WIDE BAND MAGNETOTELLURIC STATION LEMI-423

TECHNICAL DESCRIPTION AND OPERATION MANUAL

LVIV

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CONTENT

1. DESTINATION

Magnetotelluric station LEMI-423 (See general view below, further – MTS) is intended for the study of magnetic and telluric fields' fluctuations in the frequency band 0.0001 – 1000 Hz in laboratory or field conditions. The MTS is used mainly for prospecting works with magnetotelluric and magneto-variational methods. Other applications requiring the measurements and recording in autonomous mode of 3 components of the magnetic field (M1, M2, M3) and of 2 components of electric field (E_1, E_2). Magnetic field components are measured by high sensitive induction coil sensors (IC) LEMI-120 (included in the delivery set) and electric field components - by geophysical non-polarized electrodes (customized LEMI-701 electrodes may be delivered optionally). Electric channels use in input stages a filter-free technology (it means "without high-pass filters") to register super-long period signals. Automatic compensation circuits independent for every electric channel are implemented to avoid the channels saturation in case of large DC input voltage (natural or extrinsic ones). Also MTS provides visualization of the stored and/or registered data at PC display.

General view of LEMI-423 magnetotelluric station

2. MAIN TECHNICAL PARAMETERS

MTS LEMI-423 contains:

- 2 induction coil magnetometers LEMI-120
- 2 electric field channels
- Data collection unit

The measurements results from the magnetic and electric channels may be written to PC by USB interface or to SD card installed in the MTS. The parameters of magnetometers, electric channels and data collection unit are given below.

1. Induction coil magnetometer LEMI-120	
Frequency band	(0.0001-1000) Hz
Shape of transfer function	Linear-flat
Corner frequency	1 Hz
Transfer factor at flat part (differential)	200 mV/nT
Noise level: at 0.001 Hz at 0.01 Hz at 1 Hz at 300 Hz	 < 100 pT/√Hz < 10 pT/√Hz < 0.1 pT/√Hz < 0.01 pT/√Hz
Weight of one sensor	5,8 kg
Output connectors type	MS3112E12-8S
2. Electric field meter	
Frequency band	(DC-1652) Hz
Measuring range (gain=4)	± 500 mV
Noise level at 1 Hz	35 nV/√Hz
Non-polarized electrodes LEMI-701 (optional) own noise at 1 Hz	< 10nV/√Hz
3. Data collection unit	
Sample rate per second	250, 500, 1k, 2k, 4k
Power supply voltage	(9-18) V
Power consumption (with three induction coils)	1.7 W
Operation temperature range	minus 20° to +60°C
Waterproof housing IP67	
Input connectors type (for induction coils connection)	MS3112E12-8S
Weight	2 kg

3. DELIVERY SET

1	Induction Coil Magnetometer LEMI-120 (without cables)	- 2 ps
2	Data Collection Unit with SD card 32GB	- 1 ps
3	Terminal Box for Electric Lines (cable 1m) with Grounding Copper Stick for Lightning Protection	- 1 ps
4	Terminal Box for Induction Coils (cable 1m)	- 1 ps
5	GPS Antenna (Bullet III) with Cable (5m) and Holder	- 1 ps
6	PC USB Connection Cable (with double-side connector) (1.8m long)	- 1 ps
7	Power Supply Cable (with double-side connector) (1.8m long)	- 1 ps
8	Operation Manual	- 1 ps
9	Connector MS3116 Cable Mount Straight Plugs 12-8P INSERT COMBO	- 5 ps

Station Control Software is delivered through email.

4. SERVICE AND GUARANTEE

The term of guarantee is 18 months after delivery if all requirements of the present Manual as to applied voltage, weather conditions, vibrations and shocks are observed. During this term the Manufacturer is liable to repair revealed defects if it was no fault of Consumer or force majeure or if not possible to repair to change the device by other equivalent specimen.

The Manufacturer maintains its obligations to make free service and repair the MTS if necessary for still 2 years. In this case the Consumer has to cover the necessary spare parts price and transportation/visit fees only.

LEMI-423 S/N: 0016 - 0017

DELIVERY DATE: QUALITY CONTROL:

15.05.2017 Name: ***Andrii Prystai***

5. STRUCTURE AND OPERATION

5.1. Construction Description

The LEMI-423 MTS Data Collection Unit is mounted in the 1150 PELI case with silica gel cartridge for moisture absorption at the cover (see General view at Page 4). Its front panel has minimum number of control and commutation facilities (Fig. 1). There are LED panel for MTS operation mode indication, button “CONTROL” for start/stop recording and system sample rate selection, toggle switch for power on/off and SD CARD slot.

Fig.1. Front panel of LEMI-423

The connectors for coupling with external battery (“12V DC”), GPS antenna (“GPS”) and USB connector for communication with PC, electric lines terminal box (“EL.LINES”) and induction coils junction box (“SENSOR”) are installed on the left side panel (Fig. 2).

Fig.2. Side panel of LEMI-424

The terminal box with lightning protection for electric lines connection and junction box for induction coils connection are shown at Fig.3.

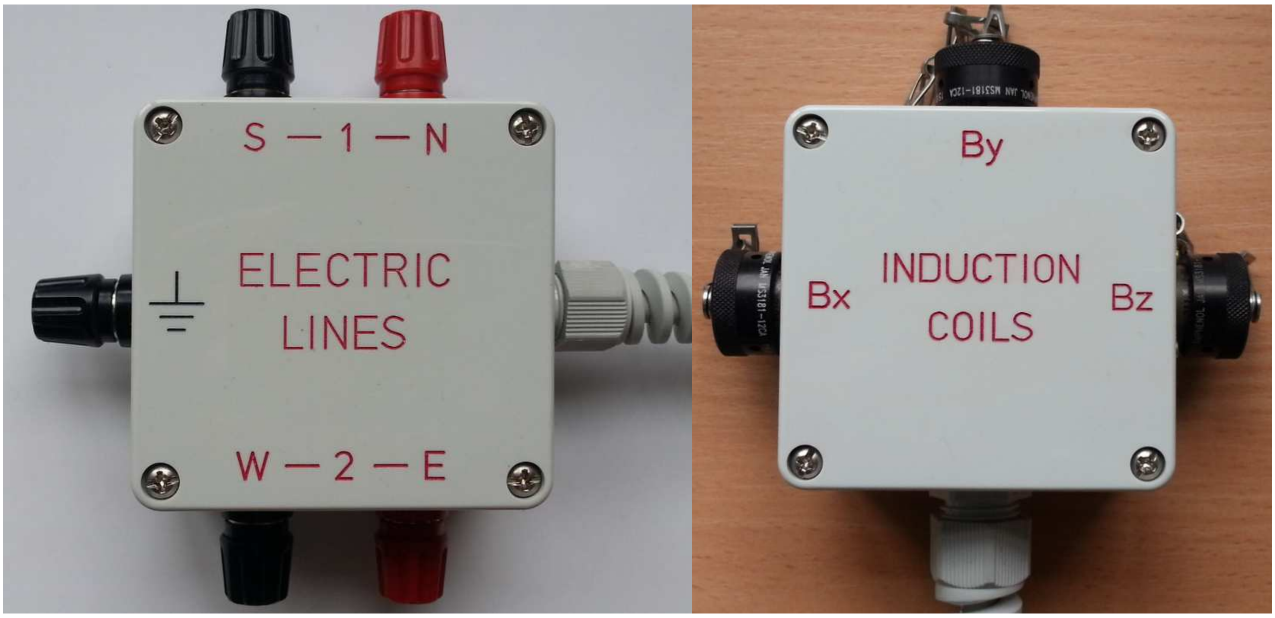


Fig.3. Terminal box with lightning protection for electric lines connection (left) and junction box for induction coils connection (right)

At the side panels of the terminal box (Fig.3 left) the binding posts for two pairs of electric lines (S-1-N and W-2-E) and one post ⏚ for grounding stick connection are fixed. Red posts correspond to positive direction of electric lines. Fig.3 right side shows junction box for the connection of induction coils Bx, By, Bz.

Optionally, non-polarised electrodes LEMI-701 are provided (see description in Appendix D). User-friendly operation software is procured (Section 7) which allows controlling the MTS, data registration and viewing.

The PELI™ 1150 case housing of data collection unit (IP67 protection group) is protected against dust, moisture and rain, and is waterproof WITH CLOSED COWER, but has not be immersed in water! The search-coil magnetometer housing is completely sealed and the magnetometer can withstand temporary immersion in the water.

Any shocks with acceleration more than 5 g both for sensors and electronic unit and vibrations other than occurred during transportation are not admissible.

5.2. Functional Diagram Description

The functional diagram of the MTS is given in Fig. 4. The analog outputs of three induction coil magnetometers (Induction coils on Fig.4) are connected to the ADC Power in the data collection unit and then to microcontroller MC through digital galvanic isolator (GI) and port UART1. The same structure is of two-channel telluric field meter (Electric sensors on Fig.4) having their own ADC. The SD Card module, LEDs, GPS unit with antenna ANT and Control unit are coupled online with MC. The data exchange of MC with external PC is realized through serial interface USB (not shown). The operation synchronization with universal time clock is realized through GPS PPS signal.

All data collection unit is mounted on one printed board. The overall stability of the electronics, both of magnetic and electric channels, is provided by using the best available voltage reference and other high-class integrated components.

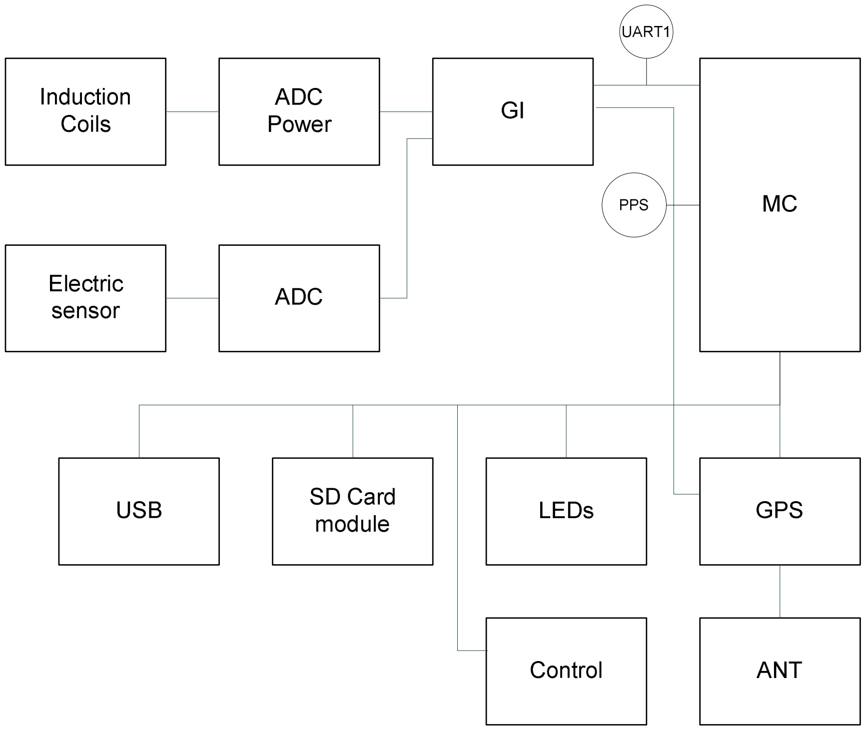


Fig.4. Functional diagram

5.3. Induction coil magnetometer LEMI-120

The induction coil magnetometer (IM) consists of an induction coil sensor and an electronic unit both of which are located inside a common protective housing. The front panel of the magnetometer has an MS3112E12-8S connector for cable coupling.

