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LandMapper™ ERM-01

USER MANUAL

Before using the device read the instructions

Астро

2007

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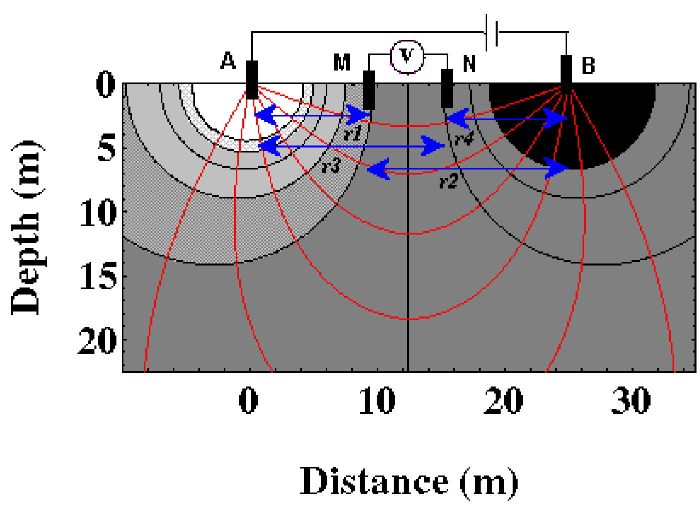
The geophysical device LandMapper ERM-01 can be used to measure **electrical resistivity** or **conductivity** of soils for fast non-destructive mapping of agricultural fields, construction and remediation sites, and similar applications. Our device is **very versatile** and can be applied on soil surface, in wells/pits, or in soil and other semisolid laboratory samples. In a typical setting the **four-electrode probe** is placed on the soil surface and electrical resistivity 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 ASTRO GROUP, LLC for Landviser, Inc., USA and based on more than 30 years of scientific research of Russian and American soil physicists. Prototype of the LandMapper ERM-01 was developed and used for soil studies in Russia, USA, and Chili (Pozdnyakov et al., 1996; Pozdnyakova et al., 1996; Pozdnyakov, 2001; Pozdnyakova, 1999; Pozdnyakova et al., 2001).

OPERATING PRINCIPLES



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

LandMapper measures potential difference ($\Delta\varphi$), 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 and laboratory conductivity cells.

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

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

The direct digital output of the device is electrical resistivity in Ohm m. Those can be converted into electrical conductivity (*EC*) by using reciprocal of the measured resistivity:

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

Thus, the measured results may as well be presented in convenient for US soil scientists form of soil electrical conductivity, measured in Sm/m.

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).

DESCRIPTION of LandMapper ERM-01

Technical Specifications

- Range of measurement…………………………………………….0,1-1M Ohm m
- Absolute error of measurement no more than…..…….……….2 %
- User-defined K (geometrical coefficient)………………………...0.01 up to 99.99
- Quantity of fixed K-coefficients …………………………………..10
- Quantity of data storage locations……………………………….1000
- Range of operation temperatures……………from -10 to + 40^0 C or 65 to 100 F
- Air humidity no more than………………………………………65 %
- Weight of the device no more…………………………………….. 250 g or 8 oz.
- Powered by one 9V Battery (included)
- Current consumption no more………….…………………………..7.0 mA

Controls

⏻ - ON/OFF key

► - FUNCTION key. The multifunction key for operation mode selection and storage of electrical resistivity values

◄ - INPUT key. The multifunction key for ER measuring, correction of a K coefficient, recording or erasing electrical resistivity 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

⊣⊢ - Socket for connection of current-inducing AB electrodes

-V- - Socket for connection of voltage-measuring electrodes

Serial port for the connection with computer for data transfer is located on the top side panel of the device.

Preparation of LandMapper ERM-01 for electrical resistivity mapping

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

2. Electrode probe is collapsed 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 collapsed even more -- one shoulder of the probe with electrodes is removed from the T-socket. In that case insert a shoulder of the probe all the way into T-socket. You may want to use 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 appears 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 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 (⊣⊢) and black for MN socket (-V-).

6. Attach the LandMapper ERM-01 measuring unit to the Velcro fastener on the top of the handle or just hold it in the other 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 OPERATION PROCEDURES on the information how to calculate K.

