GEONICS LIMITED
1745 Meyerside Dr. Unit 8 Mississauga, Ontario Canada L5T 1C6

Tel: (905) 670-9580
Fax: (905) 670-9204
E-mail:geonics@geonics.com
URL:http://www.geonics.com

EM38-4
GROUND CONDUCTIVITY METER
OPERATING MANUAL

GEONICS LIMITED

LEADERS IN ELCTROMAGNETICS

8-1745 Meyerside Drive, Mississauga, Ontario Canada L5T 1C6

Tel: (905) 670-9580 Fax: (905) 670-9204

E-mail: geonics@geonics.com Web site: http://www.geonics.com

June 2022

EM38-4
GROUND CONDUCTIVITY METER
OPERATING MANUAL

TABLE OF CONTENTS

INTRODUCTION

This manual supplies users of the EM38-4 with a basic introduction as well as operating information. The EM38-4 has an operating frequency of 14.5 kHz and uses four receiver coils with coil separations of **0.5 m, 0.75 m, 0.88 m and 1.0 m** from the transmitter coil to provide readings of apparent conductivity in millisiemens per meter (mS/m) (Quad-phase) and magnetic susceptibility (In-phase) ratio of the secondary to primary magnetic field in parts per thousand (ppt) data from each of four distinct depth ranges, all simultaneously, to an effective maximum depth of 1.5 m.

During standard operation, all receiver coils are positioned in vertical dipole orientation; for shallower measurements, the instrument can be rotated such that all coils will be in horizontal dipole orientation, thereby providing data from four additional depth ranges with an effective maximum depth of 0.75 m.

Data from multiple depth ranges supports a more complete characterization of the soil profile through inverse modelling of data. Software included with the instrument provides two-layer modelling of the profile both in real-time and during data processing; optional third-party software further offers both forward and expanded inverse modelling capabilities.

Additional features include an **automated software based calibration/zeroing procedure**, **Bluetooth** wireless communication along with traditional **RS232** cable connection. An external, lightweight **rechargeable battery pack** supports daily survey operations; a **power input connector** facilitates the use of alternate external power sources and an optional, collapsible **calibration stand** that facilitates the automated calibration procedure; using the stand, the instrument can be calibrated within a few seconds without requirement for iterative adjustments. A "Hitch-Mount Carrier" is also available for direct mounting on vehicles for towing purposes.

<u>The sensor has no LCD meters mounted on it for monitoring purposes</u> and therefore requires a separate Windows 10 (or 7) OS based PC to run the included **EM38-4 Logging software**. The program is designed primarily for the MS Windows 10 tablet Mesa3 (manufactured by Juniper Systems and offered as a primary option by Geonics). It can be operated in the vertical (portrait) as well as in horizontal (landscape) display mode, however the screen orientation must be locked during data collection. The program can be used with other Windows 10 (or 7) based field computers with vertical and horizontal oriented displays. The minimum supported display resolution is 800 x 600 pixels. In case high resolution display is employed, it is advised to set fonts to 125% or 150% to increase legibility of the screen. The maximum size of program main windows is 1024 x 762 pixels.

The **EM38-4 program** acquires and records survey data from the EM38-4 system, under the control of the operator. It also records various field information such as survey line number (line name), starting station, increment, comments, etc. Readings are displayed in real time in mS/m and ppt in graphic and numeric modes. The EM38-4 also continuously monitors the EM38-4 measured components (Conductivity or Inphase), as well as GPS signal quality parameters (if connected to a GPS receiver) without leaving the program. **A real time inversion (2 layer case) option is also provided**. If the latter option is enabled, inversion results are displayed as a vertical cross section and recorded in data file. As another option Geonics also offers a special inversion program that can be used in post processing which provides greater access to inversion options. This program is called **EM4Soil-G** (contact Geonics for further details).

The EM38-4 will accept NMEA-0183 compatible data from a GPS receiver directly connected to the field computer. GPS data which are embedded in the EM38-4 data file can be processed later in the Geonics **DAT38-4 program(also included)**. The connected GPS receiver must be able to stream NMEA0183 compatible messages. The EM38-4 uses two NMEA messages GGA and GSA. While message GGA is mandatory, the GSA string is used only to provide information related to the GPS signal quality during data collection. The EM38-4 program records data together with a time stamp at each station. Data files created with this program can be used to position a survey according to locations recorded separately by a Global Positioning System (GPS). Survey setup parameters are saved in a configuration file, therefore they can be automatically used during subsequent data collection sessions. Data files are saved to the user selected data directory. Data file names, which can be set by the program based on the computer clock or user specified, have extension names 384. Files can be converted to F38 format and viewed in the **DAT38-4 Processing program**. Number of readings in a data file is limited only by the hard drive capacity, however it is strongly recommended to avoid huge data files (i..e one to two hours long data files are adequate). The maximum speed of data collection (and instrument output) is 10 readings per second, recommended GPS receiver output stream is 1 Hz.

Additional information can be found in Geonics Technical Note TN-5, which outlines the factors affecting soil and rock conductivity, and Technical Note TN-6, which describes the general theory of terrain conductivity mapping using inductive electromagnetic techniques.

New!

