm depth map and electrical resistivity map have shown very similar patterns (Fig. 3). Low ER and mechanical resistances indicated presence in top soil of some soft clay and silt material, which was confirmed by subsequent excavations.

Electrical resistivity to outline and clarify soil series maps

The application of the geophysical methods of electrical resistivity makes it possible to define areas of electrically contrasting soils, which have distinct properties and, therefore, should be used in agriculture in different ways. Electrical resistivity is a composite characteristic of soils, which generally related to soil texture, stone, salt, and humus contents, and arrangement of the genetic soil horizons. This is the complex of the factors, which directly influence yield of the most of the crops. The advantage of measuring electrical resistivity is that it can be measured directly in the field without actual taking of soil samples and analyzing them in the laboratory. Thus, implication of the electrical resistivity techniques of soil characterization can tremendously decreases time and labor, required to delineate management zones within the fields.

The study was conducted to clarify small scale soil maps (SSURGO) in southern New Jersey, USA. The developed maps of soil electrical resistivity generally followed the pre-existing maps of soil series for the research areas, but revealed significantly more variability within the soil map units. In some cases the data from the electrical resistivity survey were in better agreement with the remote sensed imagery, which revealed cranberry stress due to water logging conditions than with the existing soil series maps for the area.

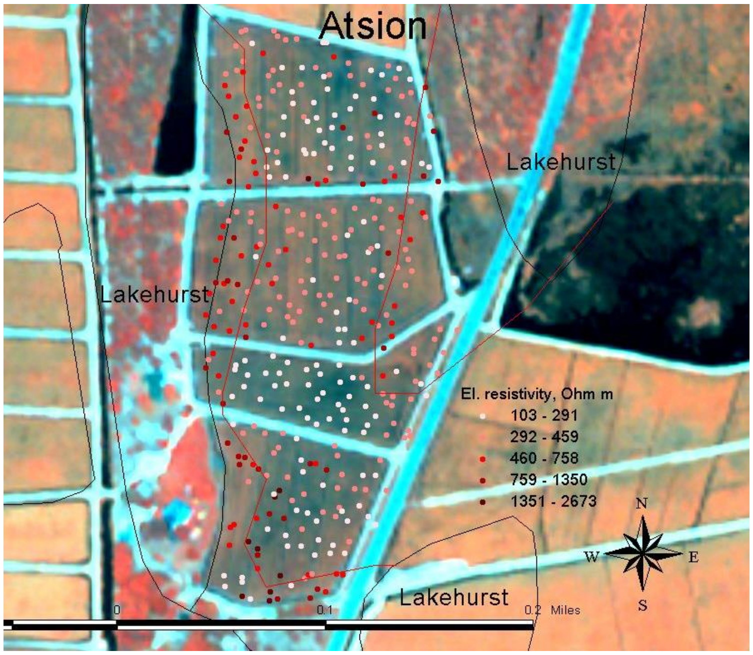


Fig. Amendment (red line) of soil series survey outlines based on electrical resistivity ground measurements and CIR satellite imagery over newly planted cranberry beds.

The results of ER mapping on blueberry farms indicated general correspondence of the spatial patterns in soil properties to the SSURGO delineated soil maps for the area. Thus, the soils of Atsion series have the highest ER (up to 10,000 Ohm m), which decreases in a row of Atsion-Berryland-Hammonton-Mullica series. The electrical resistivity for the same soil series may be quite different for different farms, but always helped to distinguish between soil series within a field.

Electrical resistivity to monitor salt solution transport

As salt concentrations and water content are two major factors influencing electrical properties of soils in arid regions, numerous studies were conducted to map soil salinity using EC methods [42], but relatively few studies applied methods of electrical imaging to study the profile distributions of salts and water content in native arid soils. Method of vertical electrical sounding can be used to study various processes in soil such as freezing-melting, wetting-drying and solution transport in soils. The measurements can be conducted repeatedly during the process by the electrodes installed on the soil surface without any disturbance. 2D visualization of the resistivity cross-section can be done with RES2DINV software.

We conducted controlled experiment of extremely saline solution infiltration in arid sandy soils with high groundwater table in Astrakhan area of Russia. The experiment is a model of technological disaster at a gas-oil refinery, but results are promising for studying lower saline solutions, i.e. fertilizer applications in agriculture.

Figure 4 shows horizontal slices of the electrical resistivity and water content in the saline solution infiltration experiment. During the experiment the highly concentrated (94% NaCl) solution applied to the 0.3 m2 frame in three doses, 20 cm, 50 cm, and 100 cm. After complete infiltration ER was measured with VES methods, then soil samples were extracted with auger at the grid at the infiltration front and below. The next day the soil pit was dug at the infiltration frame to observe horizontal variability of the saline solution and ER was measured at 5 cm grid with four-electrode probe and LandMapper ERM01 and soil samples were collected at the same grid. The control measurements were conducted on native soils nearby without saline solution application. The native sandy soils were extremely dry at the surface and had ER=1000-2000 Ohm m. Resistivity decreases with depth and reaches 200-300 Ohm m at 1.5 m. The groundwater is shallow in the area (1.7 m). However, in saline infiltration experiment resistivity is considerably lower (60-80 Ohm m) starting with 0.6 m. In 20 cm solution case the low ER=1 Ohm m layer reached 25-28 cm, but after 6 hours by VES interpretation saline solution was at 80 cm, which was verified by soil pit observations (after 24 hours solution was at 100 cm). In 50 cm solution the saline layer was detected by VES at 80 cm immediately after infiltration and was detected at 120-130 cm at 24 hours. Immediately after infiltration of 100 cm saline solution VES detected that solution reached groundwater fringe, by augering after 6 hours detected 7 cm dry layer between water fringe and solution front, but that layer was also saline (Fig. 4).