8. Device is ready for measuring.

CARE AND MAINTENANCE

Measuring unit

The measuring unit, LandMapper ERM-01, is made of rigid plastic which is adequate in protecting inside electronics during daily use carrying around outside. 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 a great height.

The LandMapper ERM-01 is poorly 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 reading recorded.

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 unit is used for the field measurements. The appropriate cable with 9-pin/25-pin male/female connector is supplied with the unit for the data transfer from the Landmapper to personal computer. The pins in the connector/ports can be damaged if forced together with a damaged or dirty female serial port in the unit or personal computer.

The LandMapper should be stored at the 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, Inc. When replacing the battery in the battery compartment, do not pull at the battery leads, because they may become disconnected inside the meter and the LandMapper will have to be returned for repair.

The LandMapper has been designed for use only with Landviser specified or recommended four-electrode probes or laboratory cells. The Landviser, Inc. is not responsible for any damage to the measuring unit caused by usage of non-authorized probes.

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, 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 is joined in 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 can be a good practice to clean the electrodes with soapy water 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

Operational modes

- Calculation, indication and input of a K coefficient.
- Measurement of electrical resistivity with an entry into the memory (RAM).
- Listing the RAM.
- Erasing contents of the RAM.
- Voltage indication of the battery.
- Display contrast regulation.
- Data transfer to computer.

Quick menu

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

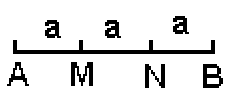
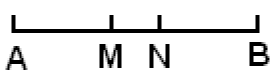
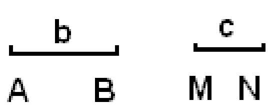
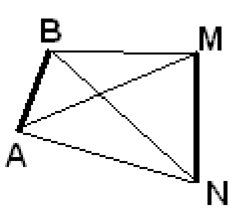
► and ◄ - **save** value of resistivity in memory, values of the K or contrast, clear memory

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

► and ▲ or ▼- move through different **operational modes**

Calculating K coefficient

LandMapper ERM-01 is typically supplied with one four-electrode probe in Wenner configuration and the probe-specific coefficient K (K1) is preset in the device memory. Users can order our universal probe that can be set for different distances among the electrodes, in which case the K coefficients are calculated for the some typical electrode arrangements and entered into device memory. However, if users wish to design their own probes for mapping (see Appendix 3); or for measuring electrical resistivity in soil pits, columns, samples; or conducting 2D imaging of soil subsurface based on electrical resistivity, they will need to calculate their own K coefficients. The table provides formulas for calculating geometric coefficients K for practically any possible four-electrode configuration used for measuring electrical resistivity from soil surface (Zdanov and Keller, 1994):

Layout	Description	Geometric coefficient
	Linear	
	<u>Wenner</u> [AM]=[MN]=[NB]=a equally spaced array	$K = 2\pi a$
	<u>Schlumberger</u> [AN]=[MB] center-symmetric array	$K = \pi \frac{[AM] \cdot [AN]}{[MN]}$
	<u>Dipole-dipole</u> [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	
	<u>“Universal”</u> any planar arrangement of the electrodes	$K = \frac{2\pi}{\frac{1}{[AM]} - \frac{1}{[BM]} - \frac{1}{[AN]} + \frac{1}{[BN]}}$

Setting up the K coefficient on the device

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 (▼).
4. Change the value of the coefficient with the keys (◄) and (▲) or (▼). The changing digit is selected with the INPUT key (◄) (digit is slightly blinking) and can be changed with the keys (▲) or (▼). The value of K0=01.00 is constant and cannot be changed by the user. Measurements with K0 represent 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 values of resistance can be post-processed into the resistivity values by multiplying with the different K coefficients, corresponding to different arrays, in any spreadsheet program.
5. To store the new value of the K coefficient press and hold (►) key, then press (◄) 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 – ID of the K coefficient (from K0 to K9)
--, -- value of the K coefficient from 00.01 up to 99.99

Note: Display reads electrical resistivity directly if the correct K coefficient is entered into the RAM of the device.