CONDUCTIVITY METER

EM38-4

While retaining all of the functionality of the standard-model EM38-MK2, the new EM38-4 Ground Conductivity Meter includes an additional two receiver coils to provide data from a greater number of depth ranges. Information available from four receiver coils supports a better understanding of the soil profile through inverse modelling of the data, both in real-time and at various stages of data processing.

Multiple modes of deployment are possible, including walking, towing behind a vehicle and vehicle-mounting, each supported by the option of continuous data collection.

EM38-4 Ground Conductivity Meter

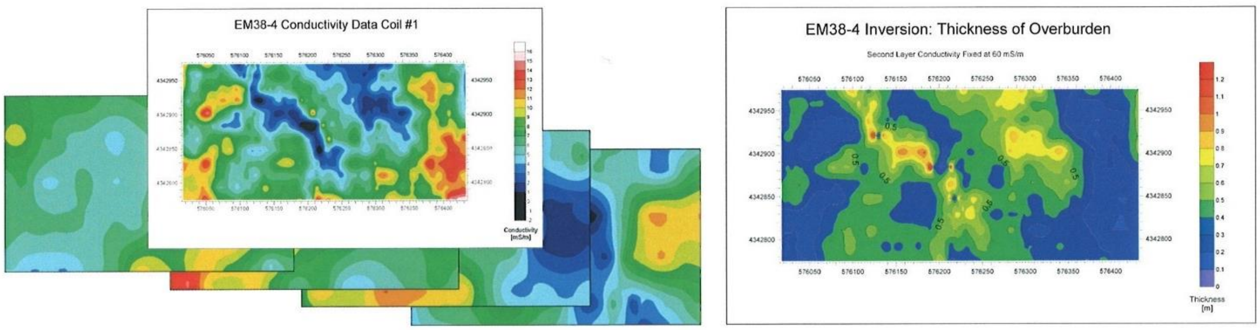
GEONICS LIMITED

8-1745 Meyerside Dr., Mississauga, ON, Canada L5T 1C6 T: (905) 670-9580 F: (905) 670-9204 E: geonics@geonics.com U: www.geonics.com

EM38-4 CONDUCTIVITY METER

OPERATING FEATURES

- Four receiver coils provide soil conductivity (quad-phase) and magnetic susceptibility (in-phase) data from each of four distinct depth ranges, all simultaneously, to an effective maximum depth of 1.5 m
- During standard operation, all receiver coils are positioned in vertical dipole orientation; for shallower measurements, the instrument can be rotated such that all coils will be in horizontal dipole orientation, thereby providing data from four additional depth ranges with an effective maximum depth of 0.75 m
- Data from multiple depth ranges supports a more complete characterization of the soil profile through inverse modelling of data. Software included with the instrument provides two-layer modelling of the profile both in real-time and during data processing; optional third party software further offers both forward and expanded inverse modelling capabilities
- Bluetooth technology provides reliable wireless communication with any compatible acquisition device (e.g. Mesa3 Rugged Tablet) within a 10 m distance
- An external, lightweight rechargeable battery pack supports daily survey operations; a power input connector facilitates the use of alternate external power sources
- An optional, collapsible calibration stand facilitates a semi-automated calibration procedure; using the stand, the instrument can be calibrated within a few seconds without requirement for iterative adjustments



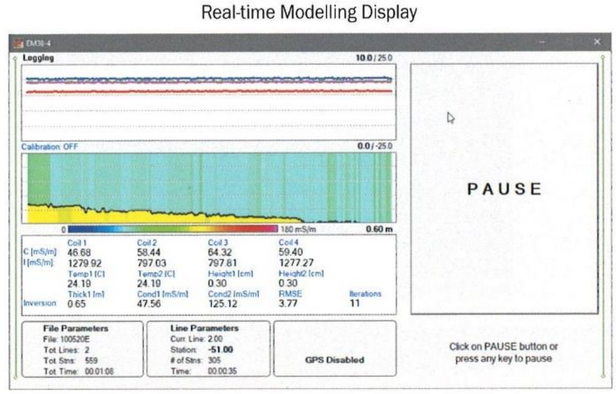
Spatial data from multiple depths provides information to describe the soil profile both vertically and horizontally

TECHNICAL SPECIFICATIONS

Displayed Quantity:	Apparent conductivity in millisiemens per metre (mS/m) at each coil separation Two-layer apparent conductivity model in real-time In-phase response in parts per thousand (ppt) of secondary to primary magnetic field at each coil separation
Intercoil Spacing:	0.5, 0.75, 0.88 and 1 m
Conductivity Range:	0 to 1,000 mS/m, all separations
In-phase Range:	+/- 28 ppt for 1 m separation +/- 22 ppt for 0.88 m separation +/- 16 ppt for 0.75 m separation +/- 7 ppt for 0.50 m separation
Measurement Precision:	+/- 0.1% of full scale
Measurement Accuracy:	+/- 5% at 30 mS/m
Noise Level:	+/- 0.5 mS/m (Conductivity) at 1 m separation +/- 0.02 ppt (In-phase) at 1 m separation