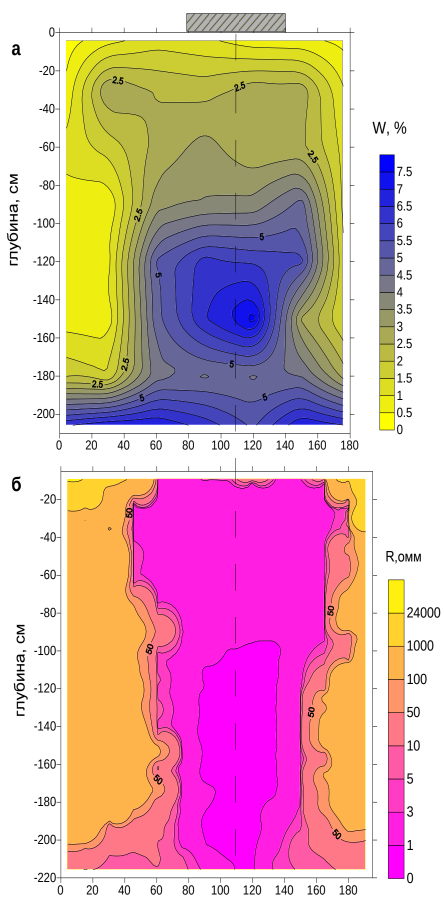


Fig. 4. 2D image of the soil water content (auger sampling) and electrical resistivity (VES) at 6 hours after infiltration of 100 cm extremely saline solution in sandy soil.

Electrical geophysical methods to study plant-soil systems

The previous section demonstrated that complex of soil properties influencing plant growth and yield can be identified and mapped with electrical geophysical methods. Moreover, our recent studies have shown that soil electrical potentials influence plant growth directly and electrical geophysical methods can be used to monitor plant health. The bio-potentials or micro electrical potentials of the plant tissues and their effect on plant growth have been studied by plant physiologists for some time. However, practically no research has been conducted on natural electrical potentials between soil and a growing plant, or “macro-potentials” of the plants.

Earth is an “electrical” planet in nature. All the processes in biosphere occur in ever-changing electrical fields, which arise due to changes in solar activity, magnetic field of earth, and electrical processes in atmosphere. These global and local fluctuations in electrical fields create electro-tropism at all levels of biosphere, including the Soil-Plant system. Electro-tropism in Soil-Plant system is a combination of the natural electrical potential differences on the interfaces inside soil (between soil horizons or peds), on the interfaces inside growing plant (between different plant tissues), as well as between soil and plant. The largest electrical potential differences were observed inside soils. The natural electrical potentials (stationary and fluctuating) in soils were studied by our group for last 40 years and the results were summarized and presented on 17th World Congress of Soil Science in 2002.

Recently, we advanced to the measurements and research of the natural electrical potentials between soil and growing plants [78]. Natural electrical potentials between soils of major genetic types and more than 100 species of native and cultural plants of Ukraine, Russia, and Philippines in different growing conditions have been studied in 2003-2005.

We used LandMapper ERM-02 (Fig. 5) and our patented non-polarizing electrodes made from standard AgCl-electrodes cupped with solidified agar solution of 1% KCl. The reference electrode was always placed in the topsoil near a growing plant and the measuring electrode was firmly contacted to the surface of the tissues of the plant (flowers, stems, or leaves).

Fig 5. Measurement of electrical potential between soil and banana plant in Philippines using LandMapper ERM-02.

The electrical potential difference between soil and a plant is always negative. This difference is highest during spring and for young plants in summer, and decreases in fall when plants in Russia are ready for dormancy. Tropical plants showed higher potential differences than plants of temperate climate. The potentials for all plants decreased in a row flower-leaf-stem. Electrical potential of herbaceous plants is directly related with the leaf area, the highest potentials were observed for burdock, cow-parsnip, and young banana palms. The research is underway for establishing relationships between natural electrical potentials/resistivity of plants/soils and plant’s water stress.

Note: Natural electrical potential measurements only possible with LandMapper ERM-02.

Four-electrode probe for detection of burial places in forensic and archaeological applications

In criminology difficulties often arise when it is necessary to find some objects hidden in soil. Search for non-metallic objects hidden in soil, such as buried decomposed corpses, documents, jewelry, and drugs, is troublesome with the conventional police methods. So far only metal objects if buried just below the surface can be found with a help of magnetometers or metal detectors (Murray and Tedrow, 1991). Such techniques, although effective in specific cases, fails to detect non-metallic objects (Murray and Tedrow, 1991). Davenport et al. (1990) conducted research on detection of corpses with ground-penetrating radar (GPR) in Colorado, USA. The GPR method, which utilized the high frequency radio waves, fails if the hidden object is small, buried on higher depth, or in clay/salt rich soil (Liner and Liner, 1997).

We proposed electrical geophysical methods to measure the disturbance of soil together with properties of a hidden object itself. The study was conducted in collaboration with Russian Ministry of Internal Affairs to test methods for fast outlining soil disturbance places to help criminological search The method is based on measurements of soil bulk electrical resistivity and principles of soil formation.

We used the prototype of LandMapper ERM-02 device with three different equally spaced arrays (*AM=MN=NB*) in Wenner configuration (Kirkham and Taylor, 1949) with distances between AB electrodes equal to 45, 120, and 240 cm. The proposed electrode arrays measured bulk electrical resistivities of soil volume from the surface to the approximate depths 15, 40, and 80 cm, respectively.