Measuring electrical resistivity

1. Connect the A, B, M, and N electrodes from the four-electrode probe to the respective color-coded sockets on the front panel of the device (red wires to AB socket ⊣⊢ and black wires to MN socket -V-).
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, device will automatically turn off after 5 min of non-functioning.
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

display a number followed by letter K, indicating that the resistivity value is in kilo Ohm m, multiply the output by 1000.

5. To store the value of electrical resistivity in the device memory press and hold FUNCTION key (►) and then press 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.

Display listing:

001 ˽ K0 * R 0000

1 2 3 4 5 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 ER reading
6 – Value of electrical resistivity (ER)

Indication of memory content (RAM)

1. Holding FUNCTION key (►), press key (▲) two times to switch to the mode of the indication of RAM contents.
2. Scroll though the RAM cells using UP (▲) and DOWN (▼) keys.
3. Arbitrary selection of the cells is done with the INPUT key (◄) (the chosen digit is blinking) and selected with keys ▲ or ▼.
4. To store the number of a selected cell press and hold the FUNCTION key (►) and then press INPUT key (◄) – the digit stops blinking. Scroll through the neighbor cells with UP (▲) and DOWN (▼) keys. The display will show the number of the cell and the stored value of electrical resistivity together with the ID of K coefficient.

Display listing:

001 --,-- KN

1 2 3

1 - Number of the cell
2 – Value of the electrical resistivity
3 – Number of the K-coefficient

Clearing memory

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

Display listing:

" >>> ______ <<< "
1

1 – changing number of a cell of the RAM from 000 to 999

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

" 000 --,-- K0 "

Test the battery voltage

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

Display listing:

Ubat = -.- V
1

1 - Value of the 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 two times.

Display listing:

"Contrast = --"
1

1 - Value of the contrast from 1 up to 27.

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

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

Transfer stored values of the resistivity to a computer

1. Connect the included serial cable to the socket on the top of the LandMapper device and to the serial port on your personal computer.
2. Copy driver “connectERM01.exe” from the root directory of the enclosed CD to the hard disk of your PC. The program was tested only on the IBM-compatible computers with different versions of Windows.
3. Double click the file "connectERM01.exe" to start the program for data transfer.
4. Choose the number of the serial port (com1 to com4) to which the device is connected.
5. On the device: holding FUNCTION key (►) select the data transfer mode by pressing DOWN (▼) key three times.

Display listing:

A PC com Wait

6. On the computer click the key “Press when unit screen reads “A PC com Wait””. During the data transfer the device lists the current storage cell.

Display listing:

PC com N

N - Storage cells from 000 up to 999

7. The transferred data are listed on the right hand side of the program window. You have an option of storing the data file in ASCII format in the file with .txt extension or to copy the data in the Window clipboard for pasting them into any suitable spreadsheet program. Data file format is:

N of cell **N of K** **Value of resistivity**

REFERENCES

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Pozdnyakova, L.A. 1999. *Electrical properties of soils*. Ph.D. Thesis. University of Wyoming, Laramie, WY. **– included on enclosed CD**

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Pozdnyakova, L.A., A.I. Pozdnyakov., and L.O. Karpachevsky. 1996. *Study hydrology of valley agricultural landscapes with electrical resistance methods.* Proceeding of XXI Assembly European Geophysical Society, HS16 "The Hydrology of Small Agricultural Catchments", The Hague, Netherlands. 341-352. **– included on enclosed CD**

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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 ready available.
The memory is full (display shows 999 for the memory cell indication)	Transfer data to PC. Perform the “Cleaning RAM” procedure.
Low visibility of the display	Change and store the contrast values in the “Contrast” mode.
Unusually low or high values of the measured resistivity (highly different from the measured in the vicinity)	Indicates the problem in a contact at any connection (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 at the wire connections to the electrodes at the bottom of the probe.
Problems with connection to PC	In the program change the com port.

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 our own repairable instruments can be supplied directly from us. These can normally be sent within 1 working day of receiving an order.

Spare parts and accessories for sensors not manufactured by Landviser, but supplied by us individually or as 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 a certain amount of additional delay is possible.

Should it prove necessary, instruments may be returned to us for servicing. We normally expect to complete repairs of our own instruments (four-electrode probes) within 2 days of receiving the equipment. The faulty measuring unit will be returned to the manufacturer, ASTRO Group, LLC in Russia for and may be subject to additional delays of two to four weeks.

