MONITORING SYSTEMS FOR VERIFICATION OF MASS AND ENERGY TRANSPORT MODELS IN POROUS MEDIA

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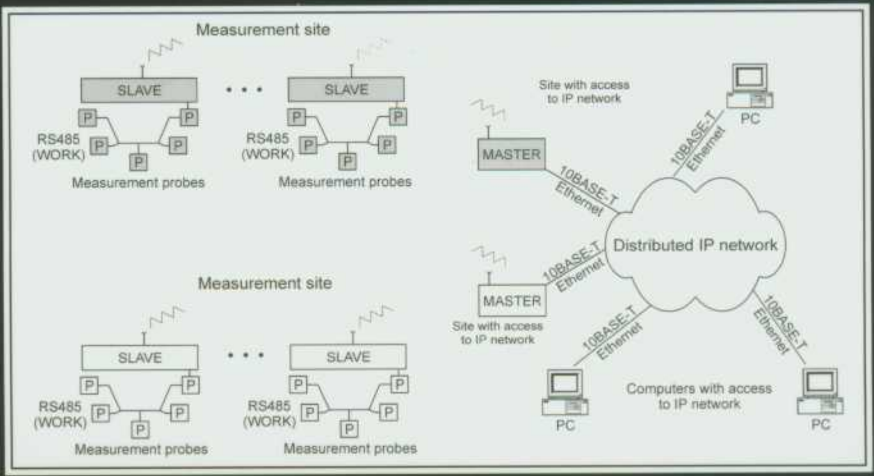

Centre of Excellence for Applied Physics in Sustainable Agriculture AGROPHYSICS

Institute of Agrophysics Polish Academy of Sciences

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PREFACE

The mechanisms for mass and energy transport in porous media include molecular liquid diffusion, molecular vapour diffusion, capillary flow, convective transport, evaporation-condensation, pure hydrodynamic flow and movement due to gravity. The mass flux is affected by the temperature gradient, as well as by the pore network, which is difficult to describe in a given solid. The dominant mechanism under a specific set of conditions in a particular material is often unknown and it is more likely that the mass and energy transport results from a combination of mechanisms. In fact there is not a single theory that can be used to cover all situations in a porous solid. Due to these complications, theoretical models generally require assumptions that limit their applicability and a lot of measurement to verify them.

Recent advances in monitoring techniques and modelling fluxes of mass and energy in porous media enhanced the research tools in this problem. New devices, including soil moisture and salinity meters based on time domain reflectometry technique, provide better observations and higher accuracy of measurement. Better modelling techniques extend and extrapolate these observations providing improved understanding at larger spatial and temporal scales.

The development of electrical measurement methods and modelling of mass and energy transport in porous media are the objectives of Work Packages 1 and 2 of the European Centre of Excellence for Applied Physics in Sustainable Agriculture with the acronym AGROPHYSICS (Contract No. QLQM-2001-00428). The Institute of Agrophysics Polish Academy of Sciences has been honoured to conduct the Centre since March 2003 for the following three years. The objectives of WP2 and WP3 have been realized by many activities including: organization and participation of scientists from the Centre at Conferences, Workshops, Summer Schools, visits to European research organizations for exchange of experience, preparation of the Centre to collaborate in the international research programmes and publication of related material.

Our long-term objective is to extent the research activities beyond this period in the form of available instruments implemented in FP6 and other scientific programs of European Community. We hope that the presented monograph will be a small contribution for reaching it.

Prof. Ryszard T. Walczak
Director of the Institute of Agrophysics PAS in Lublin, Poland
Director of the Centre of Excellence AGROPHYSICS

CONTENTS

1. INTRODUCTION

The presented study tries to evaluate the elements of monitoring systems for verification of mass and energy transport models in porous media, developed and applied in research programs in the Institute of Agrophysics Polish Academy of Sciences in Lublin as well as in other cooperating scientific institutions all over the world.

The first chapter describes the accepted models giving the theoretical background for further description of measurement devices and systems. The following chapter gives a view of modern sensors and sensor networks equipped with identification and computation facilities and capable to communicate globally. Such systems can form a “smart dust” of sensors that can react on different environmental conditions providing information for further processing. This futuristic vision is far from implementation yet. There are many obstacles to omit: scientific, economical, political and even ethical. Not everyone wants to be followed and inspected without permission even if there are emergency reasons. The need for standardisation in the field of smart sensors and smart interfaces is obvious and some proposals based on the IEEE1451 standard are presented.