A number of soil properties, such as humus content, cation exchange capacity, bulk density, structure, and texture, affect soil bulk electrical resistivity. All these properties in topsoil differ considerably from subsoil. Due to digging or mixing of soil materials the resistivity of soils in disturbed places differ significantly from the resistivity of surrounding undisturbed soils. The effect is more pronounced if topsoil and subsoil are distinctly different in the electrical resistivity, but some differences can be noted practically in any soil. The importance of such natural soil feature for criminology search is that with infringement of soil the horizons are mixed, hence the place of disturbance shows the different electrical resistivity compared with undisturbed locations. The difference exists for a considerable time, as long as it takes to create the same layered soil profile as at undisturbed locations around, i.e. thousands of years. Therefore, even the disturbance that occurred several years ago can be detected. We measured the bulk electrical resistivity on the soil surface over the former pit and on the surrounding territory (Fig). Even the 27-year old soil pits were easily located with the method.

The criminologist should be aware of the natural variability of soil. If an anomaly in electrical resistivity is detected several measurements should be taken at closer locations to check if they replicate the similar anomaly. The repeated measurements can help to outline the area of disturbance. One should be especially suspected if the disturbance has a size and form of grave (Fig. 1). The smaller sized anomalies can also be important depending on what an expert is looking for. Using different electrode spacing various volumes of soil can be measured. Thus, we can judge whether the potential soil disturbance is at the very surface or goes deeper. The places with deeper disturbance should be given special attention.

907	714	359	729	1172	898	1607	4158	1134	1370	2269
422	1021	1058	1250	498 496 398		687	1890	1512	1465	1103
262	438	431	756	432 567 473 486 504		674	987	1018	1031	1796
330	536	321	278	383	395	501	995	829	935	756

Fig. Spatial variability of electrical resistivity over the disturbed Typic Cryboralf. Rectangular boxes (0.5x1.0 m) indicate the location of filled soil pit; numbers are the values of electrical resistivity (Ohm m), and the shaded rectangle outlines the location of former (5 years old) soil pit.

The method of four-electrode probe has been shown to be a successful method for criminology search of some non-metallic objects, primarily corpses, buried in soil. The method outlines the differences in electrical resistivity between disturbed and non-disturbed soils, therefore, does not depend on the properties of the hidden object itself and the properties of bury soil. Although the proposed method is not as quick as metal detectors, magnetometers, or ground penetration radar, the method is free of their drawbacks. The efficiency of the method can be future improved by modifications: combined probes with an automatic switch between different arrays, automatic data logging and calculations of resistivity, and incorporating of a sound signal sensitive to sharp changes in measured electrical resistivity. Although the geophysical techniques employed for criminology search might be not totally successful in finding hidden graves and buried objects, they can be very useful in allowing law-enforcement officers to screen large areas and eliminate many potential targets.

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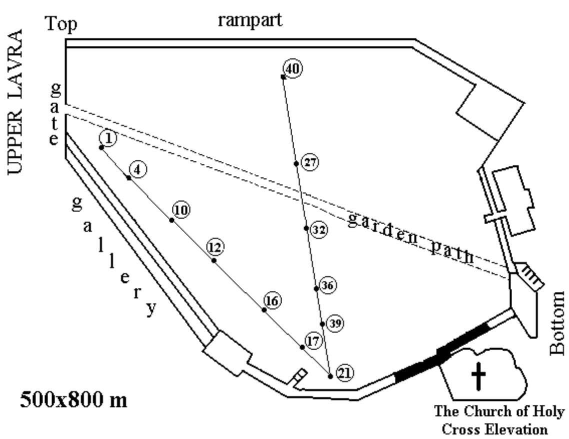
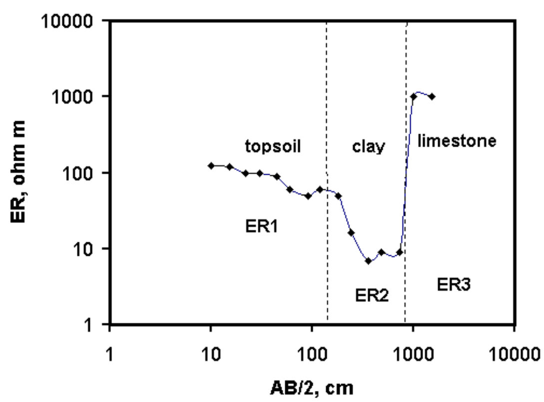
Electrical geophysical methods to study subsurface water movement in urban areas

Hazardous hydrological situation caused by unknown factors appeared in Kiev-Pechersk Lavra (Kiev, Ukraine) near The Church of Holy Cross Elevation in 1987. The church was built in 1700 above the holy caves, a place of pilgrimage of Russian Christians since XI century. The monastery is located on the high bank (near 200-m height) of the Dnipro River. The core of the bank is formed by limestone, which is covered by Quaternary deposits of loamy sand and sandy clay loam textures. The soil within a Patriarch garden was classified as eroded ordinary chernozems (Haplic Chernozems, FAO-UNESCO; Argiudolls, USA Soil Taxonomy). The caves are formed naturally in limestone and extend 228 m in length, with various depths from 5 to 20 m. The groundwater penetrated in the caves and partly destroyed wall frescoes and other masterpieces in the caves and church interiors. The problem was attributable to temporary subsurface water fluxes fed by precipitation. Excess water accumulated in subsurface in spring because of snow melting and in summer during intensive rainfalls. Due to the hill topography, water could accumulate in soil covering the whole territory of Upper Lavra and then flow into the Patriarch Garden as shallow subsurface fluxes.