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

APPENDIX A. History of the method

The first attempt to measure electrical resistivity or conductivity of soils was made at the end of the nineteenth century with the two-electrode technique. Whitney et al. (1897), Gardner (1898), and Briggs (1899) developed relationships between soil electrical resistivity and soil water content, temperature, and salt content. The two-electrode method measures the sum of both the soil resistivity and the contact resistivity between the electrode and soil. The latter is very erratic and unpredictable.

Wenner (1915) based on the work of Schlumberger suggested that a linear array of four equally spaced electrodes would minimize soil-electrode contact problems if the potential-measuring and current-injecting electrodes are separated. 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 (McCorkle, 1931; Edlefsen and Anderson, 1941; Rhoades and Ingvalson, 1971). Halvorson and Rhoades (1976) applied a four-electrode probe in the Wenner configuration to locate saline seeps on croplands in USA and Canada. Austin and Rhoades (1979) 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 (Rhoades and Schilfgaarde, 1976; Rhoades, 1979). An electrical cell used to measure electrical conductivity of soil samples, pastes, and suspensions, was also developed based on four-electrode principle (Gupta and Hanks, 1972). 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 (Richards et al., 1956). Relationships between electrical conductivity measured in-situ with four-electrode probe and conductivity of soil solution or saturated soil paste were developed (Nadler, 1982; Rhoades et al., 1989). The method of four-electrode probe was also used for evaluation of some other soil properties, such as soil water content (Edlefsen and Anderson, 1941; Kirkham and Taylor, 1949); structure (Nadler, 1991); bulk density, porosity, and texture (Banton et al., 1997); stone content and pollution by oil-mining facilities (Pozdnyakova, 1999), locations of the burial places in archeology and criminology (Pitruk et al., 1997; Butler and Llopis, 1997), etc. Recently measurements of soil electrical resistivity or conductivity were coupled with geostatistical methods to develop accurate soil maps (Pozdnyakova and Zhang, 1999; Butler, 2001).

Thus, 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. However, the new advantages in electronics technology allowed us to develop a mechanism, which automatically accounts for the spontaneous potentials arising at the electrodes and considerably improves measurements accuracy.

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APPENDIX B. Electrical fields and soil properties

A.Pozdnyakov and L.Pozdnyakova

(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, is distributed by Landviser, Inc. 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, Inc. is planning to introduce a device for non-contact electromagnetic profiling to the market soon.

Four-electrode laboratory cell. The four-electrode principle is 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). The geometrical factor for a cell is obtained from the calibration solutions of a known resistivity (conductivity). 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. The measurements in four-electrode laboratory cell were utilized to develop the relationships between various soil properties and electrical resistivity.

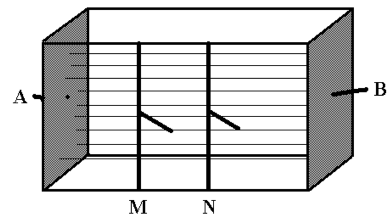

Fig. 1. Scheme of the four-electrode laboratory conductivity cell. Electrical field lines are shown with thin straight lines (uniform electrical field).

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). However, most modern geophysical methods, such as four-electrode profiling and vertical electrical sounding apply non-uniform electrical field to soils through the point electrodes. 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 (see OPERATION PROCEDURES).

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.

Results and Discussion

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.

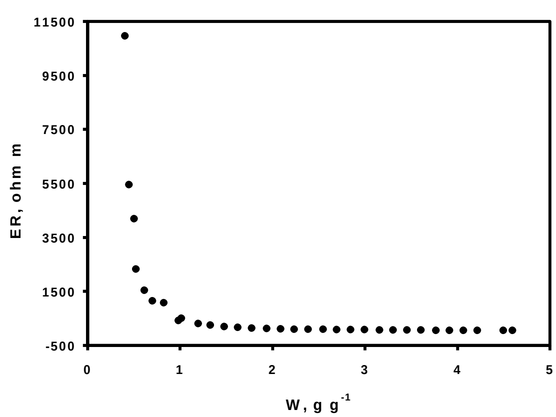

Fig. 2. An example of experimental relationship between electrical resistivity and water content of a peat soil.