Operating Frequency:	14.5 kHz
Data Communication:	RS-232, Bluetooth, USB
Temperature Range:	-40˚C to +50˚C
Power Source – External:	12 VDC Rechargeable battery
Operating Weight and Dimensions:	9 kg; 133 x 17 x 8 cm
Shipping Weight and Dimensions:	20 kg; 140 x 25 x 15 cm

Real-time Modelling Display



GEONICS LIMITED
8-1745 Meyerside Dr., Mississauga, ON, Canada L5T 1C6 T: (905) 670-9580 F: (905) 670-9204 E: geonics@geonics.com U: www.geonics.com

3. EM38-4 DATA LOGGING OPERATING INTRUCTIONS

4. DAT38-4 COMPUTER PROGRAM MANUAL

EM38-4 Specifications

Measured Quantity	:	1. Apparent conductivity in millisiemens per meter (mS/m) 2. In-phase ratio of the secondary to primary magnetic field in parts per thousand (ppt) 3. Instrument internal temperature in degrees Celsius (°C) 4. Two layer model in real time display (Two conductivity and thickness of first layer)
Intercoil Spacing	:	0.5 m, 0.75 m, 0.88 m and 1.0 m
Operating Frequency	:	14.5 kHz
Measuring Range Conductivity	:	1000 mS/m
In-Phase Range	:	± 28.6 ppt for 1.0 m ± 22.2 ppt for 0.88 m ± 16.1 ppt for 0.75 m ± 7.16 ppt for 0.5 m
Measurement Resolution	:	± 0.1% of full scale
Measurement Accuracy	:	± 5% at 30mS/m
Noise Level	:	Conductivity ± 0.5 mS/m, In-phase ± 0.02 ppt (at 1 m)
Data Output	:	RS232, Bluetooth, USB
Power Source	:	12 VDC External Battery
Operating Temperature	:	-40°C to +50°C; (-20°C to +50°C for logger)
Data Logger	:	MESA3 Field Computer
Dimensions Instrument	:	133 x 17 x 8 cm
Dimensions Shipping Case	:	140 x 25 x 15 cm
Weight Instrument	:	9 kg
WeightShipping	:	20 kg
Special Feature	:	Display of two layer model in real time

March 2022

6. CALIBRATION STAND FOR EM38-4

ASSEMBLY INSTRUCTIONS

EM38-4 INSTRUMENT CALIBRATION PROCEDURE WHEN USED WITH THE HITCH-MOUNT CARRIER

Before attempting instrument calibration, operator should familiarize himself with the EM38-4 logger operation procedure.

Even though that each EM38-4 is calibrated in the factory, including temperature compensation, the effect of the carrier and the support vehicle as well as a large change in the environment temperature will affect the instrument's accuracy, therefore the instrument should be properly recalibrated to give an accurate result.

Prior to the calibration, operating instrument enclosed in the protection box should be set on the support vehicle mounted carrier, to measure the height of the instrument from the ground surface, information later needed for proper calibration and data processing.

The target symbol (red dot) on the protection box indicates the center position of the instrument. To obtain the best possible survey data, prior to calibration, the instrument should be temperature stabilized, especially if there was a large temperature change in the instrument's environment. 10 to 15 minutes of temperature stabilization should normally be sufficient.

The following describes the calibration steps after the instrument was temperature stabilized.

STEP 1. Assemble the EM38-4 calibration monopod as per Figure 1. Adjust the monopod so that the Tray 1 is about1.5 meters from the tip of the monopod. Adjust Tray 2 so that the center of the EM38-4 is at the height previously measured with the instrument mounted on the carrier. Remove the instrument from the protection box and set it for the operation. Make sure that the logger is at least 1 metre away from the instrument.

STEP 2. The instrument should be calibrated on the calibration spot (ground), which is at least 5 m away from the carrier and the support vehicle, as well as any other interference such as pipes, cables, a metal fence or power lines. Since the instrument is very sensitive to metal objects, make sure that the operator who is performing the calibration does not have any metal objects like chains, a metal wristwatch strap, rings, metal framed glasses, keys or knives. Mark the calibration spot. Connect the battery and communication cable and set the instrument for operation.

Start the EM38-4 logger program and go to the calibration section of the program. Set the instrument to the Tray 1, secure it with the rubber latch, and follow the calibration procedure instructions. By setting the instrument at Tray 2 and taking measurement, that will establish the reference ground apparent conductivity at the calibration spot at the instrument operating height.

It is important to record the conductivity reading separately in the notebook, so it can be compared later with the final calibration value (Step 3) to make sure that all calibration steps are performed correctly.

STEP 3. After calibration is finished and the calibration spot referenced reading is recorded, set the operating instrument back into the protection box and mount it on the carrier.

Move the whole assembly, so that the EM38-4 will be at the previously marked calibration spot and reference operating height above the ground.

Check the instrument's measurement reading. Due to the instrument's proximity to the carrier and support vehicle, it will read differently than previously recorded during the calibration procedure. After recalling the reference reading (program automatic operation), the instrument should be calibrated and show the same reading as the previously recorded reference reading.