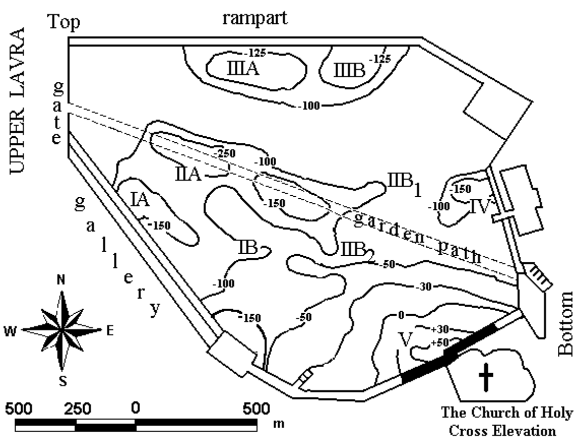
We used the vertical electrical sounding (VES) and electrical profiling (EP) methods to investigate the properties of water-bearing and waterproof layers essential for the development of the subsurface water fluxes. The directions and intensities of the fluxes were evaluated with the self-potential (SP) method (LandMapper ERM-02 in EP (mV) mode can be used).





The VES and EP methods revealed complex stratification of the hill slope in the Patriarch garden near The Church of Holy Cross Elevation (Figs). All the VES curves revealed three-layer soil profile with apparent $ER_1>ER_2<ER_3$. The top layer was represented by the eroded Chernozem of coarse textures with electrical resistivity (ER_1) about 125 ohm m for loamy sand and about 50 ohm m for sandy clay loam. The second layer was a thick clay layer (7 m) with low electrical resistivity (ER_2) from 2 to 16 ohm m. The clay was saturated and gleyed in some places, which was indicated by 2 ohm m resistivity. The third layer with the resistivity (ER_3) about 2000 ohm m was horizontally deposed limestone. The results of sounding were verified with boring at the same 12 locations. The thickness of clay layer decreased from 8 to 2 m along the line from the top of the hill to the tier wall. The low and almost constant electrical resistivity (8 ohm) for the AB/2 from 3.6 to 7.2 m for the second layer shown that clay did not bear any intrusions of sand or sandy loam,

which was verified with boring. Therefore, water flow inside second layer was impossible. The water flow could be formed only in the topsoil over the layer of waterproof clay.



Although undetectable on the surface, three gullies were revealed in the second layer of waterproof clays by the VES and EP methods. The subsurface water flow could be formed in such gullies. The method of self-potential was used to estimate water flux directions and intensities through the measured variation in electrical potential on the soil surface. An iso-potential map (Figure) was developed with the method on a 5 x 10 m grid; 299 locations were measured with five replications. Three major iso-potential areas detected from the figure. Two areas with negative potentials were formed near rampart and along the gallery (including the garden path) and indicated the areas of water infiltration into the soil and development of groundwater flow (I, II, and III). The third area with positive potentials outlined the seepage zone near The Church of Holy Cross Elevation (V). The most negative potentials (-250 mV) along the garden path indicated the most intensive subsurface water flow in this area (IIA, IIB_1, and IIB_2). The –250-mV iso-potential area developed in surface peaty sand with electrical resistivity (ER_1) about 170 ohm m. The less negative potentials (-150 mV) and, therefore, the less intensive water flow occurred near the gallery (IA and IB). The same negative potential areas were detected in the middle of the garden path and near the rampart (IIIA, IIIB, and IV). The seepage area was outlined by the 0-mV iso-potential near The Church of Holy Cross Elevation (V). The seepage area was enriched with clay material having electrical resistivity about 5 ohm m. The percentage of clay in the soil increased toward the corner of the church along with the electrical potential.

To protect The Church of Holy Cross Elevation, the following procedures were proposed based on our geophysical exploration near the architecture memorial. First, a hedge should be constructed across the gate to the garden to prevent the surface water flow to the Patriarch Garden from the pavement of Upper Lavra. Second, a small dike should be built perpendicular to the gallery and the garden path to direct subsurface water flow from fluxes II and I into the drain system. Third, to enhance evapotranspiration, trees and bushes with the intensive transpiration ability, such as willows and poplars, should be planted along the gallery and rampart, especially in the areas indicated by low potentials. All the measures were implemented in 1990 and still provide adequate preservation for the church and the surrounding caves. The cost of the proposed measures was about one twentieth of the previous construction of concrete wall, which, nevertheless, did not solve the problem of water penetration into the caves.

Electrical geophysical methods to evaluate soil pollution from gas and oil mining

Electrical geophysical methods were successfully used for exploration of gas and oil fields (Kalenev, 1970). However, the methods are not widely used for estimation of the soil pollution with petroleum products (Znamensky, 1980; Pozdnyakov et al., 1996). The possibility of using the methods of electrical resistivity to evaluate the places of petroleum pollution or natural petroleum and gas deposits is based on highly different resistivities of soil and petroleum products. Petroleum and various products of petroleum manufacture, such as oil, gasoline, bitumen, and kerosene have very high electrical resistivity compared with soils. Electrical resistivity of petroleum varies from 10^4 to 10^{19} ohm m (Fedinsky, 1967), whereas resistivity of petroleum-saturated sand is much lower (2200 ohm m) (Znamensky, 1980), but is still higher than that of any non-polluted soil.

Soil pollution by the products of gas and petroleum mining was studied near Urengoi in northwest Siberia, Russia. The soils of the area, Glacic and Aquic Haplorthels, were extremely polluted with various by-products of petroleum extraction and manufacturing, such as bitumen, gasoline, kerosene, and mining brine solutions. The study area was thoroughly investigated with four-electrode profiling on Wenner array (a=0.4 m) and vertical electrical sounding.