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

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

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 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).

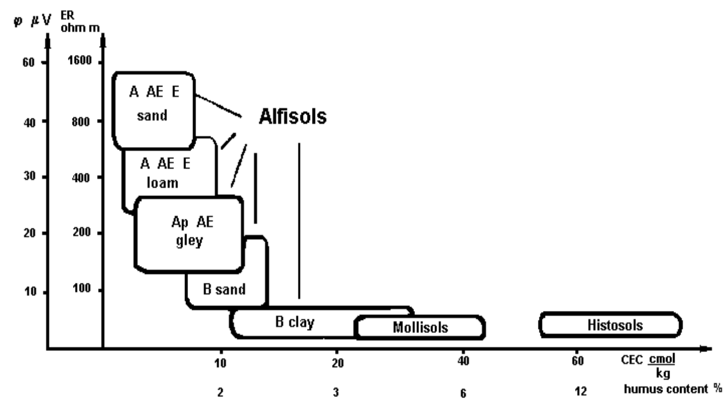

Fig. 3. Schematic relationship between electrical parameters properties showing approximate distribution of data for soils i areas.

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.

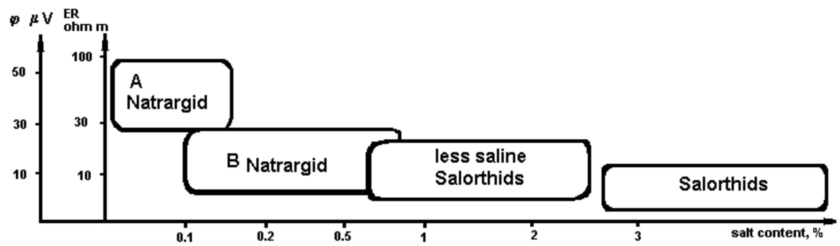

Fig. 4. Schematic relationship between electrical parameters and soil properties in arid soils.

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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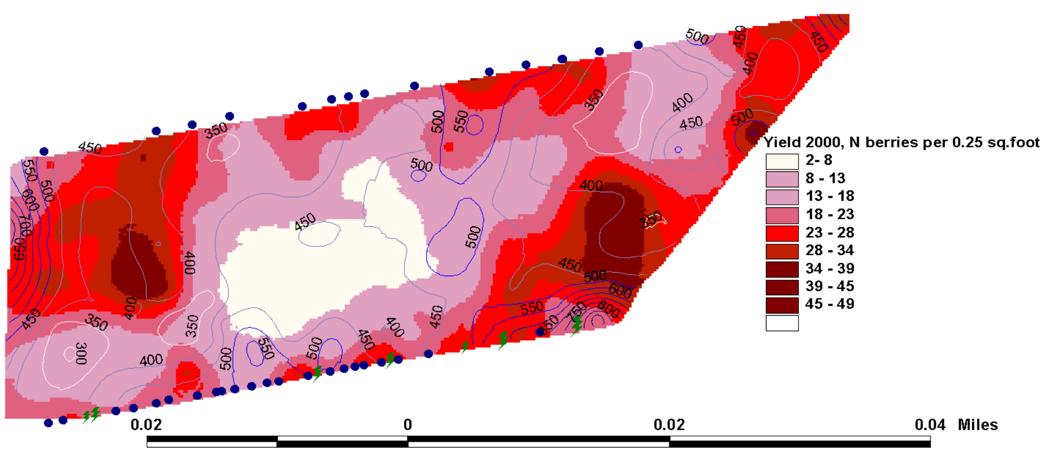
APPENDIX C. Case Studies

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.

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.

Figure below 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-01 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.

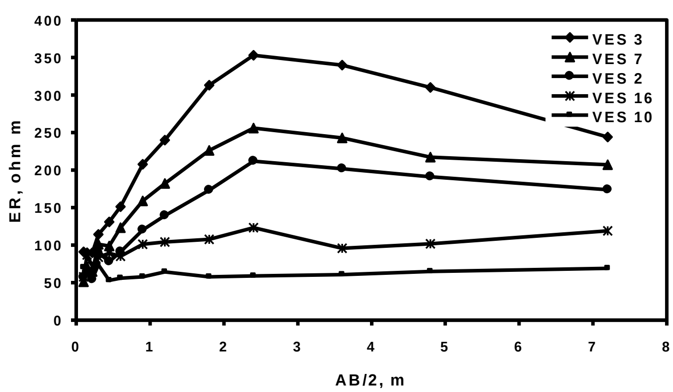


Evaluation of soil stone content with electrical geophysical methods to aid orchard planning

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 (planned to be available from Landviser, Inc. in 2004) 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 ohmm. 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 Nikitskii 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			Depth to	Potential
	0-50 cm	50-100 cm	>100 cm	rock	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.**

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 a 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.