The sensor part consists of a magnetic core, the main winding W2 and a magnetic feedback winding W1 (Fig.5). The magnetic core is made of a number of μ-metal tapes, which are insulated one from another and installed inside the protective tube on which both windings are made. A set of electrostatic screens is installed to reduce the interference to a negligible minimum value.

The electronic unit consists of two circuit boards which are fixed to the internal part of the magnetometer front panel.

The output signal of the main winding W2 is coupled to the input of ultra low-noise modulator-demodulator amplifier A1. The local feedback loop of amplifier A1 consisting of R1, R4, R5, and C2 components fixes its total amplification factor at low frequencies to approximately 200.

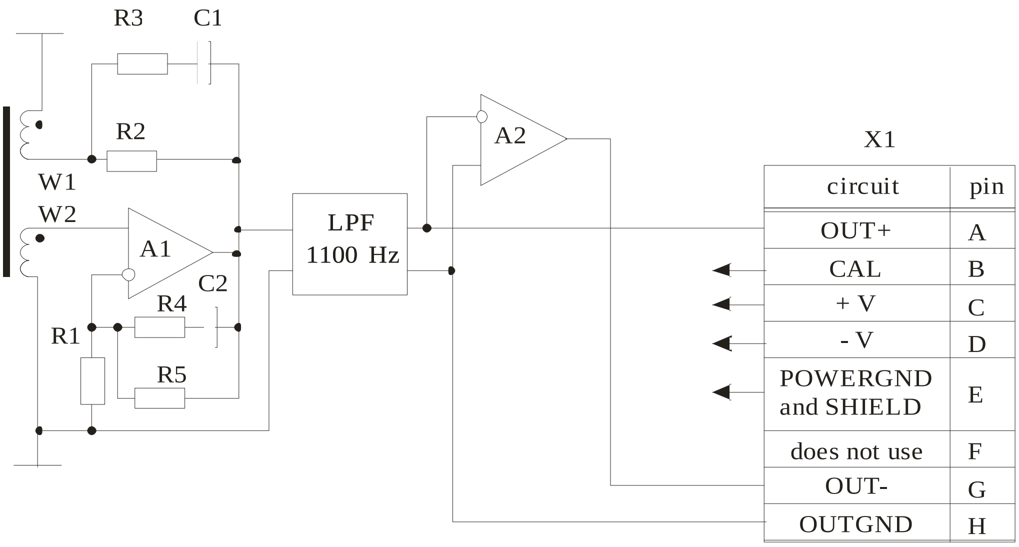


Fig.5. Simplified functional diagram of induction coil magnetometer LEMI-120

The output of amplifier A1 through the correction circuit R2, R3, and C1 is coupled to the magnetic flux feedback winding W1. Magnetic and local feedbacks circuits help to develop the flat part of the magnetometer transfer function within the frequency band from 1 to ~ 1000 Hz.

The output of A1 is also connected to a 6-th order LPF filter (1100 Hz cut-off frequency) with the gain 10 and forms output OUT+. The symmetrical output voltage OUT- is formed with the inverter A2.

CAUTION: The A1 amplifier input is protected from damage by overloading signals but not from strong ones, such as nearby lightning!

The amplifier A1 was specially developed for this magnetometer using the principle of modulation-demodulation (M-DM). The processing of input signals uses three stages:

- modulation of high-frequency signal (**f_m=6000Hz**) by input low-frequency signal (DC to 1000Hz);
- amplification of the modulated high-frequency signal;
- demodulation of this modulated the signal.

NOTE: *The amplifier has extremely low noise at the low-frequency end, but each M-DM amplifier is sensitive to all signals in the band **±1000Hz** around the frequencies **n*f_m**. The LEMI-120 magnetometer suppresses these signals by 40dB, but it is not* *recommended to use the LEMI-120 in a noisy environment with a high content of upper frequencies, e. g., close to powerful LF transmitters.*

A reference signal may be applied to pin E (TEST) of the output connector to test the device. Applying a 10 Hz $5V_{ptp}$ signal to pin E (with pin D as the return wire) produces output signal about 2 nT_{ptp}.

NOTE: This procedure serves only for IM operation checking and not for its calibration. The IM calibration has to be done exclusively in a specialized calibration facility!

The external housing of the induction coil magnetometer has a tubular shape and is made of a fiberglass tube with the built-in electrostatic screen. The housing is also covered by a protective plastic tube to withstand environmental exposure, shocks, and vibrations within allowed limits without damage. The front panel has the cable connector, and electronic unit and induction coil sensor with all windings are also fixed to it, what allows IM to be removed in order to access the housing interior.

NOTE: *Opening the sensor housing before the end of the warranty term without written permission from the Manufacturer cancels all guarantee obligations.*

The LEMI-120 magnetometer is ready for operation within three minutes after power is applied.

In order to obtain extremely low noise level at the lowest frequency, it is recommended to increase the time interval between the installation of the sensor and measurement up to 10-20 minutes.

The amplitude and phase frequency responses of the LEMI-120 magnetometer are given in APPENDIX A.

5.4. MTS electric channels

Functional diagram of the LEMI-423 electric channels (electrometer) is presented at Fig. 6.

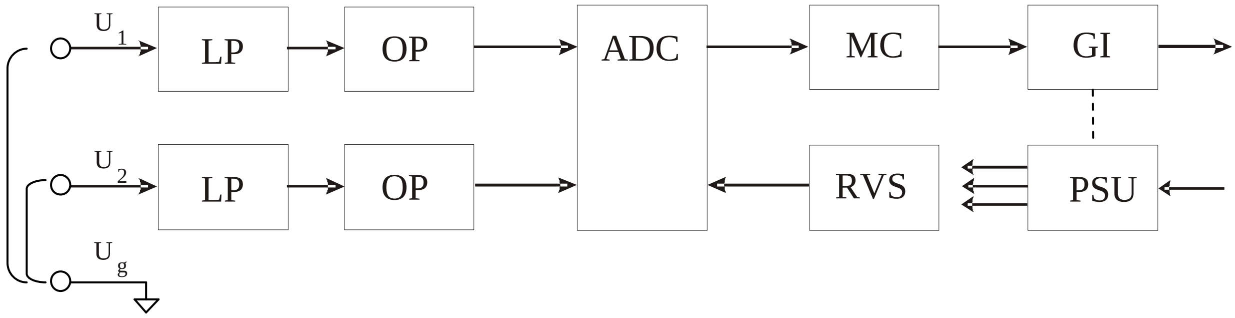


Fig. 6. Functional diagram of the LEMI-423 channels for electrical measurements, here:

U_1, U_2, U_g – input voltage;

LP – circuit which protects against lightning induced large voltage;

OP –operational amplifier;

ADC – analog/digital converter;

RVS – reference voltage source;

MC –microcontroller;

GI –galvanic isolation;

PSU – power supply unit.

Such an electrometer has an extended measurement range of the input signal up to ± 500 mV, its sensitivity threshold is reduced up to 35 nV, and the power consumption is less than 100 mW for two channels. The frequency response of the electrometer may be selected from the pre-programmed versions or to be controlled by the Customer.

<u>NOTE</u>. If inputs of the electric channels are not in use for given installation, they have to be short-circuited and connected to the grounding terminal on the terminal block (Fig.3)!

6. OPERATION MANUAL

<u>Caution!</u>

When installing the MTS, the requirements of international series (IEC TC81) and national standards for Lightning Protection must be used to prevent losses of human life and electronic equipment.

6.1. Field installation

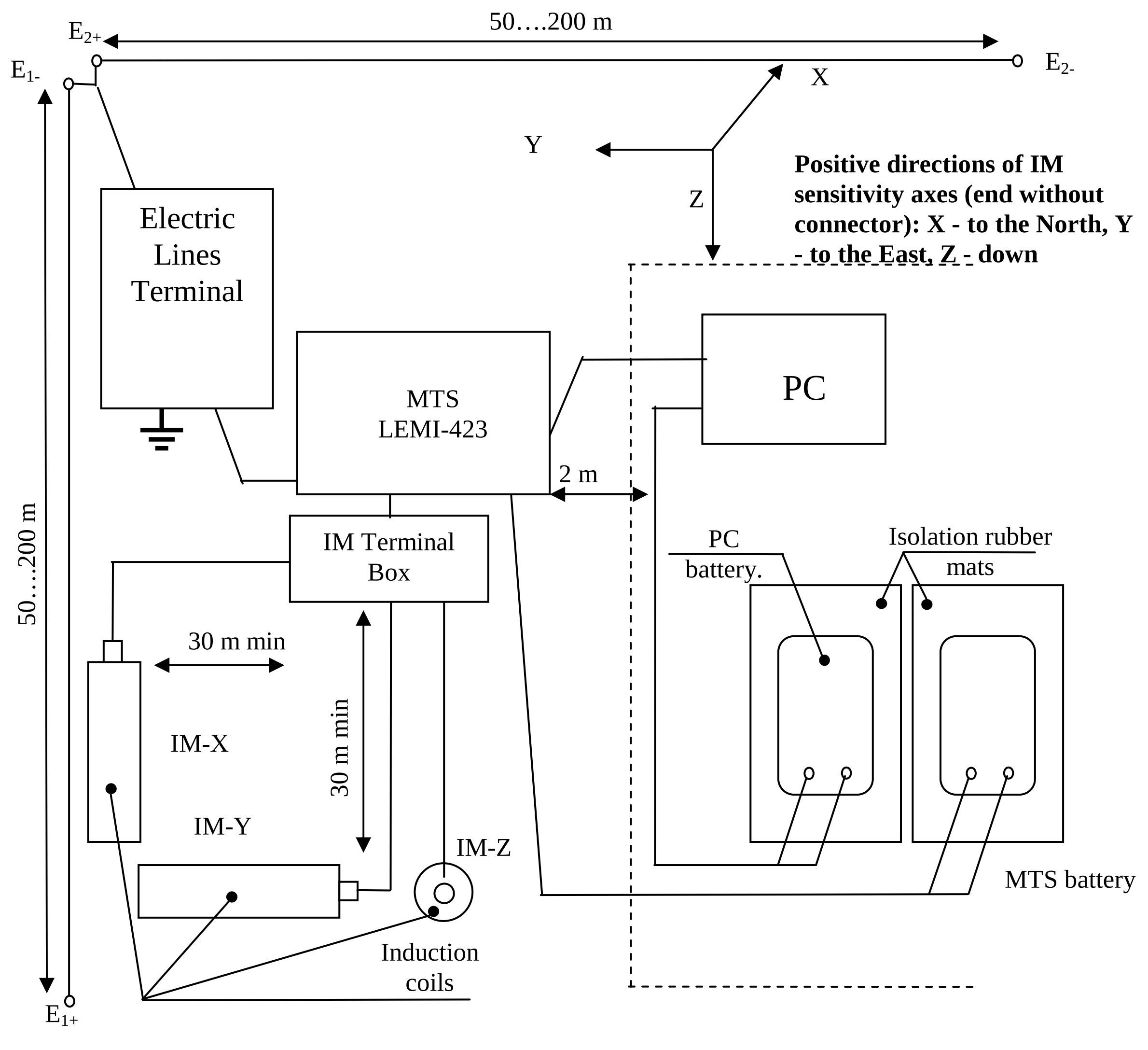


Fig.7. Recommended layout of MTS LEMI-423 at the field site

Recommended layout of MTS LEMI-423 at the field site is shown on Fig. 7. The PC and the batteries must be placed in dry place (tent, car). When installing the cables, it is desirable to place them in parallel, especially for IM sensors cables.