Four-electrode profiling was conducted on transect through the most common pollution features within the area. Figure 1 shows a clear distinction between non-polluted areas and areas with bitumen or brine pollution. The salty mining solutions can decrease resistivity of Gelisols to 20-50 ohm m, and wetland formed with salty mining solutions is outlined by the lowest resistivity in the profile. The places polluted by bitumen, on contrary, have the very high resistivity, about 3000 ohm m. Non-polluted soils are indicated by resistivity of about 1000-1500 ohm m.

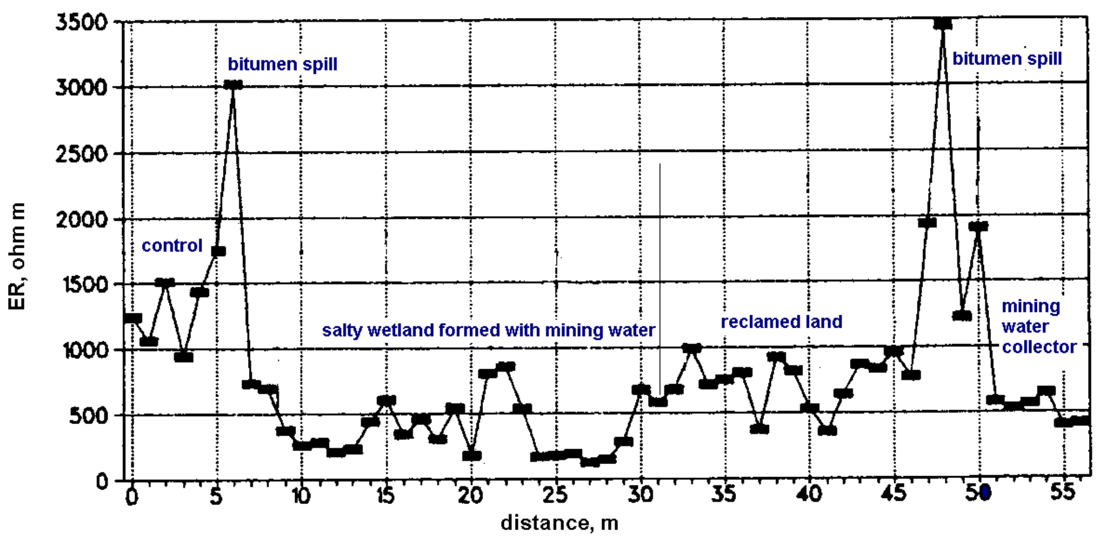


Fig.1 Electrical resistivity profile across the bitumen and salty mining water polluted areas. Measurements conducted with 4-electrode probe.

The variation in electrical resistivity indicating the pollution distribution in soil profiles can be seen on VES profiles. Pollution by heavy fraction of petroleum, such as bitumen appeared at the top part of soil profile and was indicated by electrical resistivity as high as 6×10^5 ohm m (Fig. 2c). The pollution by salty mining solutions lowered soil electrical resistivity. The resistivity of the soil near the stream where brine mining solution was discharged, varied from 50 to 200 ohm m (Fig. 2b). The surface soil at the brine collector has resistivity as low as 20 ohm m (Fig. 2d), while the electrical resistivity of the native pergelic soils was about 1000 ohm m at the surface (Fig. 2a). Some non-polluted native soils shown increase in electrical resistivity up to 8000 ohm m at the AB/2=2.4 m (about 0.6-m depth) indicated the presence of permafrost in soil profile (Fig. 2a). The depth of the permafrost was verified by soil excavation.