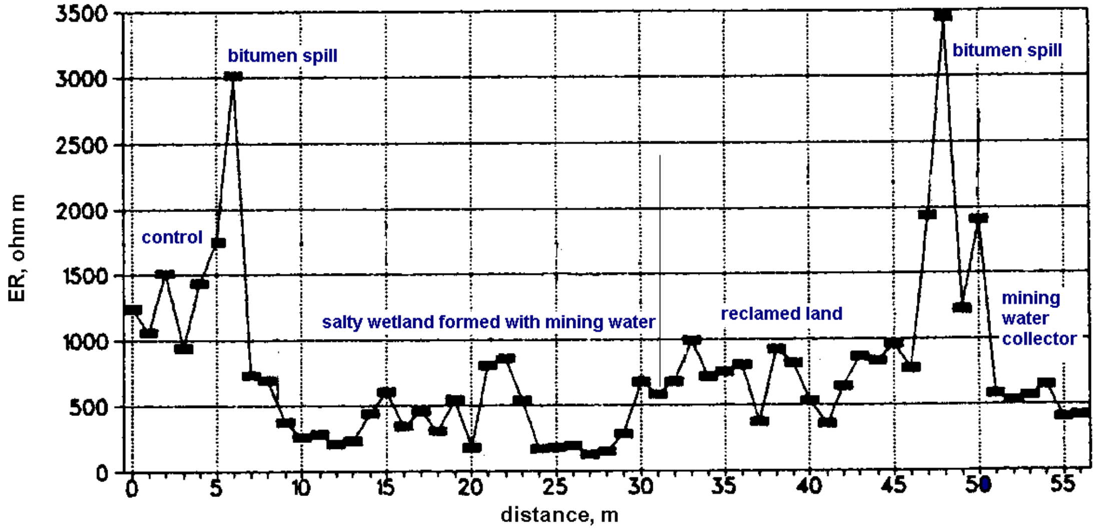


Fig.1 Electrical resistivity profile across the bitumen and salty mining water polluted areas. Measurements conducted with 4-electrode probe.