Follow the recommended below rules during sensors installation to get right polarities of output signals:

- Free end of IMx (without connector) has to be directed to North
- Free end of IMy (without connector) has to be directed to East
- Free end of IMz (without connector) has to be directed down
- Couple electric lines to the binding posts on the electrodes terminal. Before connection clean thoroughly the contact surfaces of cables and posts, then fix the cables, trying to provide as big contact surface as possible, and then cover the connections with any weatherproof non-conductive grease. Recommended directions of telluric lines pairs are: 1st line – positive (RED terminal) to the North, negative (BLACK terminal) to the South; 2nd line – positive to the East, negative to the West.
- The grounding binding post ⏚ of electrodes terminal must be connected to the enclosed copper earthing electrode that has to be inserted into the ground directly near the station and also connected to post ⏚ of electronic unit.

<u>NOTE</u>. Without this connection, the telluric channels will be unstable and even may be in saturation!

It is highly recommended to poor the water, better taken from a local spring, at every electrode and at grounding pole.

If any telluric channel is not in use, short-circuit corresponding pair of terminals and couple it to the grounding post.

In field condition it is desirable to place MTS into plastic bag and put it into the hole in the ground. Cover the hole with thermo-insulation material for the better thermal stabilization. The PC computer and both PC and MTS batteries have to be placed inside the car or tent.

It is obligatory to use isolation rubber mats under the batteries even for dry weather!

6.2. MTS preparation for work

The measurement should be carried out in electromagnetically clean area and users should take into account possible magnetic signals from, e.g., nearby thunderstorms, solar bursts etc. The MTS should be located as far as possible from mains power lines and large ferromagnetic objects.

The cable lengths of the LEMI-120 sensors have to be not less than 35 m (minimal distance to the LEMI-423 electronic unit has to be 30 m).

The distance between each of the three induction coils in a three-component set must be not less than approximately 2.5 m.

Do not select measurement sites near large trees - strong wind will produce soil oscillations and consequently sensor vibrations.

Maximum stabilization and damping efforts should be made to provide a stable position for the sensors (e.g., the 1" rotation of the induction coil in the Earth's magnetic field may produce up to ~250 pT of parasitic signal). In order to ensure a stable position it is usually necessary to bury the sensors in the ground when installing a temporary station, or to make beds (holes) with concrete walls for permanent installations. If there are expected microseisms in the region it is advisable to fill the concrete bed to a half of depth with elastic material such as soft polyurethane or at least sack of sand, to put the sensor on top of it and put another sack of sand on the sensor. The first three to five meters of cable connected to the sensor must also be buried. Ensure that the sensor is protected from rain as good as possible. These installation procedures allow avoiding influence of blowing wind and decreasing sensor temperature fluctuations.

The horizontal and vertical sensors must be oriented with compass and level.

Couple IMs to the connectors “Bx”, “By “, “Bz” on the junction box for IM and then to the “SENSOR” connector at the right side of MTS panel (Figs 2 and 3) with cables made using the delivered connectors (cables schematics see in the APPENDIX E). It is very desirable to protect both sides of lines with IM connectors with additional waterproof covers. It will extend connectors lifetime.

It is desirable to install IM at least 1 hour before operation for temperature homogenization inside IM to decrease IM magnetic noise level to the lowest values.

Couple the electrode terminal box cable with the electronic unit connectors “EL. LINES”. Connect batteries to both MTS and PC. If necessary, use for PC powering mains voltage converters. Turn on MTS with POWER ON switch. If needed, connect PC to the MTS by USB cable. Start PC and then initialize lemi423.exe program. Wait while red led “SYSTEM” turn off, select sample rate by short pressing button “CONTROL” and start recording by long, more than 1 second, pressing the same button. For stop recording, push the button “CONTROL” again. If MTS is connected to the PC, data will be recorded to the PC hard disk, if not connected to PC, data will be recorded to the MTS SD card.

7. LEMI-423 PROGRAM MANUAL

(Version 1.6 – 22.01.2017)

The program set consists of following files:

lemi423.exe	Control program
***.def**	Configuration files
lemi423.log	Log-file
***.b423**	Binary data files
***.b423.txt**	Text data files (decoded)
lemi.s423	Text data file of the status mode

After starting the program «lemi423.exe» it automatically detects the device and is coupling to it. The main program window (Fig.7.1) appears at the PC display:

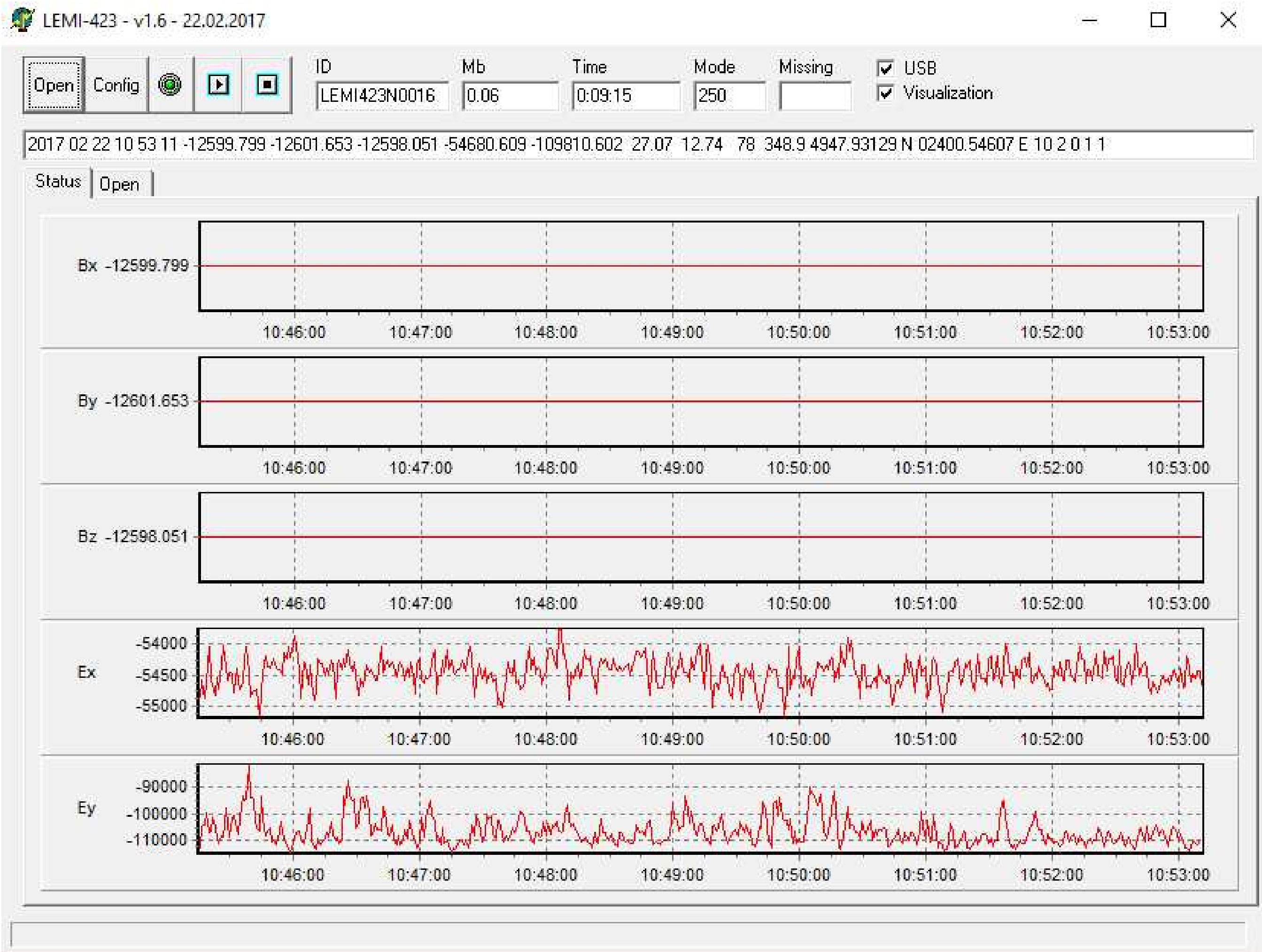


Fig.7.1 Main program window in the status mode.

It shows that the device is in status mode, the tab #1 (upper left) is called «Status» and status line (upper one) shows that the MTS is ready for operation (Fig. 7.1). If MTS is in the data collection mode, this tab is changed to a file name in which the data is being recorded

(Fig. 7.2). By this the real-time data are visualized in the plots at 250, 500, 1000, 2000 or 4000 Hz, depending on the selected instrument operation mode (see below Operating with «Config» window).