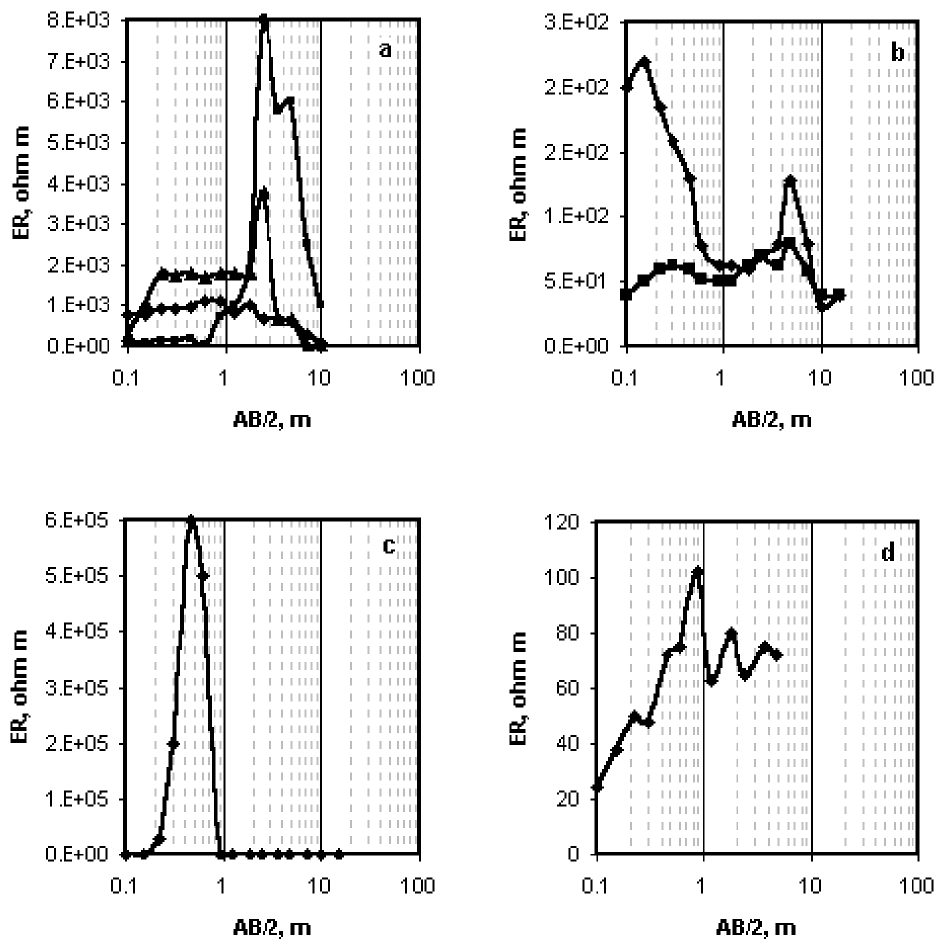


Fig. 2. Characteristic VES profiles for the soils polluted with different by-products of oil mining and refinery.

Table shows the average values of electrical resistivity of natural non-polluted soils (Glacic and Aquic Haplorthels) and soils polluted during petroleum and gas mining in northwest Siberia. In this particular case the pollution by petroleum products highly increased the soil electrical resistivity, whereas brine solutions used for the mining considerably decreased soil resistivity.

Soil	Electrical resistivity
	— ohm m —
Surface layers of non-polluted Gelisols	**$2\times10^2 - 2\times10^3$**
Permafrost at apprx. 0.6 m in soil profile	**$4\times10^3 - 8\times10^3$**
Polluted by bitumen and other heavy fraction of oil	**$1\times10^5 - 6\times10^5$**
Polluted by gasoline	**$1\times10^4 - 4\times10^4$**
Polluted by salty mining water	**$2\times10 - 2\times10^2$**

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CONCLUSIONS

The electrical parameters were related with soil properties influencing the density of mobile electrical charges in soils by exponential relationships based on Boltzmann's distribution law of statistical thermodynamics.

The electrical properties of soils can be easily measured with geophysical methods in situ and in laboratory conditions and provide information about densities of mobile electrical charges in soils on different levels of soil organization ranging from core sample to landscape scales. Soil electrical properties reflect the transport of substances in landscapes, geochemical connection, and formation of soil climatic and topographic sequences. Mobile electrical charges concentrate in subordinated soils of landscapes.

Our research team studied the relationships between electrical properties and other commonly considered soil properties for over forty years and evaluated the applications of various electrical geophysical methods for quick in-situ soil characterization for agricultural and environmental applications.

The case studies revealed significant correlation of the electrical resistivity, measured in-situ with many soil properties, mainly soil water content, pH, resistance to penetration, texture, and stone content. The difference in complex soil properties distinguishing various soil series in humid areas are reflected in measured electrical resistivity. Application of LandMapper in routine soil survey can help to speed up soil mapping and fine-tune the existing spatial soil databases.

The within-field variation in soil properties causes the variation in crop yields, revealing the stable patterns in crop loss, especially on perennial horticultural crops. As an indicator of the complex of soil properties influencing yield, electrical resistivity was found correlated with crop yields.

Electrical potentials between topsoil and growing plants can be used to monitor plant growth and health continuously and non-destructively.

With the advantages of quickly obtaining extensive data on the vertical and lateral distributions of electrical properties in soil profiles without soil disturbance and possibility of measuring parameters of growing plants in natural conditions electrical geophysical methods should be utilized in archaeology, hydrology, civil and environmental engineering, precision agriculture and plant physiology research more often. Future research will bring up more interesting applications.

Landviser, LLC is striving to develop the most versatile, portable and affordable devices for near-surface geophysical applications. We are listening to our customers and continue to modify LandMapper and accessories to suit ever increasing range of applications. Please, do not hesitate to contact us with you intended application (info@landviser.net) or post a comment on

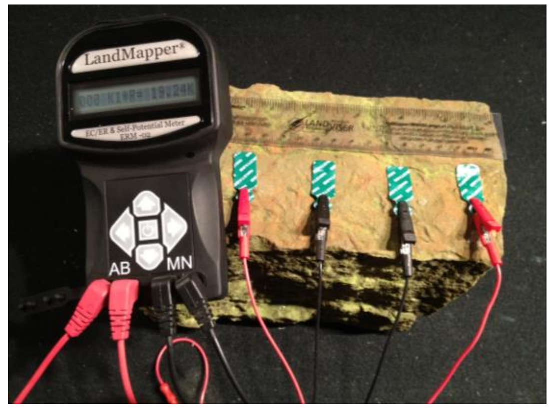
http://www.landviser.net/content/applications-landmapper-handheld-near-surface-soil-surveys-and-beyond

Optional accessories for LandMapper ERM-01

Landmapper ERM-01 and ERM-02 are shipped with 4-electrode test leads that can be inserted directly into the soil in laboratory or field settlings, just make sure you measure and calculate geometric coefficient correctly for your electrode arrangement.

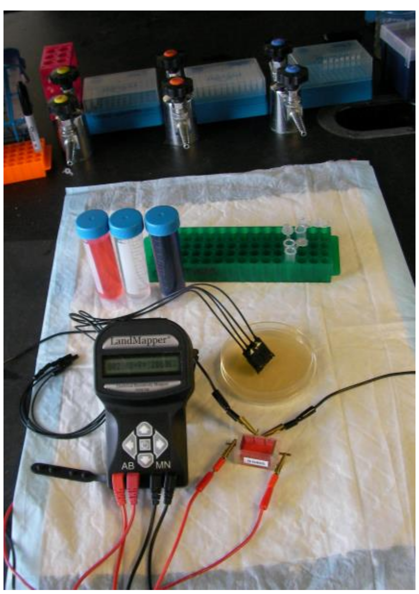
Additional accessories described below can be ordered separately.