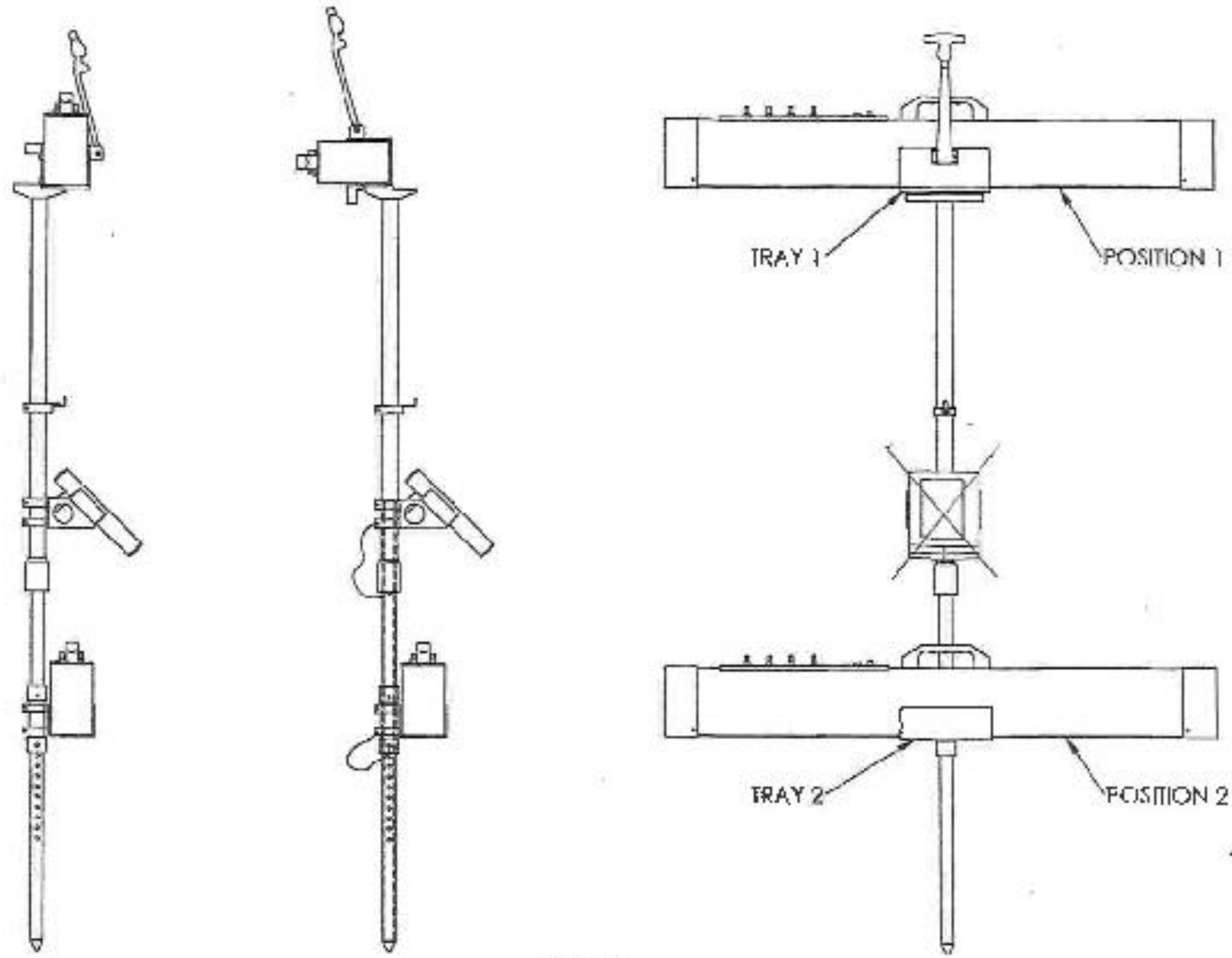


FIG.1

GEONICS LIMITED
1745 Meyerside Dr. Unit 8 Mississauga, Ontario Canada L5T 1C6
Tel: (905) 670-9580
Fax: (905) 670-9204
E-mail:geonics@geonics.com
URL:http://www.geonics.com

Technical Note TN-38

A TECHNIQUE FOR CALCULATION OF THE SOIL SUBSURFACE LAYERS PARAMETERS IN AGRICULTURAL APPLICATION, USING THE NEW GEONICS EM38-4 MULTI-COIL CONDUCTIVITY METER

M. BOSNAR

OCTOBER, 2020

This Technical Note describes a simple procedure on how to determine electrical conductivity and thickness of the soil subsurface layers in applications for agricultural field management practices.

The technique is based on the combination of field measurements with EM38-4 Soil Conductivity Meter and post processing calculation using fast forward and inversion modelling software. The technique shows results with low equivalence (different models that give the same result) as well as less sensitivity to errors in data, in contrast to conventional techniques.