The following section gives examples of application of measurement devices of soil physical and chemical properties developed or in development in the Institute of Agrophysics Polish Academy of Sciences in Lublin, Poland. The main area of interest is the selectivity of measurements, development of sensors, which are smaller, faster, wireless, ‘smart’, cheaper and with decreased power demand. We focus our attention on the measurement of soil water content, soil water potential and concentration of selected ions in the soil, which we recognize as basic soil parameters influencing the others. Also we try to implement advanced technology arising from telecommunication and informatics. We present a modern data acquisition system for the application in field condition, especially in precision agriculture, working in real time and equipped with identification, localization features as well as advanced telecommunication systems for the wireless exchange of information.

2. MODELLING OF WATER AND HEAT MOVEMENT IN THE SOIL

For the description of this process the mass conservation law is used, expressed by the equation of continuity, which for solenoidal field can be written as:

$$\left(\frac{\partial\theta}{\partial t}\right)+\nabla\vec{q}=0\,, \tag{1}$$

and for the field with sources:

$$\left(\frac{\partial\theta}{\partial t}\right)+\nabla\cdot\vec{q}=f(\vec{r},t)\,, \tag{2}$$

Comparing the equation of continuity for a field with sources with Darcy equation of water flow in unsaturated zone:

$$\vec{q}=K(\theta)\cdot grad\Psi\ , \tag{3}$$

the Richard's equation is obtained in the form:

$$\frac{\partial\theta}{\partial t}=-\nabla\cdot K(\theta)grad\Psi+F(\vec{r},t)\,, \tag{4}$$

where: θ - water flux, $K(\theta)$ - water conductivity coefficient in unsaturated zone, θ - soil water content, Ψ - soil water potential, $F(\vec{r},t)$ - source function (*eg* water uptake by the roots, watering-dewatering drainage systems).

By solving Richard's equation for given initial and boundary conditions it is possible to predict the dynamics of soil water content changes in the soil profile. For stability of solving the differential equation (*eg* Richards equation), the errors of its solution generated in successive time steps should be of decreasing amplitude.

The main source of the heat provided to the soil is solar energy. This energy is transformed on the active surface, which is the soil surface with plants growing on it. The heat flow in the soil can occur by conduction, radiation, the change of water aggregation state and convection. The heat radiation is a process, which consists in energy emission in the form of electromagnetic radiation. The convection is a process of moving of the energy stored in the soil air. The heat transport as a result of changing of water physical state consists in evaporation of water in some soil parts and its condensation in some other parts. The energy flow as radiation, convection and change of water aggregation state plays an important role on the soil surface. In the soil profile, the main way of heat transfer is the process of its conduction.

The process of heat transfer in the soil can be described by the equation proposed by Philip and De Vries [45]:

$$C\frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) - L\nabla \cdot (D_{\theta v} \nabla \theta), \tag{5}$$

where: C - the heat capacity [$\mathrm{Jm^{-3} \cdot K^{-1}}$], T - the temperature [K], t - the time [s], λ - the thermal conductivity [$\mathrm{Wm^{-1}K^{-1}}$], L - the latent heat of vaporisation of water [$\mathrm{Jm^{-3}}$], θ - the volumetric soil water content [$\mathrm{m^3m^{-3}}$], $D_{\theta v}$ - the water vapour diffusion coefficient in isothermal condition [$\mathrm{m^2s^{-1}}$].

This equation describes the three-dimensional heat transfer in a three-phase capillary-porous medium, which is the soil. The first term in this equation describes the process of heat conductivity under the temperature gradient, while the second term describes the heat transfer as a result of evaporation and condensation of water which term in reference to the heat transport in the soil profile can be omitted with good approximation [18].