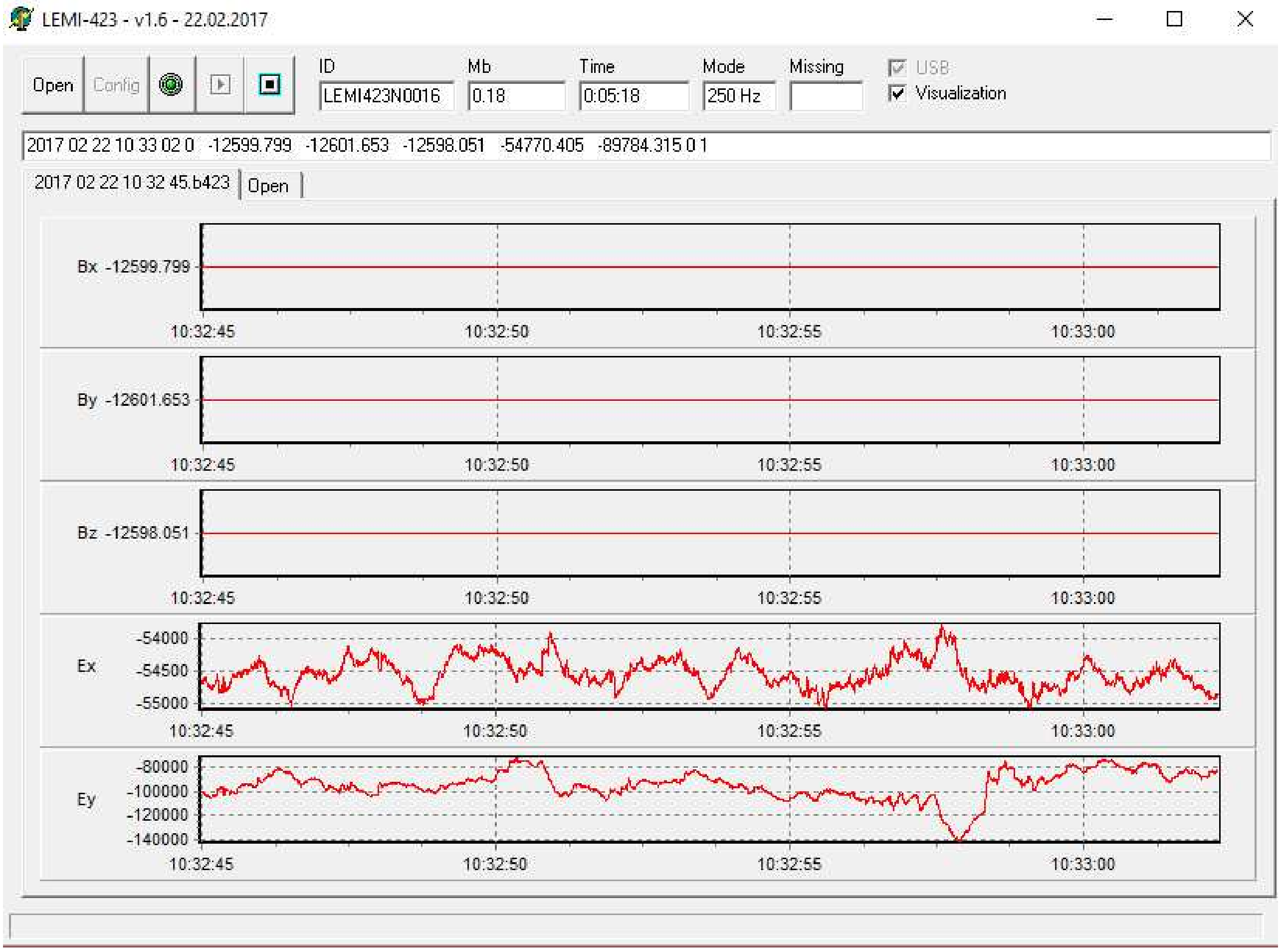


Fig.7.2 Main program window with tab # 1 in the file mode.

The tab # 2 («Open», second from upper left in Figs. 7.1 and 7.2) is intended for viewing the recorded files (the file is opened with «Open» button, see Operating with «File manager» window below).

If there is no MTS coupled, the program waits for the instrument connection (Fig. 7.3). If necessary to look-over the program operation without instrument connection, it is desirable to turn off the USB option).

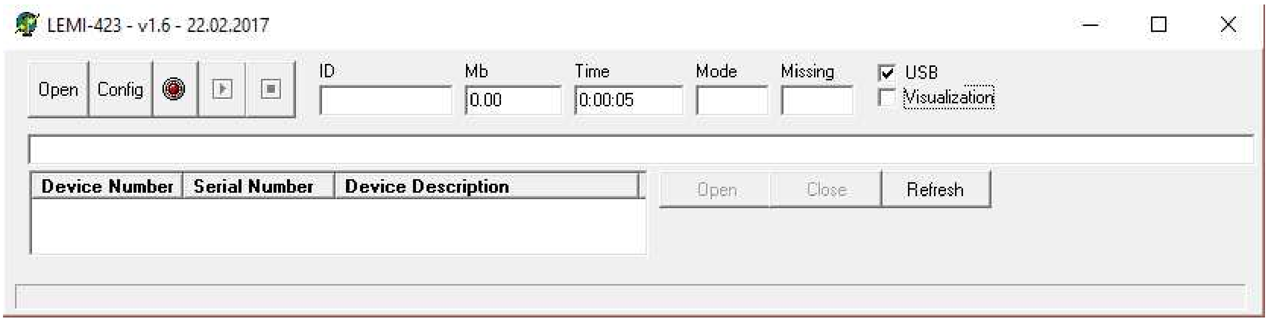


Fig. 7.3. Waiting for an instrument connection.

After a few seconds after the instrument connection, it is necessary to click «Refresh» button (Fig.7.3). If the instrument is found (Fig. 7.4) the program passes to the status mode (Fig. 7.1.) or in data record mode (Fig. 7.2) depending on the instrument operation mode at the moment.

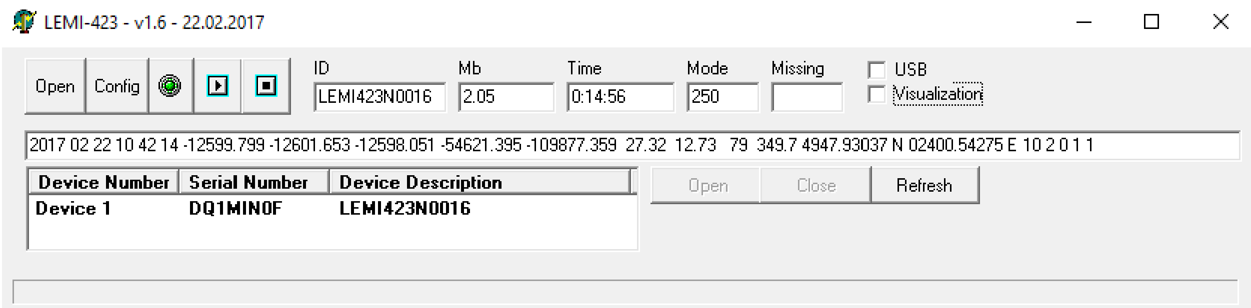


Fig. 7.4. The instrument is found.

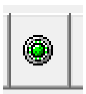
Indicative parameters in the main program window (Fig. 7.1)

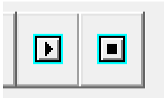
- **ID** – serial number.
- **Mb** – the number of Mbs, transferred to the program by the instrument.
- **Time** – the total time of the program operation.
- **Mode** – the current operating mode of the device.
- **Missing** – the number of missing data.

Control elements of the main window

«Open» - opening the window **«File manager»** to work with binary files (Fig. 7.5): visualization, decoding, testing.

«Config» - opening of the **«Config»** window (Fig. 7.6.), in which it is possible to select an operation mode of the instrument, see ID and calibration coefficients.

 **-** indication of synchronization ("green" - the instrument is synchronized or "Red" if not synchronized).

 **-** Start/stop data record (the buttons will not be active if the synchronization is failed).

«USB» - switch on (Fig. 7.3) or off (Fig. 7.4) the operation with MTS via USB-port. If operation of the program with MTS through USB-port is turned off the data processing in the window «File manager» will be faster because the data from the MTS will not be processed.

«Visualization» - data visualization switched on/off (data record to the file at the same time is not interrupted).

Operation with window «File manager»

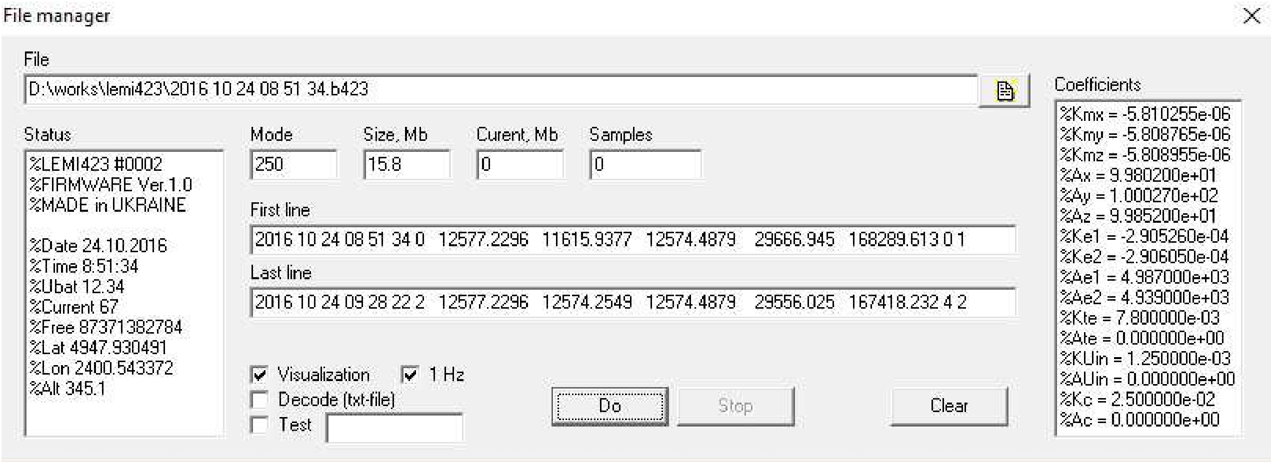


Fig.7.5. «File manager» window.

The window «File manager» is intended for visualization, decoding and testing of binary files. When a file is selected, a header of the binary file is read in the window “**File”** at Fig. 7.5, as well as the first and the last data are recorded in corresponding windows. “**Do”** button starts the process of decoding/visualization/testing of the files.

Control buttons in the window:

- **Visualization** – switch on/ switch off the visualization of binary files.
- **1 Hz** – switch on/ switch off the data visualization with 1Hz frequency.
- **Decode** - switch on/ switch off the decoding of binary file into the text one.
- **Test** - switch on/switch off the data testing.
- **Clear** – empty all fields in the window (also empties visualization window).
- **Do** - starts file decoding/visualization/testing.
- **Stop** - allows the process of file decoding/visualization/file testing interruption.

Operation in this window is carried out in the background mode; because of this the data decoding/visualization/ testing will be slowed down, if the USB port is enabled and there is a data stream from the instrument.

When the file visualization, the tab (№2) will be named after the opened file.

Fragment of decoded data:

2016 02 05 12 02 02 0	-943283.483	-20517.001	-946725.443	-2430937.137	-792053.407	-1	1
2016 02 05 12 02 02 1	-943281.075	-20519.193	-946721.784	-2430937.137	-792055.714	-1	1
2016 02 05 12 02 02 2	-943278.887	-20526.232	-946737.879	-2430937.137	-792055.152	-1	1
2016 02 05 12 02 02 3	-943281.583	-20539.420	-946741.293	-2430937.137	-792057.291	-1	1
2016 02 05 12 02 02 4	-943282.890	-20533.823	-946741.605	-2430937.137	-792058.315	-1	1
2016 02 05 12 02 02 5	-943278.409	-20514.202	-946752.200	-2430937.137	-792055.402	-1	1

It contains: date, time, number of the sample within the second (0-3999), data of 3 magnetic channels, 2 electric channels, deviation from PPS, PLL accuracy).

Operation in «Config» window.