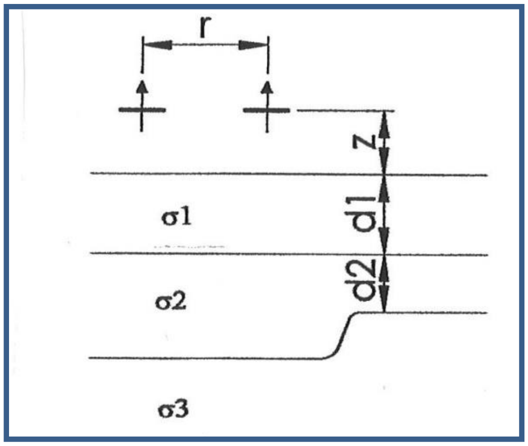
The Technical Note specifically describes applications for three problems in the field of agriculture: first is an estimation of the compaction layer thickness in paddy rice fields and the second shows how to determine thickness of soil above a clay layer and third the depth to bedrock.

In the described examples calculations are performed using the instrument's four coil separations in the vertical dipole mode. Similar calculations can be performed using the instrument in the horizontal dipole mode.

Note that in the following examples the calculations are performed on the basis of theoretical values, so that in practice due to the reading (data) errors and real ground layers, results are not going to be as precise as indicated, but hopefully will still provide useful practical results.

I. ESTIMATION OF THE COMPACTION LAYER THICKNESS IN PADDY RICE FIELD USING EM38-4 CONDUCTIVITY METER

The compaction layer in a paddy rice field is a sub-soil layer of higher compaction and electrical conductivity, which restricts water, as well nutrient losses. Therefore it is important to be able to have an understanding of the thickness of such a layer as part of field management information.
Typically cross sections of such a field comprise of three layers: wet paddy soil, compaction layer and undisturbed sub soil.



An example value for layers is as follows:

σ_1 = 20 mS/m d_1 = 0.15 m

σ_2 = 185 mS/m (?) d_2 = ?

σ_3 = 35 mS/m (?) z = 0.1 m

r_i = 0.5, 0.75, 0.88 and 1.0 m

The following is a compaction layer thickness estimation procedure:

a) Measurement of electrical conductivity of the first and second or third layer σ_1, σ_2 or σ_3 by the soil EC meter (Field Scout from Spectrum Technology – for example.) Measurement of thickness of first layer can be best done by penetrometer. Note that the parameters, except compaction layer thickness, are typically constant through a particular paddy rice field but should be checked at several spots throughout the survey field.

b) Calculation of response of first layer for EM38-4, using forward modelling, (for example "Forward EM38-4" Geonics' forward modelling software).

The entry values for the example model are:

σ_1 = 20 mS/m (measured value)
d_1 = 0.15 m (measured value)
r_i = 0.5, 0.75, 0.88 and 1.0 m (EM38-4 Coils Separation)

Calculated values of apparent conductivity for all four coil separations are:

$\sigma_{c\ 0.5}$ = 4.4 mS/m, $\sigma_{c\ 0.75}$ = 2.7 mS/m, $\sigma_{c\ 0.88}$ = 2.1 mS/m,
$\sigma_{c\ 1.0}$ = 1.7 mS/m

c) Field measurement of apparent conductivity for the four coil separations using the EM38-4.

The value for the example model:

$\sigma_{m\ 0.5}$ = 54.9 mS/m, $\sigma_{m\ 0.75}$ = 52.7 mS/m, $\sigma_{m\ 0.88}$ = 50.5 mS/m, $\sigma_{m\ 1.0}$ = 48.3 mS/m

d) Subtraction of calculated value σ_{ci} from measured values σ_{mi} for all the four coil separations. Where: Subscript "i" indicates EM38-4 transmitter-receiver coil separations of 0.5, 0.75, 0.88 and 1.0 meters, subscript "c" calculated values and "m" measured values at four separations.

The value for the example model:

$\sigma_{mi}' = \sigma_{mi} - \sigma_{ci}$

$\sigma_{m}'_{0.5}$ = 50.5 mS/m, $\sigma_{m}'_{0.75}$ = 50 mS/m, $\sigma_{m}'_{0.88}$ = 48.4 mS/m, $\sigma_{m}'_{1.0}$ = 46.6 mS/m

e) Use of inversion software (for example, "Inversion EM38-4" Geonics' inversion modelling software) calculates thickness d_2 of the compaction layer, and σ_2 or σ_3 (whichever is unknown), where:

- Instrument height $z' = z + d_1 = 0.25$ m
- σ_2 or σ_3 is known
- $\sigma_{mi'}$ are calculated values for inversion

From inversion we obtain the following: $d_2 = 0.151$ m ± 0.002 m
$\sigma_2 = 186.3$ mS/m (if σ_3 is known)
or
$\sigma_3 = 34.9$ mS/m (if σ_2 is known)

Error Analysis

Table No.1 indicates the error in compaction layer thickness (d_2) calculation due to the error in inversion input parameters for case I.