As the result, the transport equation can be written in following way:

$$C\frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) \tag{6}$$

In general, the equations of heat and water transport in soil medium are second order non-linear differential equations because the coefficients are temperature and moisture dependent:

$$C\frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) - L\nabla \cdot (D_{\theta v} \nabla \theta), \tag{7}$$

$$\frac{\partial \theta}{\partial t} = -\nabla \cdot (D_{\theta} \nabla \theta) - \nabla \cdot (D_T \nabla T) - \nabla K, \tag{8}$$

In natural conditions, the periodical changes of temperature in particular layers of soil profile are noticed. These changes are observed for both daily (**Fig. 1** from Rose, 1968 [49]) and annual scales (**Table 1** from Carson and Moses, 1963 [14]).

Table 1. Soil temperature changes at Argonne, Illinois

Depth	Mean annual variation in temperature °C	Maximum daily variation in temperature °C
1 cm	25	12
10 cm	24	9
20 cm	23	3
50 cm	22	0.5
10 feet (304.8 cm)	8	0
29 feet (884 cm)	1	0

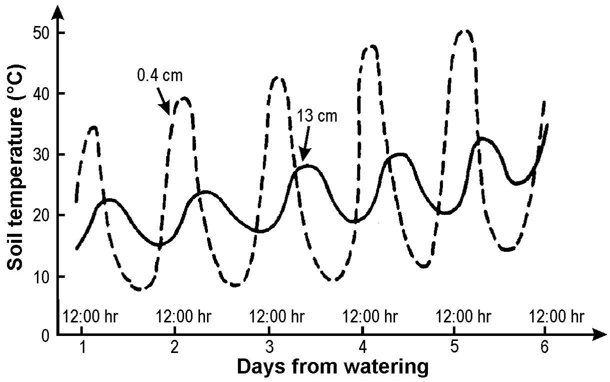


Fig. 1. History of soil temperature (in days) after watering at depths of 0.4 and 13 cm below the surface

Wijk and de Vries [73] assumed that diurnal changes in temperature might be described by a diminishing since wave (**Fig. 2**) as per the formula:

$$T_{z,t} = T_o - c \cdot z + T_a \exp\left(\frac{z}{d}\right) \sin\left(\omega t - \frac{z}{d}\right), \tag{9}$$

where: T_o – mean temperature of soil surface [°C], T_a – amplitude of temperature at soil surface [°C], c – coefficient of mean temperature changes with depth [°C cm^{-1}], z – depth [cm], t – time [s], ω – angular frequency [s^{-1}], d – attenuation depth [cm].

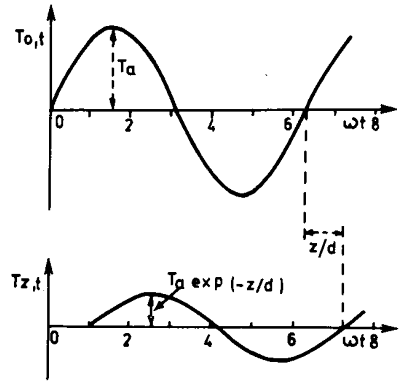


Fig. 2. Cycling variation of temperature at soil surface and at depth *z*

Knowledge of the soil hydrophysical characteristics is essential for the description, interpretation and prediction of the progress of practically all physical, chemical and biological processes in the soil-plant-atmosphere system. Modelling of these processes requires also representative data of the soil hydrophysical properties. Generally, the majority of the simulation-prognostic models describing the hydrophysical processes taking place in the soil-plant-atmosphere system are more efficient when the accuracy of the data describing the water characteristics of the soil are more accurate. Due to the large variability range of the water conductivity coefficient in the whole range of soil water potential values, the correct determination of its value is essential to acquire sufficient accuracy of the applied models.

There are a few methods found in literature for the determination of water conductivity coefficients of capillary-porous media in unsaturated zone. The evaporation method of Wind [62,75] is one of them. Bertuzzi et al. [7] presented the influence of the temperature effect, position of tensiometers in the soil column and their calibration as well as the stratification of the soil sample on the accuracy of determination of the water conductivity coefficient using this method. The authors emphasized on the decisive influence of the temperature change, the accuracy of the calibration curve determination and the non-homogeneity of the sample. Tamari et al. [60] presented the comparison of the water conductivity coefficient values in the non-saturated zone acquired by Wind method, modified Wind method and the instantaneous profiles method as the reference one.