4-patch electrodes for hard surfaces or living plants



Patch electrodes can be placed on the surfaces that are hard to penetrate with electrode test leads. Although those electrodes are sterile and are of medical grade, we do not advise you to use them to measure electrical properties of humans and pets. Both Landmapper ERM-01 and ERM-02 use safe level of output current when measuring electrical resistivity or conductivity; however, Landviser, LLC does not advise to use our devices on human and animal subjects. This constitutes a legal warning and we declare to hold harmless in cases of non-proper use of our devices. Those electrodes can safely be used to measure electrical properties of non-living matter and plants. When placing electrodes on small areas, you can trim the electrodes to suite your application.

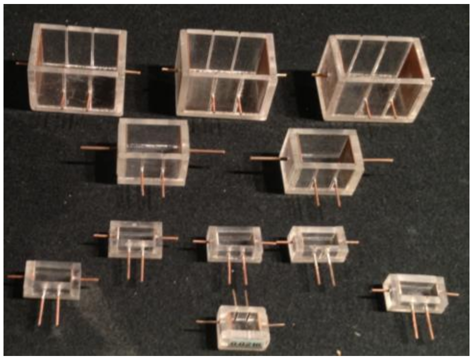
Note: trim all electrodes used in one experiment to the same size. If you conducting monitoring studies it is best not to move electrodes through the whole course of the measurements, just disconnect measuring device through the banana plugs at the terminal.



4 needle electrodes for living plants or food samples

Needle electrodes can be pierced into solid soft objects to measure EC/ER of solid mini-samples, such as fruits, vegetables, leaves, stems, soil aggregates, agar solutions, etc. Needles are connected permanently to insulated copper wires terminated with no-touch connector. To connect to Landmapper terminals, the tester leads (supplied with any order of LandMapper, see above) can be pushed into no-touch connector and isolated with electric tape.

4-electrode laboratory cell for measuring electrical resistivity or conductivity in soil samples, pastes or solutions



Conductivity cells of different sizes can be ordered from Landviser, LLC. Those cells are calibrated for electrical resistivity and K-coefficient is printed on the cell. Four leads terminated with banana plugs and alligator clips are provided with the cell to connect to LandMapper.

Bigger cells can also be ordered from geophysical companies such as AGI http://www.agiusa.com/agicatalog.shtml#Accessories

920 019 Test box
Test box for soil samples (ASTM standard) used with the SuperSting R1, MiniSting and Sting for laboratory measurement on soil samples. The dimensions of the soil box is such that the read-out is in Ohm cm. The soil box is delivered with connecting cables.

Non-polarizing electrodes for measuring natural electrical potentials

Landviser, LLC carries whole range of mini non-polarizing solid-state electrodes (Ag-AgCl) with banana connectors for LandMapper terminals. These insulated or mounted reusable electrodes are specifically designed for use in electrophysiology, but can be adapted for soils and plants with ease. They are made with high quality sintered Ag-AgCl sensor electrodes. Those silver-silver chloride electrodes are very stable, performance is exceptionally reproducible. Unlike plated or chlorided silver, those Ag-AgCl electrodes are solid throughout, no fillers or binders are used - only pure silver-silver chloride. Should the surface become damaged or contaminated, a new surface can be exposed to restore the electrode's original performance. Because of their electrochemical stability and reproducibility, Ag-AgCl electrodes make excellent STANDARD and REFERENCE electrodes.

Salient Features	***Applications***
Essentially non-polarizable	Reference electrodes
Sintered	Sensors of electrical potentials in soils, plants, animals
Never need chloriding	Membrane potential monitoring
Reusable - Resurfaceable	Stimulation of nerve cells in tissue culture

Note: non-polarizing electrodes are only necessary when measuring natural electrical potentials (self-potential technique) with LandMapper ERM-02

DO-IT-YOUSELF probes, cables, and other accessories

Make your own four-electrode probe for soil mapping

Materials

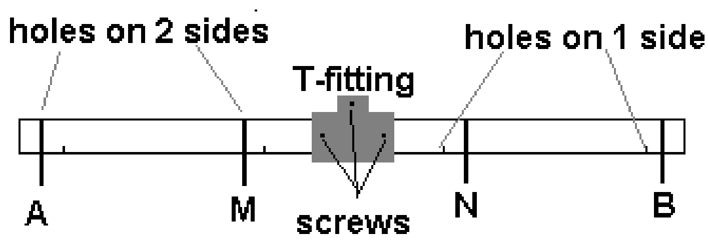
- ¾" PVC pipe, one section of 10'.
- 2 T-shaped PVC pipe connectors fitting ¾" pipe from all three ends.
- 2 ¾" PVC cups (optional).
- #16 AWG isolated stranded wires, red and black, 15' each.
- 1"x2" Velcro strip (optional).
- 3 #6 1.5" screws for wood (optional).
- 4-electrode probe kit (available from Landviser, LLC) including:
  - 4 stainless steel electrodes (sharpened d= ¼" L=6" bolts)
  - 8 stainless steel ¼" nuts for connecting electrodes with the wires
  - 4 nylon isolated terminals for 18" AWG wire with 5/16" opening
  - 4 banana plugs (2 black, 2 red) for connecting with LandMapper terminals

Tools

- PVC pipe cutter
- Wire cutter
- Wire stripper
- Wire crimper
- Electric drill
- Rubber mullet (optional)

Procedure (example for Wenner probe configuration)