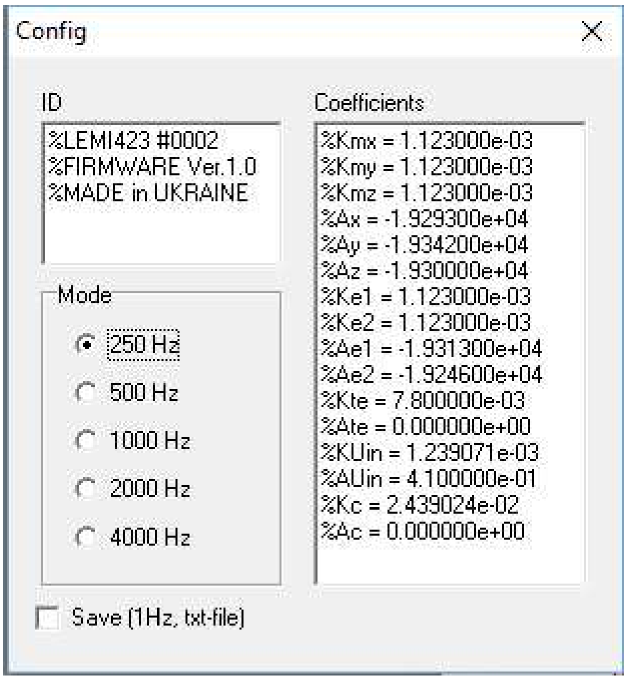


Fig. 7.6. «Config» window.

This window is called with «Config» button. From this window it is possible to:

1. View ID information about the instrument.

2. Change the operation mode of the station (1-250Hz, 2-500Hz, 3-1000Hz, 4-2000Hz, 5-4000Hz).

3. View the current calibration coefficients.

4. Enable/disable the status bar record (more details about the status bar see "Status bar parameters") to «lemi.s423» text file.

5. When tick **Save**, the 1-second data from Status line will be recorder to PC hard disc. By this following **«lemi.s423»** file will be stored:

Fragment of «lemi.s423» file:

```
2017 02 22 10 45 23 -12599.799 -12601.653 -12598.051 -54829.824 -104977.578  27.28  12.73   80  351.4 4947.93173 N 02400.54383 E 10 2 0 1 1
2017 02 22 10 45 24 -12599.799 -12601.653 -12598.051 -54546.023 -109122.359  27.21  12.73   77  351.4 4947.93172 N 02400.54381 E 10 2 0 1 1
2017 02 22 10 45 25 -12599.799 -12601.653 -12598.051 -54727.781 -110839.398  27.22  12.73   78  351.5 4947.93172 N 02400.54380 E 10 2 0 1 1
2017 02 22 10 45 26 -12599.799 -12601.653 -12598.051 -54342.594 -108333.531  27.27  12.73   79  351.6 4947.93176 N 02400.54382 E 10 2 0 1 1
2017 02 22 10 45 27 -12599.799 -12601.653 -12598.051 -54022.391 -108844.367  27.28  12.74   77  351.7 4947.93176 N 02400.54383 E 10 2 0 1 1
2017 02 22 10 45 28 -12599.799 -12601.653 -12598.051 -54363.125 -97911.320  27.20  12.73   77  352.1 4947.93171 N 02400.54392 E 10 2 0 1 1
2017 02 22 10 45 29 -12599.799 -12601.653 -12598.051 -54592.930 -103392.211  27.26  12.74   78  352.2 4947.93172 N 02400.54400 E 10 2 0 1 1
2017 02 22 10 45 30 -12599.799 -12601.653 -12598.051 -54471.727 -108925.383  27.25  12.74   78  352.2 4947.93184 N 02400.54412 E 10 2 0 1 1
```

Status bar parameters

The status line has following dimensions:

«2017 02 22 10 37 34 -12599.799 -12601.653 -12598.051 -54628.535 -95448.398 27.34 12.73 78 355.0 4947.93085 N 02400.54616 E 12 2 0 1 1».

The explication is below:

1	2017 02 22	UTC date
2	10 37 34	UTC time
3	-12599.799 -12601.653 -12598.051	3 magnetic channels
4	-54628.535 -95448.398	2 electric channels
5	27.13	temperature, ^{o}C
6	12.45	voltage, B
7	66	consumption current, mA
8	361.1 4947.920696 N 02400.537864 E	GPS data(altitude, latitude, longitude)
9	12	Number of satellites
10	2	GPS accuracy
11	0	Deviation from PPS
12	1	PLL accuracy
13	1	Operation mode (1–250Hz, 2–500Hz, 3–1000Hz, 4–2000Hz, 5–4000Hz)

Binary data files

The name of binary data file is created automatically from UTC time as follows (example): “2017 01 15 13 50 00.b423”. This structure contains: yyyy mm dd hh nn ss.b423, where yyyy - year, mm - month, dd - day, hh - hour, nn- minute, ss – second, b423 – file extension.

At the beginning of each binary file there is a text header of 1024 bytes size, and then data in binary format follows.

An example of file header:

```
%LEMI423 #0016
%FIRMWARE Ver.2.0
%MADE in UKRAINE

%Date 22.02.2017
%Time 10:32:45
%Ubat 12.73
%Current 77
%Free 24491786240
%Lat 4947.93273
%Lon 2400.54522
%Alt 355

%Kmx = 5.820760e-06
%Kmy = 5.821640e-06
%Kmz = 5.819960e-06
%Ax = -9.981200e+01
%Ay = -9.977600e+01
%Az = -9.978200e+01
%Ke1 = 2.912260e-04
%Ke2 = 2.911620e-04
%Ae1 = -5.005000e+03
%Ae2 = -4.979000e+03
%Kte = 7.800000e-03
%Ate = 0.000000e+00
%KUin = 1.250000e-03
%AUin = 0.000000e+00
%Kc = 2.500000e-02
%Ac = 0.000000e+00
```

8. STORAGE AND TRANSPORTATION

1. MTS storage conditions:
   - Temperature - from +5 to +40 °C;
   - Relative humidity - not more than 85%.
2. MTS can be transported by any transporting vehicles without limitation
3. During storage and transportation the shocks more than 5 g are inadmissible.
4. As MTS housing is hermetically sealed it is very desirable to keep under the MTS cover the Peli™ desiccant cartridge with dry silica gel (Peli ref. number 1500D) to prevent water condensation from trapped air when case is opened in high humidity condition or an ambient temperature is decreased.
5. A user has to check periodically the color of the silica gel through the inspection window at the cartridge. When it becomes pink, the cartridge has to be reactivated by oven drying at 150 °C during 3 hours.
6. In order to keep the silica gel desiccant active as long as possible, try to keep the case lid closed all the time during operation and storage of the MTS.
7. To remove the cartridge for silica gel drying two fixing screws (at the lower surface of the case cover) have to be loosened. After drying, install the cartridge back and carefully fix it by screws.

IMPORTANT!

The electrodes have to be washed by spring- or rainwater after use. If a short break between the measurements is expected (up to one week), it is allowed to put the electrodes in the common can with clay-$CuSO_4$ suspension. If longer break is expected, put the electrodes back in their containers. Before this, moisture the porous plastic at the container bottom with 10% $CuSO_4$ solution (see Manual below).

Any questions about MTS exploitation and operation can be sent to designers:

vakor@isr.lviv.ua **– general and electrodes**

pristaj@isr.lviv.ua **– MTS**

leon@isr.lviv.ua **–LEMI-423 operation program**

APPENDIX A

LEMI-423 electronic unit measuring channels frequency and phase response (both for electric and magnetic channels)

The digital filter receives the signal from modulator output and decimates the data stream. By adjusting the amount of filtering, tradeoffs can be made between resolution and data rate: filter more for higher resolution, filter less for higher data rate.

The digital filter is comprised of two cascaded filter stages: a variable-decimation, fifth-order sinc filter; a fixed-decimation FIR, low-pass filter (LPF) with linear phase. For more information see http://focus.ti.com/docs/prod/folders/print/ads1281.html document.

Bandwidth for each data rate:

DATA RATE	FILTER	-3dB BW (Hz)
250	FIR	103
500	FIR	206
1000	FIR	413
2000	FIR	826
4000	FIR	1652

Induction coil magnetometers LEMI-120 frequency and phase responses

The first column contains frequency in Hz, the following columns contain transformation factor(s) values in mV/nT and phase shift in degrees of angle between input and output signals. Both are measured with error 2 %

For all magnetometers, the parameters at 0.0001 Hz, 0.001 Hz, and 0.01 Hz are obtained by calculation.

f, Hz	0.00011	0.0011	0.011
S, mV/nT	0.02	0.2	2
Phase, °	90	90	89

LEMI-120 №641

f, Hz	S, mV/nT	Phaze, °
2.1000E-2	1.876E0	8.8074E1
3.1770E-2	2.918E0	8.7675E1
4.8062E-2	4.478E0	8.7968E1
7.2711E-2	6.633E0	8.6284E1
1.1000E-1	1.010E1	8.3758E1
1.3249E-1	1.210E1	8.3558E1
1.5959E-1	1.391E1	8.0998E1
1.9222E-1	1.695E1	8.0482E1
2.3153E-1	2.048E1	7.8659E1
2.7888E-1	2.483E1	7.5947E1

3.3590E-1	2.895E1	7.4084E1
4.0459E-1	3.493E1	6.9931E1
4.8733E-1	4.092E1	6.5732E1
5.8698E-1	4.654E1	6.2221E1
7.0702E-1	5.400E1	5.7255E1
8.5160E-1	6.141E1	5.1741E1
1.0257E0	6.952E1	4.6814E1
1.2355E0	7.494E1	4.1120E1
1.4881E0	8.065E1	3.6146E1
1.7925E0	8.551E1	3.1124E1
2.1590E0	8.947E1	2.5770E1
2.6005E0	9.222E1	2.2093E1
3.1323E0	9.454E1	1.8263E1
3.7728E0	9.607E1	1.5093E1
4.5443E0	9.739E1	1.2454E1
5.4736E0	9.819E1	9.8238E0
6.5929E0	9.881E1	7.6967E0
7.9411E0	9.917E1	5.6445E0
9.5649E0	9.937E1	3.9419E0
1.1521E1	9.963E1	2.2939E0
1.3877E1	9.985E1	7.2162E-1
1.6715E1	9.991E1	-8.8516E-1
2.0132E1	1.000E2	-2.4259E0
2.4249E1	9.996E1	-4.0446E0
2.9208E1	9.997E1	-5.8066E0
3.5181E1	1.001E2	-7.8255E0
4.2375E1	1.001E2	-9.9146E0
5.1041E1	1.022E2	-1.2780E1
6.1478E1	9.996E1	-1.5929E1
7.4050E1	1.002E2	-1.9463E1
8.9192E1	1.000E2	-2.3715E1
1.0743E2	1.002E2	-2.8957E1
1.2940E2	1.001E2	-3.5051E1
1.5586E2	1.000E2	-4.2442E1
1.8773E2	1.000E2	-5.1407E1
2.2612E2	9.989E1	-6.2288E1
2.7236E2	9.957E1	-7.5531E1
3.2806E2	9.882E1	-9.1566E1
3.9514E2	9.754E1	-1.1139E2
4.7595E2	9.473E1	-1.3554E2
5.7328E2	9.008E1	-1.6487E2
6.9050E2	8.380E1	1.5961E2
8.3171E2	7.761E1	1.1514E2
1.0018E3	7.170E1	4.9153E1