The studies about the about the determination of water conductivity coefficients in the unsaturated zone by instantaneous profiles method began in the 60-ies of the former age [69], and continued in 70-ies. This method requires simultaneous measurements of water potential and moisture of the soil, therefore it was recognized as time consuming and demanding expensive and specialized measurement equipment, especially for moisture measurement [48]. With the development of the measurement techniques of capillary-porous media moisture, including TDR technique [35,36,56,61], the instantaneous profiles method is now being applied as a standard for the determination of the water conductivity coefficient in unsaturated zone in a number of scientific centres [25,48,56, 63,68], including the Institute of Agrophysics PAS.

3. SMART SENSORS AND SMART NETWORKS IN THE MEASUREMENT OF SOIL PARAMETERS

A sensor is the portion of a measurement system that responds directly to the physical variable being measured [22] such as thermal energy, electromagnetic energy, acoustic energy, pressure, magnetism, or motion by producing quantitative, usually electrical signals. Sensors are input devices of the measurement system while actuators are output devices translating electrical signals into usually mechanical actions. Transducers are defined as devices that convert one type of energy to another, for example temperature to an electrical signal. A sensible distinction is to use 'sensor' for the sensing element itself and 'transducer' for the sensing element plus any associated circuitry. All transducers would thus contain a sensor and most (though not all) sensors would also be transducers.

Smart transducers must incorporate some element of control, computation or decision-making. They enhance functionality, performance or cost of the measurement system.

Sensors and actuators are everywhere: at home appliances, in the office, in factories etc., and they are intended to increase the control of human environment, increase production efficiency and enhance our security. Because of the inherent intelligence smart sensors implementation would give many advantages as compared to standard sensors, *eg*:

- self-test and self-calibration;
- increased accuracy of the measurement by minimizing analog signal wire transmission;
- remote programmability, digital communication, networked wireless and WEB based remote monitoring and control;
- implementation of Plug-and-Play features.

3.1. **Smart sensors and smart sensor interfaces**

The driving forces that develop smart sensor technology are mainly: aerospace, automotive and military industries, industrial control and automation, building automation, security and also environmental monitoring.

Currently there are two ways for the development of smart sensing technologies [72]. The first one represents basic physical and (bio) chemical research in sensor’s conversion phenomena: thermoelectric, photoelectric, photomagnetic, electromagnetic, thermooptic, etc. in the context of integrating the sensing element with microelectronic-based "smart" capabilities. The problems facing researchers in this field concern selectivity, materials compatibility and integration of different technologies. The example of technology and material incompatibility is a thermocouple operating at temperatures 300 °C to 500 °C enhanced by "smart" microelectronic element. The most microelectronics circuits do not work at temperatures above 150 °C and the materials used to manufacture thermocouples are generally not compatible with high purity conditions of silicon based microelectronics fabrication process. Other example is the Micro-Elecro-Mechanical System (MEMS) that integrate mechanical elements, sensors, actuators, and electronics on a common silicon substrate through micro-fabrication technology. The successful applications of MEMS sensors are: pressure transducers integrated with analog signal processing circuits and digital interfacing circuits, accelerometers available in the form of integrated circuits. Apart from technical obstacles there are also economical reasons that hamper the wide implementation of integrated smart sensors, i.e. users and producers implementation costs as well as the lack of widely accepted standards.

Use of smart interfaces is another way for implementing smart sensor technologies. Smart interfaces allow moving technology specific sensor elements from microelectronics of analog signal conditioning, conversion, digital signal processing and communication to enhance existing sensors with intelligence by means of smart interfaces [72]. This solution enables to use existing sensors the users are accustomed to, and do not force the sensor producers to sometimes expensive research in solving technology and material incompatibilities. A set of standards under development, aimed to simplify sensors connectivity is coordinated by National Institute of Standards and Technology (NIST) and is adopted by Institute of Electrical and Electronics Engineers (IEEE) under the name IEEE 1451 [28].