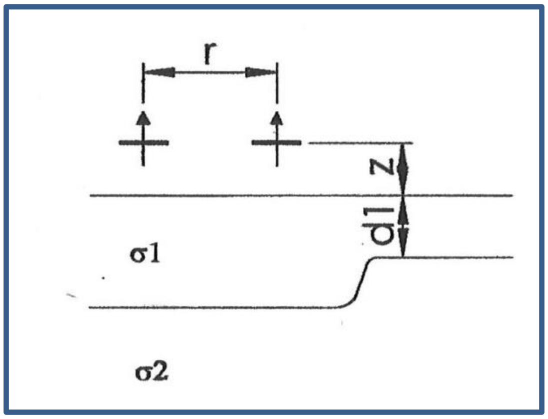
			d_2 nom = 15 cm
Error in instrument height above ground	Δz = ± 2 cm		Δd_2 = ± 3 cm
Error in Subsoil layer conductivity	$\Delta\sigma_3$ = ± 2 mS/m		Δd_2 = ± 0 cm
Error in compaction layer conductivity	$\Delta\sigma_2$ = ± 2 mS/m		Δd_2 = ± 3 cm
Error in instrument conductivity reading	$\Delta\sigma'_{mi}$ = ± 1 mS/m	Coil 1	Δd_2 = ± 3 cm
		Coil 2	Δd_2 = ± 0.5 cm
		Coil 3	Δd_2 = ± 1.5 cm
		Coil 4	Δd_2 = ± 2.5 cm

Table 1

II. ESTIMATING A DEPTH TO CLAYPAN USING THE EM38-4 CONDUCTIVITY METER

The depth to claypan, or the thickness of soil above a clay layer is important for agriculture field management.
The following method describes how to calculate depth to a conductive clay layer, using the EM38-4 Multi Coil Conductivity Meter. This approach significantly reduces result equivalence as well as sensitivity to errors in the data, often associated with EM measuring technique. The procedure assumes that either σ_1 or σ_2 are known.

Example 1.



Example 1 value:

$d_1 = 0.15$ m (?)

$\sigma_1 = 20$ mS/m

$\sigma_2 = 100$ mS/m (?)

$r_i = 0.5, 0.75, 0.88$ and 1.0 m

$z = 0.1$ m

The following describes a procedure to obtain the depth to clay pan d_1 and apparent conductivity of the top or clay layer.

a) Measure σ_1 (mS/m) using the soil EC Meter (For example Field Scout from Spectrum Technology). In the above example $\sigma_1 = 20$ mS/m.

b) Use the EM38-4 to measure apparent conductivity for all four coil separations as entry parameters for inversion software “Inversion 38-4”.
For above example:

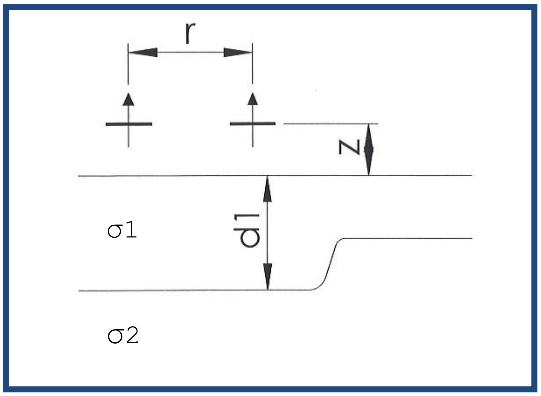
Coil Separation r_i (m)	0.5	0.75	0.88	1.0
Apparent Conductivity σ_{mi} (mS/m)	71	80	82	83.3

From inversion we obtain:
$d_1 = 0.148$ m (inversion result)
$\sigma_1 = 20.0$ mS/m (fixed known value)
$\sigma_2 = 100.2$ mS/m (inversion result)

Note that similar results would be obtained if σ_2 is known with d_1 and σ_1 unknown.

Example 2.

Example 2 value:



d_1 = 0.5 m (?)

σ_1 = 20 mS/m

σ_2 = 100 mS/m (?)

r_i = 0.5, 0.75, 0.88 and 1.0 m

z = 0.1 m

The following describes a procedure to obtain depth to clay pan d_1 and the apparent conductivity of the top or clay layer.

a) Measure σ_1 (mS/m) using the soil EC Meter (For example Field Scout from Spectrum Technology). In the above example σ_1 = 20 mS/m.

b) Use the EM38-4 to measure apparent conductivity for all four coil separations as entry parameters for inversion software "Inversion 38-4".
For above example:

Coil Separation r_i (m)	0.5	0.75	0.88	1.0
Apparent Conductivity σ_{mi} (mS/m)	45.5	56	60.1	63.2

From inversion we obtain: d_1 = 0.5 m (inversion result)
σ_1 = 20.0 mS/m (fixed known value)
σ_2 = 100.2 mS/m (inversion result)

Note that similar results would be obtained if σ_2 is known with d_1 and σ_1 unknown.

<u>Error Analysis</u>

Tables No.2 and 3 indicate the error in topsoil layer thickness (d_1) calculation due to the error in inversion input parameters for case II. Examples a) and b).

			d_1 nom = 15 cm
Error in instrument height above ground	Δz = ± 2 cm		Δd_1 = ± 2.5 cm
Error in clay layer conductivity	$\Delta\sigma_2$ = ± 2 mS/m		Δd_1 = ± 4 cm
Error in topsoil layer conductivity	$\Delta\sigma_1$ = ± 2 mS/m		Δd_1 = ± 0.5 cm
Error in instrument conductivity reading	$\Delta\sigma_{mi}$ = ± 1 mS/m	Coil 1	Δd_1 = ± 2 cm
		Coil 2	Δd_1 = ± 1 cm
		Coil 3	Δd_1 = ± 1.5 cm
		Coil 4	Δd_1 = ± 2 cm