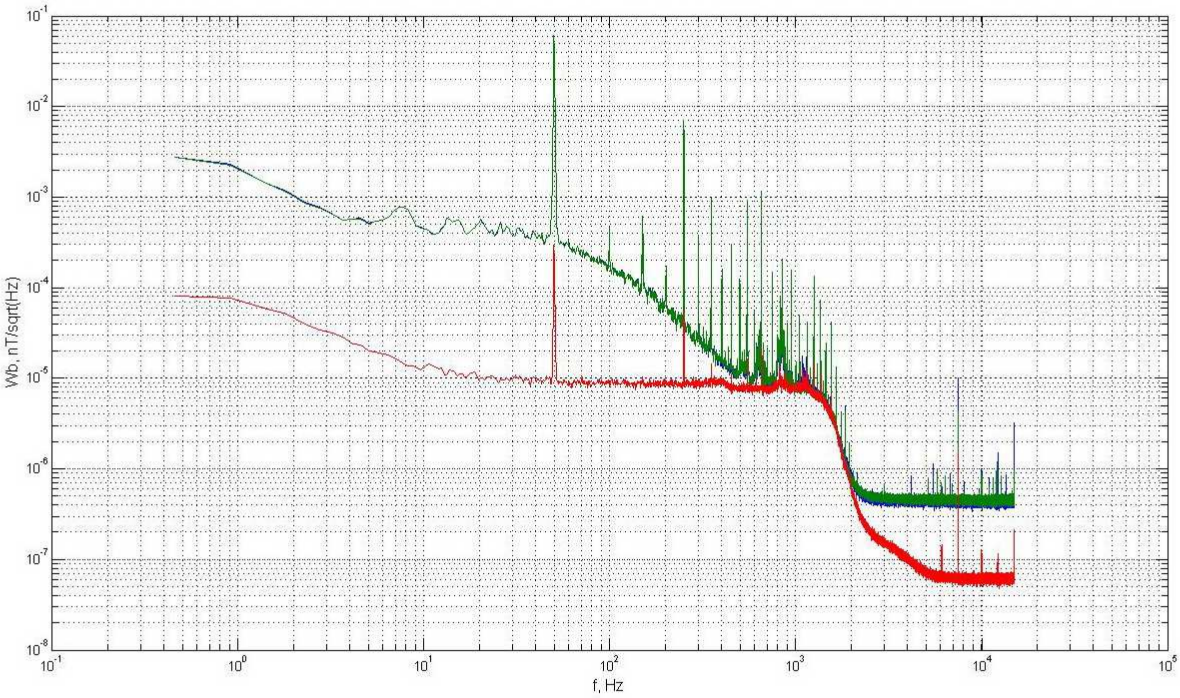
LEMI-120 N644

2.1000E-2	1.923E0	8.9170E1
3.1770E-2	2.900E0	8.8462E1
4.8062E-2	4.399E0	8.7364E1
7.2711E-2	6.650E0	8.6322E1
1.1000E-1	1.002E1	8.4264E1
1.3249E-1	1.219E1	8.3491E1
1.5959E-1	1.433E1	8.3726E1
1.9222E-1	1.736E1	8.0267E1
2.3153E-1	2.042E1	7.6944E1
2.7888E-1	2.456E1	7.5477E1
3.3590E-1	2.906E1	7.3349E1
4.0459E-1	3.472E1	7.0558E1
4.8733E-1	4.040E1	6.6627E1

5.8698E-1	4.737E1	6.1710E1
7.0702E-1	5.445E1	5.7170E1
8.5160E-1	6.120E1	5.1583E1
1.0257E0	6.855E1	4.6502E1
1.2355E0	7.495E1	4.1634E1
1.4881E0	8.045E1	3.5968E1
1.7925E0	8.555E1	3.0899E1
2.1590E0	8.950E1	2.6262E1
2.6005E0	9.260E1	2.2195E1
3.1323E0	9.470E1	1.8627E1
3.7728E0	9.610E1	1.5084E1
4.5443E0	9.710E1	1.2230E1
5.4736E0	9.800E1	9.8118E0
6.5929E0	9.865E1	7.6440E0
7.9411E0	9.910E1	5.6541E0
9.5649E0	9.935E1	3.8653E0
1.1521E1	9.955E1	2.3060E0
1.3877E1	9.970E1	7.6407E-1
1.6715E1	9.980E1	-7.8710E-1
2.0132E1	9.985E1	-2.3826E0
2.4249E1	9.995E1	-4.0052E0
2.9208E1	1.000E2	-5.7664E0
3.5181E1	1.000E2	-7.7687E0
4.2375E1	1.003E2	-1.0064E1
5.1041E1	1.011E2	-1.3348E1
6.1478E1	1.000E2	-1.5726E1
7.4050E1	1.001E2	-1.9214E1
8.9192E1	1.001E2	-2.3532E1
1.0743E2	1.001E2	-2.8582E1
1.2940E2	1.002E2	-3.4718E1
1.5586E2	1.002E2	-4.2073E1
1.8773E2	1.003E2	-5.0971E1
2.2612E2	1.003E2	-6.1797E1
2.7236E2	1.002E2	-7.4966E1
3.2806E2	9.970E1	-9.0935E1
3.9514E2	9.880E1	-1.1082E2
4.7595E2	9.625E1	-1.3509E2
5.7328E2	9.175E1	-1.6459E2
6.9050E2	8.535E1	1.5961E2
8.3171E2	7.865E1	1.1482E2
1.0018E3	7.095E1	4.9698E1

Appendix B. Typical noise spectral density

Noise spectral density was measured in the field by subtraction of output signals of the two magnetometers placed in similar conditions. Green and blue curves are output signals spectra of two LEMI-120 magnetometers. The red curve is noise level of LEMI-120 magnetometer.



Appendix C. Selecting the measurements site and conditions

Important!

The induction sensors are very sensitive to the mechanical movements and vibrations. It is recommended to follow the advice below in order to realize their full sensitivity.

1) The measurement should be carried out in the electromagnetically clean area and users should take into account possible magnetic signals from, e.g., nearby thunderstorms, solar bursts etc. The sensor should be located as far as possible from mains power lines and large ferromagnetic objects. It is difficult to give accurate recommendations about the distance to them as it depends on the magnetic moment of such objects; the maximal distance between the sensors and registration unit should be no more than 200 m (recommended at least about 100 m). For example, we can clearly observe the process of car doors opening and closing at distances of about 25 meters. Do not select measurement sites near large trees - strong wind will produce soil oscillations and consequently sensor vibration. The distances between each of the three sensors in a three-component array have to be not less than 2 meters.

2) Every effort should be made to provide a stable position for the sensor (FYI, only 1" rotation of the sensor in the Earth magnetic field may produce ~250 pT of parasitic signal). In order to ensure a stable position, it is necessary to make beds (holes) with concrete walls for permanent installations.

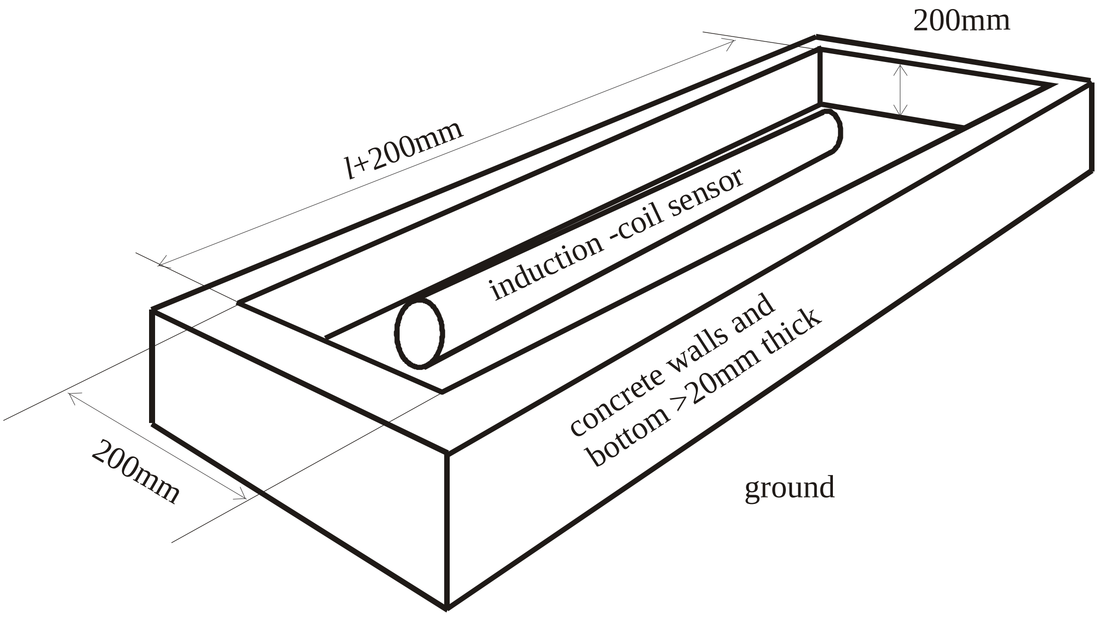


Fig. 5. LEMI sensor permanent installation site

All dimensions of the sensor hole are given for orientation - any deviations in the bigger side are possible. The hole has to be covered with any hut against rain and wind, the external dimensions of which have to be at least 20 mm bigger than the hole dimensions. The hut has to be made from the non-magnetic and non-conductive material. It is necessary to foresee small gaps between the inner part of the hut and the edges of concrete walls in order to allow the outer air inside freely.

The edges of the concrete walls have to be at least 50-100 mm above the ground level in order to protect from water when covered by the hut.

To avoid water and moisture penetration into the connector, we recommend encapsulating connector and the adjacent part of the cable (~10-15 cm) together into heat-shrinkage insulation tube.

If there are microseisms supposed in the region it is advisable to fill the concrete bed to half of depth with an elastic material such as soft polyurethane, and to put the sensor on top of it, then to press from above by the heavy bag with sand. The first three to five meters of cable connected to the sensor must also be buried.

3) When installing a temporary station it is necessary to bury the sensor in the ground at the depth not less than 2-3 sensor diameters, to pile up about 2-3 cm layer of the sand on the bottom, put then the sensor and press from above by the bag with sand. Such an installation procedure allows for avoiding influence due to blowing the wind and decreases sensor temperature fluctuations. If burying the sensor and cable is not possible (e.g., rocky ground) it is advisable that you put the heavy bag with sand on the sensor and cover against the rain.

4) Proceed as follows to connect the sensor to the acquisition system. Prepare a sensor cable, preferably shorter than 200 m, which should contain three twisted wires for the power supply, a shielded twisted pairs for the signal and one wire for analog ground.

5) It is important that a good quality power supply be used, especially when working in the high-frequency range. The best way to ensure this is to use a battery placed on an insulating cover such as polyethylene film.

When using DC-DC transformers in the receiving equipment, ensure that they do not produce noise, especially spikes, in their input circuits.

6) Earthing of the analog ground and common power supply lines is necessary and it is advisable that this grounding is made according to "star" system - in one point, using a buried copper stick to connect to it all ground wires together.

The lead-free non-polarized electrodes LEMI-701

The lead-free non-polarized electrodes LEMI-701 are for the measurement of the electric field variations in the soil.