The purpose of IEEE 1451 standards (http://ieee1451.nist.gov) is to define a set of common interfaces for connecting transducers to microprocessor-based systems, instruments and field networks in a network-independent fashion. The IEEE 1451 standard include five complete sub-standards. The IEEE 1451.1 and 1451.2 have been published and accepted by the IEEE. The sub-standards IEEE P1451.3, IEEE P1451.4 and IEEE P1451.5 are in progress, which is denoted by the letter "P". The IEEE 1451.1 defines the way the transducers are connected by a Network-Capable Application Processor (NCAP) to networks such as Ethernet. This standard supports all of the interface module communication with transducers used by the rest of the IEEE 1451 family. IEEE 1451.2 standard defines point-to-point digital communication between a Smart Transducer Interface Module (STIM) and the NCAP (**Fig. 3**) by means of a Transducer Independent Interface (TII). The STIM contains a Transducer Electronic Data

Sheet (TEDS) with information (the manufacturer data, and the optional calibration and correction data) in standardized format about every transducer connected. TEDS is always attached to the transducer and its content is electronically transferred to NCAP or a host computer connected to the arbitrary network, thus the human errors associated with manually entering sensor parameters are avoided and Plug-and-Play features can be implemented.

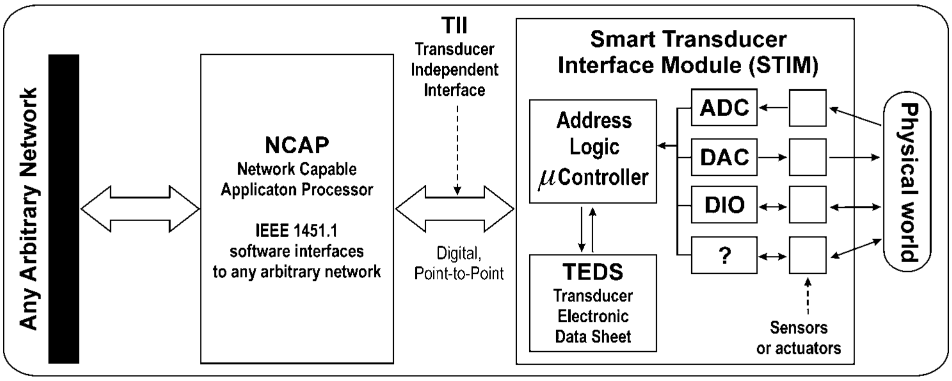


Fig. 3. IEEE 1451.2 standard of digital point-to-point system interface, ADC-Analog to Digital Converter, DAC-Digital to Analog Converter, DIO-Digital Input/Output

The IEEE P1451.3 standard is designed for distributed multidrop smart sensor systems, where a large amount of sensors need to be read in a synchronized manner.

In some cases it is not possible to locate the TEDS with the transducers, as it is accomplished in the IEEE 1451.2 standard, for instance due to harsh environment. The physical representation of the proposed IEEE P1451.3 standard is presented in **Fig. 4**.

A single transmission line is intended to supply power to the transducers and to provide the communication between the bus controller located in NCAP and the Transducer Bus Interface Modules (TBIM). A transducer bus is expected to have one bus controller and many TBIMs, and a TBIM may contain one or more different transducers.

The proposed standards IEEE P1451.4 and IEEE P1451.5 are intended for: mixed-mode (analog and digital) communication and wireless communication protocols, respectively.

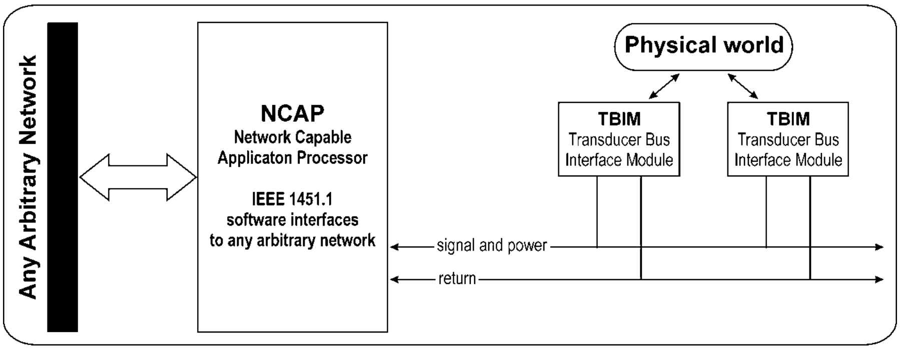


Fig. 4. IEEE P1451.3 proposed standard of the digital multidrop system interface

3.2. Measurement systems in Agrophysics

The example of quantitative evaluation of agrophysical processes will be discussed on the example of the soil solid phase. Similar discussion can be done for other porous media and related processes in Agrophysics.