Table 2

		d_1 nom = 50 cm
Error in instrument height above ground $\Delta z = \pm 2$ cm		$\Delta d_1 = \pm 1$ cm
Error in clay layer conductivity $\Delta\sigma_2 = \pm 2$ mS/m		$\Delta d_1 = \pm 2.5$ cm
Error in topsoil layer conductivity $\Delta\sigma_1 = \pm 2$ mS/m		$\Delta d_1 = \pm 6$ cm
Error in instrument conductivity reading $\Delta\sigma_{mi} = \pm 1$ mS/m	Coil 1	$\Delta d_1 = \pm 3.5$ cm
	Coil 2	$\Delta d_1 = \pm 1$ cm
	Coil 3	$\Delta d_1 = \pm 1.5$ cm
	Coil 4	$\Delta d_1 = \pm 2$ cm

Table 3

References

1. M.M. Islam, T. Saey, P. De Smedt, E. Van De Vijver, S. Delefortrie & M. Van Meirvenne, 2014, Modeling within field variation of the compaction layer in a paddy rice field using a proximal soil sensing system: British Society of Soil Science, 30, p. 99-108.

2. J.A. Doolittle, K.A. Sudduth, N.R. Kitchen, and S.J. Indorante, 1994, Estimating depths to claypans using electromagnetic induction methods. Journal of Soil and Water Conservation, 49 (6): p. 572-575.

III. ESTIMATING A DEPTH TO SHALLOW BEDROCK UNDER MODERATELY TO HIGHLY CONDUCTIVE TOPSOIL LAYER, AN AGRICULTURAL APPLICATION

In order not to pollute drinking water in some parts of the USA (specifically in Eastern Wisconsin), a new regulation requires farmers not to apply manure on the farmland if the topsoil above bedrock is less than 2 feet thick.

This note describes a non-contacting method using the Geonics Limited new Multi-Coil Conductivity Meter EM38-4 and newly developed fast inversion software, that can be used to determine apparent electrical conductivity and thickness of the topsoil layer above bedrock.

The procedure requires mapping of the apparent conductivity of the field with the EM38-4 Conductivity Meter and simultaneously applying the "Inversion 38-4" inversion software to obtain information about the topsoil layer thickness and conductivity. Calculation can also be performed during post processing.

The examples below describe two layer earth models with different first layer thickness and conductivity, with a constant bedrock conductivity. Note that bedrock electrical conductivity is typically very low, in the range of 0.1 to 2 mS/m. In the following example we will assume the bedrock conductivity to be 1 mS/m. In practice though the value can be established by measuring the bedrock conductivity, using the EM38-4 on the bedrock outcrop (bedrock exposure).

Figure 1. depicts a two layer earth model representing a layer of soil with 3 thicknesses over bedrock.

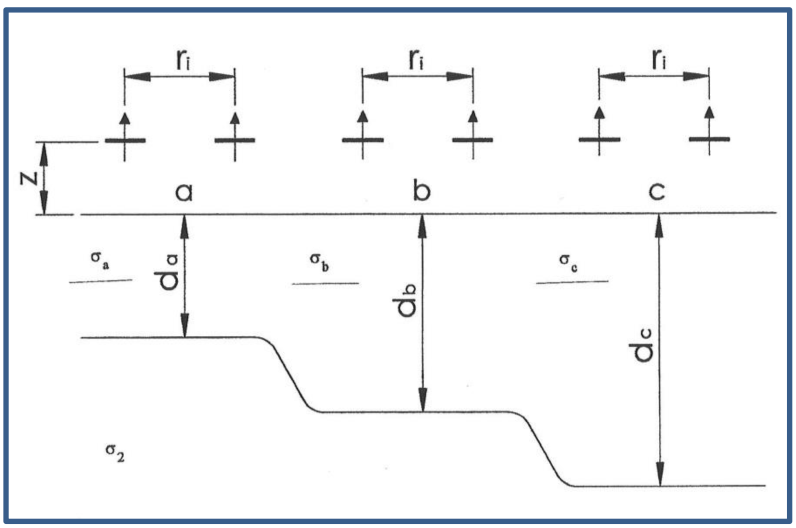


Figure 1.

The following describes a procedure to determine the thickness and apparent conductivity of the top layer.

Position "a".

σ_a = 30 mS/m (?)
σ_2 = 1 mS/m (assumes or measured value)
d_a = 15 cm (?)
z = 0.3 m (instrument height above ground)

Use the EM38-4 to measure apparent conductivity for all four coil separations as entry to the inversion software “Inversion 38-4”

For example Position "a":

Coil Separation r_i (m)	0.5	0.75	0.88	1.0
Measured Apparent Conductivity σ_{ai} (mS/m)	5.1	4.9	4.4	4.2

From inversion we obtain: σ_2 = 1 mS/m (fixed known value)
d_a = 0.15 m (inversion result)
σ_a = 29.1 mS/m (inversion result)

Position "b".

σ_b = 30 mS/m (?)
σ_2 = 1 mS/m (assumed or measured value)
d_b = 30 cm (?)
z = 0.3 m (instrument height above ground)

Same as the example Position "a"., measure apparent conductivity and apply inversion.