The quality of the electrodes used for electric field measurements in magnetotelluric (MT) soundings is the main limitation in accuracy, corresponding to the reliability of the resulting Earth models. Different types of electrodes as well as different materials are used to provide as low as possible electrode noise and long-term drift. The most common materials for non-polarized electrodes are combinations Ag-AgCl and Pb-PbCl (Petiau and Dupis, 1980). The latter is reported to be best (Petiau, 2000).

Recently, the new directive (Dir. 2011/65/EU (RoHS 2) of the European Parliament and of the Council of 2 January 2013) was adopted in Europe requiring elimination of lead and lead composites from use in every application. This led to the development of other electrode construction and materials. As a starting point, a standard Schlumberger electrode based on copper - copper sulphate was used. Its drawbacks were studied (Korepanov and Svenson, 2007), and new improved non-polarized electrode construction LEMI-701 based on Cu-$CuSO_4$ combination was developed.

Our long-term study revealed that the new LEMI-701 geophysical electrodes, besides their ecological safety, also have considerable metrological advantages compared to Pb-PbCl ones. The measured noise of randomly selected pair LEMI-701 non-polarized electrodes was ~20 nV at 1 Hz versus 0.4 µV for Pb-PbCl (Petiau and Dupis, 1980). For a matched pair selected by using a test assembly and special selection procedure, the drift over about 4 months was approximately 50 microvolt versus 1 mV/month for Pb-PbCl (Petiau and Dupis, 1980). The new electrode is shown in Figure 1 and in its transportation container in Figure 2 and the view of the contact surface made from porous ceramic, in Figure 3.

Figure 1: LEMI-701 non-polarized electrode.

Figure 2: Non-polarized electrode in its protective container.

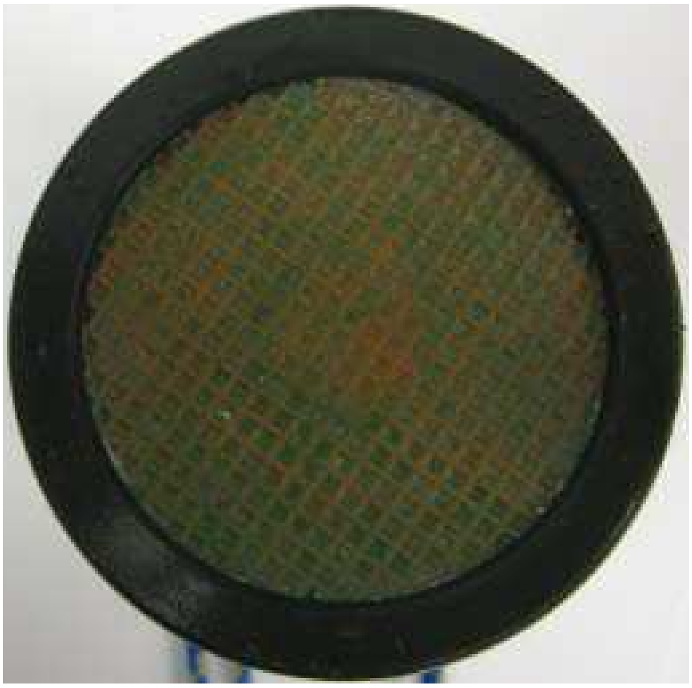


Figure 3: Electrode ceramic contact surface

The plot of LEMI-701 electrode noise density mean value spectral dependence is demonstrated in Figure 4.

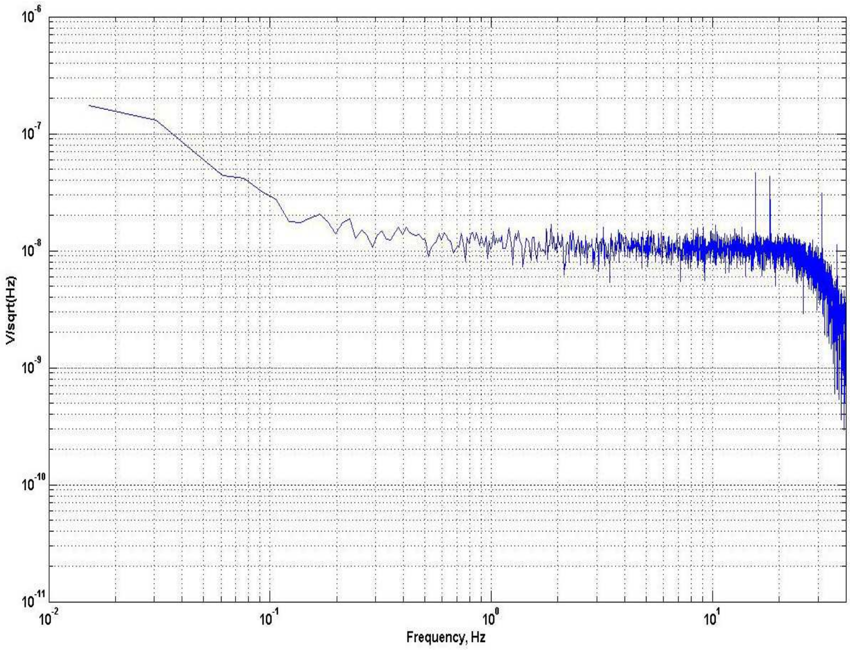


Figure 4: LEMI-701 electrode spectral noise density (mean value).

The next advantage of these electrodes is that, if all storage and handling requirements, as given in the Operation Manual are fulfilled, they do not need any maintenance during all their service life.

In Figure 5 the results of short-period (5 day) tests for selected matched pairs are given which show the worst-case rms error of about 13 µV.

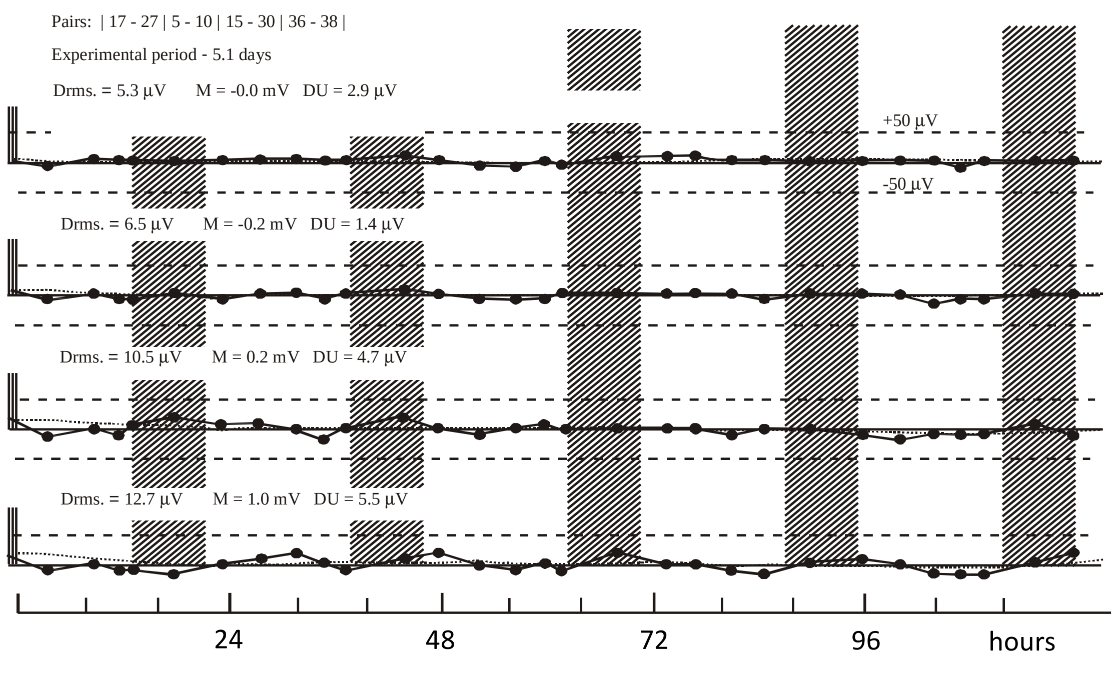


Figure 5: Drift of selected electrode pairs (short term): Drms – root mean square error; M – baseline shift; DU – averaged dispersion.

There is the possibility to restore their workability even after improper use or after drying or long-term storage. The conditions of this are the absence of the mechanical damages and enough big amounts of electrodes (minimum 10). If these conditions are fulfilled, it is necessary to install all available electrodes in a tank with 10% $CuSO_4$ solution and keep there minimum for a week. Then the electrodes may be re-used as they are, but already not in matched pairs combination providing minimal temporal drift. If again, minimal drift is required, the selection procedure exposed in (Korepanov and Svenson, 2007), should be used to combine matched pairs.

REFERENCES

Petiau, G., and Dupis, A., 1980. Noise, temperature coefficient and long time stability of electrodes for telluric observations. Geoph. Prospecting. 28 (5), 792-804.

Petiau, G., 2000. Second generation of lead-lead chloride electrodes for geophysical applications. Pure and Appl. Geophysics, 157 (3), 351-382.

Korepanov, V. E., and Svenson, A. N., 2007. High precision non-polarized electrodes for field geophysical prospecting. NAUKOVA DUMKA, Kiev, Ukraine, 96, (in Russian).

INSTALLATION PROCEDURE

Important! Special attention has to be paid to the electrode installation procedure, especially if long- term measurements are required. The best results may be used if the procedure given below will be strictly followed.

STEP 1: Select the proper places for the electrodes burial. It is important to choose similar places for the two electrodes in one line. The requirements are: similar soil composition, orographic features (i.e., hill-hill or valley-valley, same sun exposure), and especially the moisture conditions. Clayish grounds are recommended for long-term measurements as they keep the moisture longer.

STEP 2: Dig the electrode holes (deeper for long term - > 1 day and shallower for shorter recordings). Practice shows that for the majority of soils, a hole depth of about 70 - 80 cm is enough to avoid daily thermal variations. Make at the hole bottom a cylindrical hollow with a diameter of ~7-8 cm and depth ~15-18 cm. (A bottle is a useful tool to form this).

STEP 3: Next, the clayish suspension has to be prepared (about 3 liters for each electrode pair depending upon moisture condition). For this, light-colored clay has to be taken which does not contain ferrous oxides and calcareous impurities. To check this, about 200 g of clay is diluted with distilled (or at least boiled) water in a plastic can to form the consistency similar to yoghurt. Then add a 10% CuSO4 solution, stir it thoroughly and leave it for about 1 hour. The clay will deemed suitable if it conserves a blue color after this time. Instead of clay you can also use Bentonite.

STEP 4: For wetting the electrode plant, a suitable amount of clay is mixed with 10% CuSO4 solution (in as clean as possible water) into a yoghurt consistency emulsion (~ 3 liters for each electrode pair).

STEP 5: Take matched pair of electrodes (they are marked!) and remove them from their protective transportation containers. Each electrode fits tightly into these containers to avoid leakage of the $CuSO_4$ solution (the soft insert at the container bottom is impregnated with it). Pull the electrode from the container gently by hand, softly swinging it laterally. Do not pull it with force, especially by cable, as this may damage electrode!

STEP 6: Put extracted electrodes in the plastic can with the prepared clay-$CuSO_4$ mixture and keep them there until the moment of installation into the ground (at least for 15 minutes). Several pairs can be placed in one plastic can.

It is recommended to check the electrode pair transient resistance before and after installation!