1. Choose the inter-electrode distance **a.** Calculate the length of one shoulder of the 4-electrode probe: L1=3***a**/2" (for example if **a**=10" then L1=15 ")
2. Cut 2 shoulders from the PVC pipe each L1 long (15" in our example). Cut 3' pipe for the handle.
3. Connect 2 L1 shoulders in the T-fitting to form a straight line. Use rubber mullet to force tubes all the way into the T-connection. Mark locations of A and B electrodes at each end of the probe 2" from the shoulder's end. Mark the locations of M and N electrodes each at **a** inches from A and B (**10"** in our example).
4. Drill ¼" holes through the pipe at each electrode mark (try to keep the drill bit perpendicular to the tube).
5. Drill holes for the wires on one side of the pipe only approximately 1 inch from each electrode.
6. Cut 4 pieces of wire (2 black and 2 red):
   - red for A or B -- L2=a+a/2+4' long (4' 15" in our example)
   - black for M or N -- L3=a/2+4' long (4' 5" in our example)

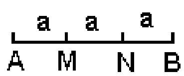
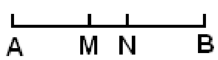
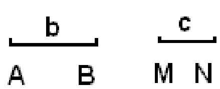
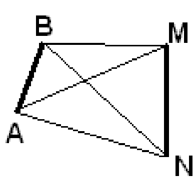


7. Put the wires through the one sided wire holes (red for AB, black for MN) and lead them through the pipe out of the top opening in the T-connector.
8. Strip ¼" at the end of the each wire in the wire holes and crimp ring terminals to the wire ends.
9. Insert electrodes through the corresponding electrode holes and secure them to the pipe with nuts. Put ring terminals over the electrodes and secure them with another nut so the ring terminal is positioned between the nuts.
10. Optional: Fit 2 cups at the end of each probe shoulder (near A and B electrodes).
11. Strip ¼" at the end of each wire and connect appropriate color-coded banana plugs to the wires as described on the banana-plugs' package.
12. Thread the wires with banana plugs through the PVC pipe handle. Insert the handle all the way into the top opening of the T-connector. You may want to use a mullet to force the handle into the fitting, but it may make the handle difficult to disassemble.
13. Optional: Drill small holes through the T-connector connecting the handle with the probe. Using three #6 1.5" wood screws secure the pipes to the T-fitting (see figure).
14. At the other side of the handle, run the wires with banana plugs through the shoulders of another T-connector and mount it on the top of the handle.
15. Optional: attach Velcro strips to the back of the LandMapper and to the top of the handle's T-connector and snap the unit to the probe.
16. Calculate the K coefficient for the new probe and enter it in the device memory. (see next page).
17. Connect red AB banana plugs with AB socket and black MN banana plugs with MN socket. The device is ready for measuring electrical resistivity.

Calculate K coefficient for any four-electrode probe

If you build your own probes for mapping; plan to measure the electrical resistivity/conductivity in soil pits, columns, samples; or to conduct a 2D imaging of soil subsurface based on electrical resistivity, you will need to determine the K coefficients accordingly for your custom four-electrode arrangement accordingly. The table below provides formulas for calculating geometric coefficient K for practically any possible four-electrode configuration used for measuring electrical resistivity from soil surface:

Table 1. Typical four-electrode probe arrangements. All distances are in meters!

Layout	Description	Geometric coefficient
	Linear	
	Wenner [AM]=[MN]=[NB]=a equally spaced array	$K = 2\pi a$
	Schlumberger [AN]=[MB] center-symmetric array	$K = \pi \frac{[AM]\cdot[AN]}{[MN]}$
	Dipole-dipole [AB] and [MN] as separate dipoles inline array	$K = \pi r^3 / [AB]\cdot[MN]$ where r is the distance between the centers of dipoles
	Plane	
	"Universal" any planar arrangement of the electrodes	$K = \frac{2\pi}{\frac{1}{[AM]} - \frac{1}{[BM]} - \frac{1}{[AN]} + \frac{1}{[BN]}}$

Calibrate (calculate) K-coefficient for lab four-electrode cell

Laboratory cells supplied by Landviser, LLC have been calibrated and the respective K-geometric coefficient is printed on the cell. The cells have to be filled to the top rim, in order for the coefficient to be accurate. Also, sometimes due to corrosion of conductive plates (electrodes) the coefficient of the cell might change slightly. Thus, you can verify K-coefficient of any cell, just follow instructions below:

Materials:

1. Laboratory cell with embedded four-electrodes
2. Distilled water and/or standard resistivity solution (f.e. from Fisher Scientific, Inc.)
3. LandMapper with four banana plugs to alligator clips connectors.

Procedure:

1. Connect LandMapper to electrodes embedded in the cell. Landviser's supplied rectangular cells have current (AB) electrodes as metal plates at the end of rectangular prism and potential (MN) electrodes as wire lines embedded on the front. Connect LandMapper terminals accordingly.
2. Fill cell with standard solution (**ERss=X**) with known resistivity. Measure ER on K0=1.
3. Record measured resistivity **ERm=Y**.
4. Measured ER times cell K-coefficient should be equal ERss:

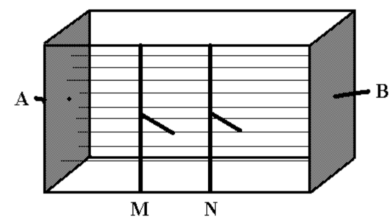


Fig.. Scheme of the four-electrode laboratory conductivity cell. Electrical field lines are shown with thin straight lines (uniform electrical field).

ERss=K*ERm

Therefore, K of the cell is equal **ERss** divided by **ERm**:

K= ERss/ERm

5. Verify with distilled water (ER ~ 1000 Ohm m) or other standard resistivity solution.