For example Position "b":

Coil Separation r_i (m)	0.5	0.75	0.88	1.0
Measured Apparent Conductivity σ_{mi} (mS/m)	8.1	8.1	7.6	7.2

From inversion we obtain: σ_2 = 1 mS/m (fixed known value)
d_b = 0.30 m (inversion result)
σ_b = 30.3 mS/m (inversion result)

Position "c".

σ_c = 30 mS/m (?)
σ_2 = 1 mS/m (assumed or measured value)
d_c = 60 cm (?)
z = 0.3 m (instrument height above ground)

Following the example as per Positions "a". and "b"., measure with EM38-4 apparent conductivity for all coil separations.

For example Position "c":

Coil Separation r_i (m)	0.5	0.75	0.88	1.0
Measured Apparent Conductivity σ_{mi} (mS/m)	11.4	12.3	12.0	11.5

From inversion we obtain: $\sigma_2 = 1$ mS/m (fixed known value)
$d_c = 0.6$ m (inversion result)
$\sigma_c = 30.4$ mS/m (inversion result)

For all three (3) top layer thicknesses, calculation gives excellent unique results of thickness and conductivity of top layer.

In the above examples, conductivity of bedrock was assumed to be 1 mS/m. The above calculation will be automatically performed by inversion software, part of the EM38-4 Software package, either directly in real-time in the logger, or in post processing on the computer.

Note that the above calculation is based on the theoretical calculation of a two layer model. In practice the results will depend on the precision of measurement which will also depend on the accuracy of the instrument calibration, drift and noise level. Even though it will be difficult to achieve the accuracy of the result as per example Position "a" with a very thin topsoil layer, but for layers of soil thickness of 2 feet and thicker, the response (measured value) should be sufficiently large, that the small error will not significantly affect result accuracy.

Error Analysis

The Tables No. 4, 5 and 6 indicate the error in the depth to bedrock (d_1) calculation due to the error in inversion input parameters for case III, positions "a", "b" and "c".

			d_1 nom = 15 cm
Error in instrument height above ground	$\Delta z = \pm 2$ cm		Δd_1 = 11 to 21 cm
Error in bedrock conductivity	$\Delta\sigma_2 = \pm 1$ mS/m		Δd_1 = 5 to 25 cm
Error in instrument conductivity reading	$\Delta\sigma_{mi} = \pm 1$ mS/m	Coil 1	Δd_1 = 0 to 44 cm
		Coil 2	Δd_1 = 19 to 21 cm
		Coil 3	Δd_1 = 11 to 29 cm
		Coil 4	Δd_1 = 5 to 41 cm

Table 4

			d_1 nom = 30 cm
Error in instrument height above ground	$\Delta z = \pm 2$ cm		$\Delta\ d_1 = 24$ to 36 cm
Error in bedrock conductivity	$\Delta\sigma_2 = \pm 1$ mS/m		$\Delta\ d_1 = 23$ to 36 cm
Error in instrument conductivity reading	$\Delta\sigma_{mi} = \pm 1$ mS/m	Coil 1	$\Delta\ d_1 = 16$ to 53 cm
		Coil 2	$\Delta\ d_1 = 31$ to 35 cm
		Coil 3	$\Delta\ d_1 = 26$ to 42 cm
		Coil 4	$\Delta\ d_1 = 18$ to 45 cm

Table 5

			d_1 nom = 60 cm
Error in instrument height above ground	$\Delta z = \pm 2$ cm		$\Delta\ d_1 = 51$ to 70 cm
Error in bedrock conductivity	$\Delta\sigma_2 = \pm 1$ mS/m		$\Delta\ d_1 = 54$ to 65 cm
Error in instrument conductivity reading	$\Delta\sigma_{mi} = \pm 1$ mS/m	Coil 1	$\Delta\ d_1 = 41$ to 94 cm
		Coil 2	$\Delta\ d_1 = 53$ to 59 cm
		Coil 3	$\Delta\ d_1 = 48$ to 64 cm
		Coil 4	$\Delta\ d_1 = 46$ to 81 cm

Table 6

It can be concluded from the above Error Analysis Tables that it would not be possible to obtain sufficient accuracy in the calculation of depth to bedrock, since a relatively small error in inversion input data produces a large error in calculated depth to bedrock.

A more efficient way to calculate if the depth to bedrock is more than 61 cm (2 feet) is to compare if the measured values of the apparent conductivity are larger than the value indicated in Table 7, showing minimum value between 4 coil separations, at a particular value of topsoil conductivity, which can be obtained by measuring apparent conductivity over an area with depth to bedrock larger than 1 m.

Topsoil Conductivity (mS/m)	Measured Apparent Conductivity with instrument height of 0.3 m $\sigma_{mi\ min}$ (mS/m)
10	5
15	7
20	8
25	11
30	13
35	15
40	17

Table 7

For example, if the topsoil apparent conductivity, measured with the EM38-4 at the ground level over an area where bedrock is deeper than one meter is 10 mS/m, and minimum reading among all 4 coil separations is larger than 5 mS/m, than at that point the bedrock depth is over 60 cm.