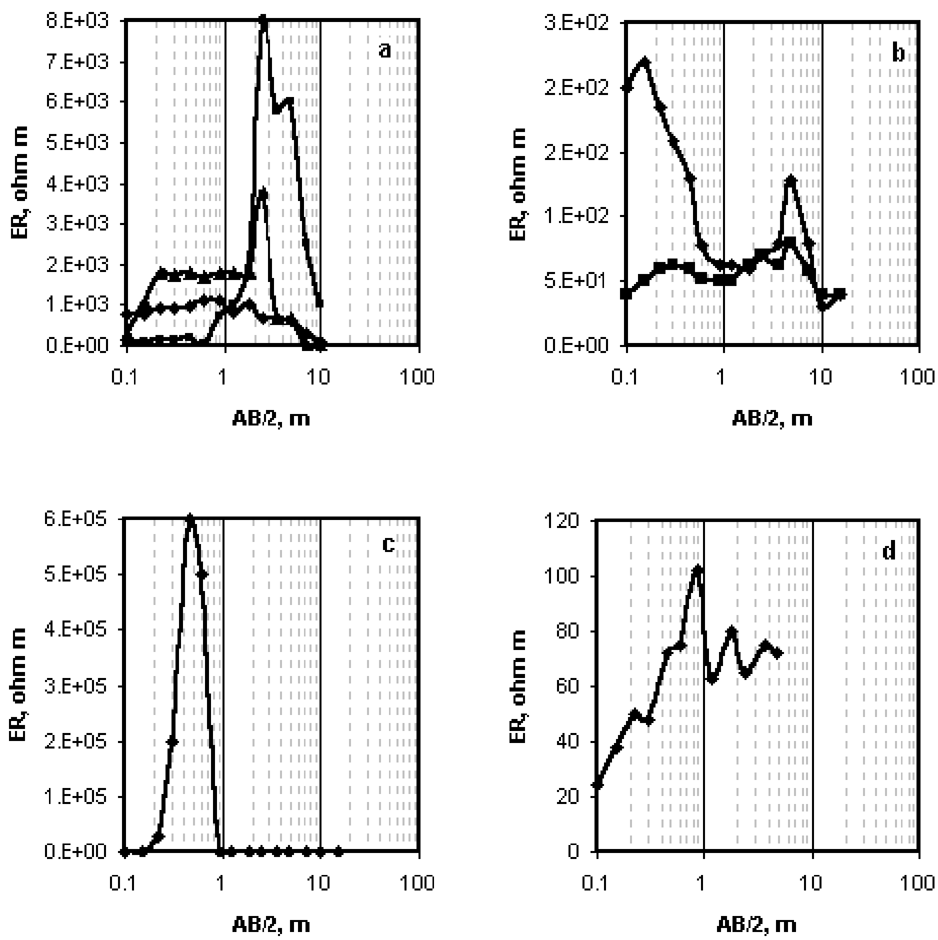


Fig. 2. Characteristic VES profiles for the soils polluted with different by-products of oil mining and refinery.

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.

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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Pozdnyakov, A.I., L.A. Pozdnyakova, and A.D. Pozdnyakova. 1996a. Stationary electrical fields in soils. (In Russian with English summary) KMK Scientific Press. Moscow.

Znamensky, V.V. 1980. Field geophysics. (In Russian.) Nedra, Moscow.

Four-electrode probe for detection of burial places of criminal origin

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-01 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. 1 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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APPENDIX D. How to make your own four-electrode probe for soil mapping

Materials

- ¾" PVC pipe, one section of 10'.
- 2 T-shaped PVC pipe fitting accepting ¾" pipe from all three ends.
- 2 ¾" PVC cups (optional).
- About 30' #18 AWG isolated stranded wire, preferably 2 colors (red and black), 15' of each.
- 1"x2" Velcro strip (optional).
- 3 #6 1.5" screws for wood (optional).
- 4-electrode probe kit (available from Landviser, Inc.) 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

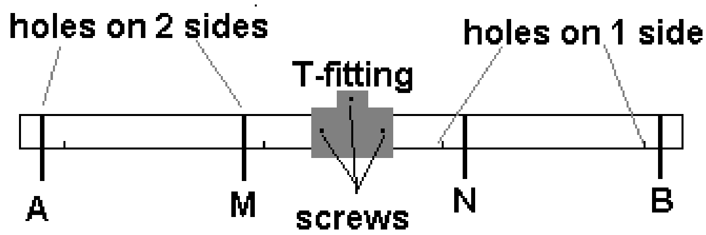
- PVC pipe cutter
- Wire cutter
- Wire stripper
- Wire crimper
- Electric drill
- Rubber mullet (optional)

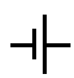
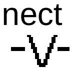
Procedure (example for Wenner probe configuration)

1. Choose the inter-electrode distance **a** (assuming 10"). Calculate the length of the one shoulder of 4-electrode probe: L1=3***a**/2+1 ¼ "=16 ¼ "
2. Cut 2 pieces of the PVC pipe of length L1=16.5". Cut 3.5' pipe for the handle.
3. Connect 2 pieces of length L1 in T-fitting to form a straight line. Use rubber mullet to force tubes all the way into T-connection. Mark locations of A and B electrodes at the each end of the probe, at the 2" from the ends. Mark the locations of M and N electrodes at **a=10"** distance from A and B.
4. Drill ¼" diameter openings at the each mark through the both sides of the pipe for the electrodes (try to keep the drill bit perpendicular to the tube).
5. At approximately 1 inch from the each opening drill holes for the wires only at one side of the pipe.
6. Cut 4 pieces (2 black and 2 red) of wire in the length:

   red for A or B -- L2=a+a/2+4.5'

   black for M or N -- L3=a/2+4.5'



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