For this, use a voltmeter with an input resistance >10 MOhm, 10 μV resolution and a 3-5 kOhm reference resistor R. First, connect the voltmeter to the electrodes output (of each matched pair in the can) and measure the voltage U1. Then connect to both electrode outputs of the pair the reference resistor R for a short time and measure the voltage U2. Then the value of transient resistance Rl has to be calculated as:

$$R_l = \frac{R(U1 - U2)}{U2}$$

Normally, the value of this resistance in the can is within 200-300 Ohm or lower.

STEP 7: In order to remove the electrodes safely back after measurements the pull cord on the electrodes is twisted and for long-time recording installation fixed to the electrode surface with adhesive tape. This will help to pull electrodes out without damaging them. Not following this may damage the electrodes, especially for heavy clayish and stony soils.

STEP 8: Just before the installation, take ~1.5 liters of emulsion from the can, and mix it with the soil taken directly from the bottom of the hole

STEP 9: Implant a pair of electrodes from the can into the hollow at holes bottom as follows: for long-time recording we recommend to install electrodes “bottom-up” (see Figure 6a); for short-time (≈ 1-2 days) in a tilted position as shown in Figure 6b.

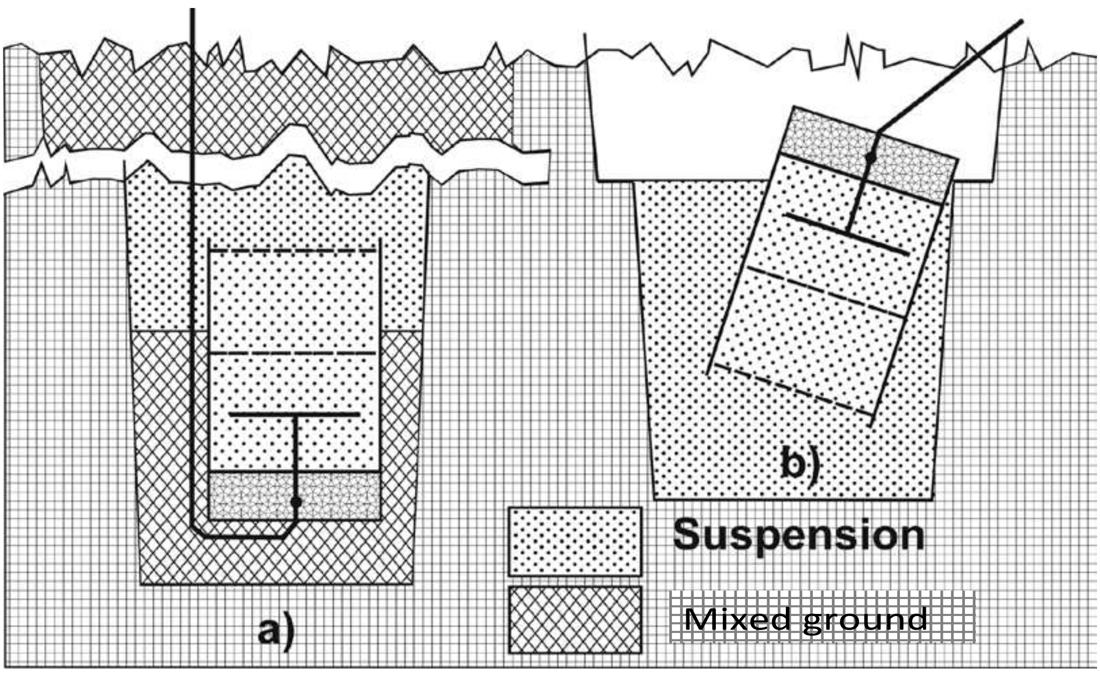


Figure 6: Electrode installation in operation position: a- left – long-time; b- right – short-time.

For this type of electrode, we DO NOT recommend to install the electrodes in a vertical position.

This is because the Cu-$CuSO_4$ solution in the water may produce free oxygen O_2 due to its dissociation even with very small currents flowing through the electrodes (often caused by wrong transient resistance measurements, particularly when an ohmmeter is directly applied to the electrodes). If the electrode is not tilted, oxygen is gathered below its ceramic partition, and significantly increases the transient resistance.

STEP 10 (a): For long-term recordings, as recommended, put the electrode in the hole with the contact surface up (Figure 9a).

- First fill in the hollow with soil taken from the hole bottom to cover approximately half of the electrode length.
- Pour the prepared mixture of emulsion & soil in the hole until you cover the sensitive part of the electrode by a layer of ~3-5 cm.
- Fill the hole with remaining ground.

After the hole is filled, water it with spring- or rainwater taken in the area (approximately 10 liters per one hole) and then cover with a plastic about 1x1 meter in size. This will protect the electrodes from instantaneous potential changes caused by rain.

STEP 10 (b): For short-time recordings fill the hollow with the emulsion/soil mixture, and again, fill up the hole with the ground taken from the hole and cover it with plastic.

STEP 11: The instrument cables are connected first to the electrode wires. In recent versions a special contact socket may be provided as shown in Figure 7. If a terminal box as given here is used, to the other end of the electrode line a fork-type contact has to be fixed for convenience (Figure 8).

STEP 12: To connect the cables to terminal box, the terminals are released, and then the cable ends are inserted into them and tightly fixed with plastic nuts observing the polarity of lines and nuts colors. For long-term recordings, to grease the connected places with any water-resistant grease is recommended. Also we recommended protecting the electric lines with plastic pipes or digging the lines into the ground at ~ 5 cm. This will help to protect them from animals.

STEP 12: To connect the cables to terminal box, the terminals are released, and then the cable ends are inserted into them and tightly fixed with plastic nuts observing the polarity of lines and nuts colors. For long-term recordings, to grease the connected places with any water-resistant grease is recommended. Also we recommended protecting the electric lines

with plastic pipes or digging the lines into the ground at ~ 5 cm. This will help to protect them from animals.

Figure 7: Electrode contact socket

Figure 8. Fork-type connector to connect an electric line to the terminal box

STEP 13: A special procedure is recommended for dry sand. A plastic can without the top has to be filled with local sand impregnated with a 10% solution of $CuSO_4$ and local spring or rainwater. The electrode is placed inside the can as for short- or long-time recordings. Then bury the plastic for ~1 m deep in the sand and cover it with foil.

STEP 14: For a stony or rocky ground the only solution is to look for local cracks and then try to widen / deepen them. In this case, it is possible that exact orthogonality of the electric array may not be possible. This needs to be measured to allow correction during the processing.

STEP 15: As it was stated, it is possible to use the LEMI electrodes that are not matched pairs as recommended, but in this case the initial voltage zero shift of the electrode pair may reach units of millivolts (no more than ~ 10) and its variations may be within ~ 100 microvolt.

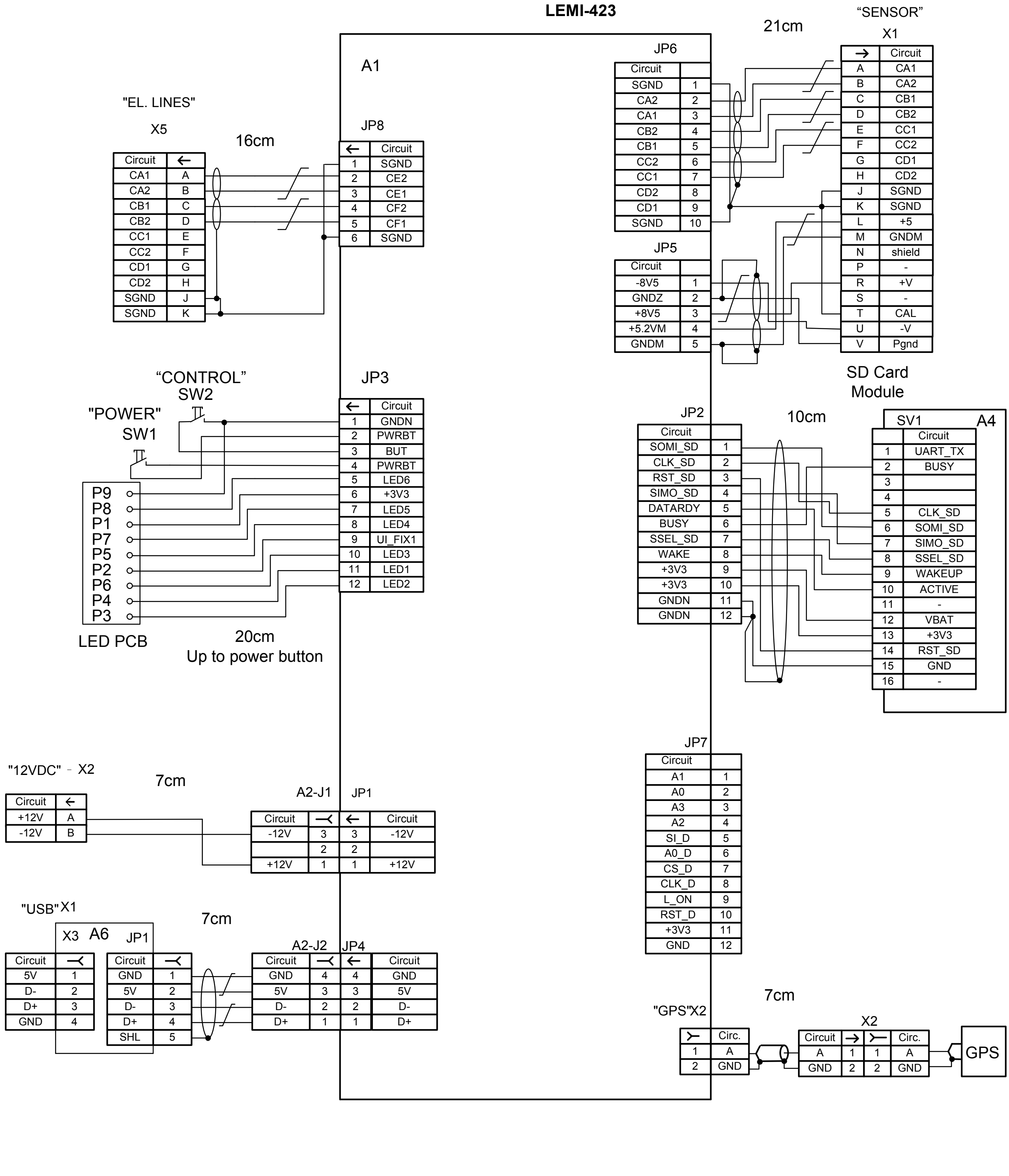
As recommended, just after installation of electrodes in the ground, the same procedure of the transient resistance Rl verification possibly with the similar R should be repeated. (Recommended value of Rl is < 20-50 kOhm for sandy soil and < 10 kOhm for clayish soil.)

STEP 16: After recording, take from the ground and wipe every electrode with a wet and clean rag and then pour a small amount of the 10% $CuSO_4$ solution into the transportation container to wet the soft material at the bottom. Then insert the electrodes as shown on Figure 2.

It is highly recommended to keep the matched electrodes pairs tied together for storage!

APPENDIX E

MTS connectors



The junction box for induction coils