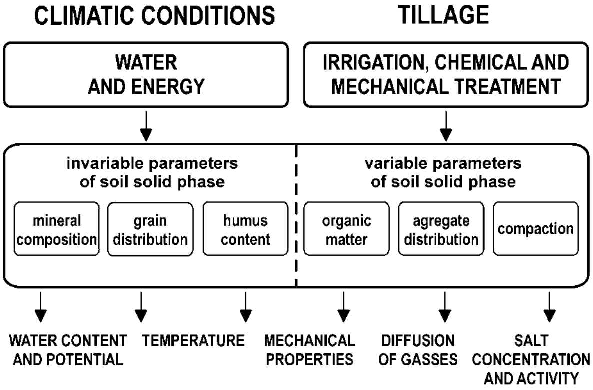


Fig. 5. Factors influencing invariable and variable parameters and physical quantitative indicators of soil solid phase

Soil physical parameters change continuously for climatic reasons and human activity (**Fig. 5**). Mineral composition, grain distribution and humus content are practically not affected by spatial and temporal change. Human activity: organic and chemical fertilization, as well as mechanical influence modify the variable parameters of the soil solid phase including: organic matter content, aggregate distribution and soil compaction. The basic quantities describing the soil physical status in the quantitative way are: soil water content and potential, soil temperature, mechanical properties (texture and porosity), gas diffusion, salt concentration and ions activity.

The selected field sensors used to determine the basic soil solid phase by means of direct or indirect indicators are:

- water content and potential: TDR moisture probes, capacitive probes, neutron scattering probes, gypsum blocks, tensiometers, thermocouple psychrometers;
- temperature: semiconductor, thermocouple and mercury thermometers, heat flux sensors (soil thermal conductivity measurement);
- mechanical properties: penetrometers, density and texture measurement require laboratory equipment;
- diffusion of gases: redox potential meter, ODR – platinum electrodes;
- salt concentration and ions activity: soil electrical conductivity sensors, ion selective electrodes.

The most important soil physical property for the monitoring, directly influencing the others, is soil water content. A very promising method for soil moisture determination is based on Time Domain Reflectometry – TDR [36,34,39,52,61]. Its methodology and measurement equipment including TDR soil moisture sensor has been developed in the Institute of Agrophysics Polish Academy of Sciences (IAPAS) since 1985. Also the concentration of selected ions in the soil giving the information about its fertility and/or intoxication seems to be of major concern. Research on the application of ion selective electrodes in three-phase medium has recently become the research subject of IAPAS.

3.3. Material and methods

The measurement system under development in IAPAS is intended to work in compliance with IEEE 1451.3 standard of digital multidrop (**Fig. 4**) system interface. Also it will accomplish some elements of wireless communication (IEEE 1451.5). The schematic description of this system is presented in **Fig. 6**.

The main element of the system is the NCAP for communication with the Ethernet network from one side and the transducers from the other side. NCAP may work as a MASTER or SLAVE unit, both based on the same electronics, but the MASTER unit serves only as an interface between multiple SLAVEs and the Ethernet network, without the ability to manage transducers (sensors or actuators). The transducers are connected to the SLAVES by means of a digital multidrop system interface constructed on the hardware base of a serial RS485 interface, serving as a small and cheap TBIM that fits easily into a transducer. For the purpose of compatibility with old versions of sensors and instruments developed in IAPAS there is also RS232C asynchronous serial interface for digital point-to-point communication, like in the IEEE 1451.2 standard. In the case of multiple SLAVEs they communicate with the MASTER unit by means of wireless communication using 433 MHz ISM (Industrial, Medical and Scientific) licence free frequency band. Each SLAVE has a large amount of non-volatile memory, for the storage of data collected from transducers, in the form a popular and not expensive removable Secutity Digital (SD) or Multi-Media Card (MMC). The information about the connected transducers is stored in TEDS being a part of the microprocessor unit.

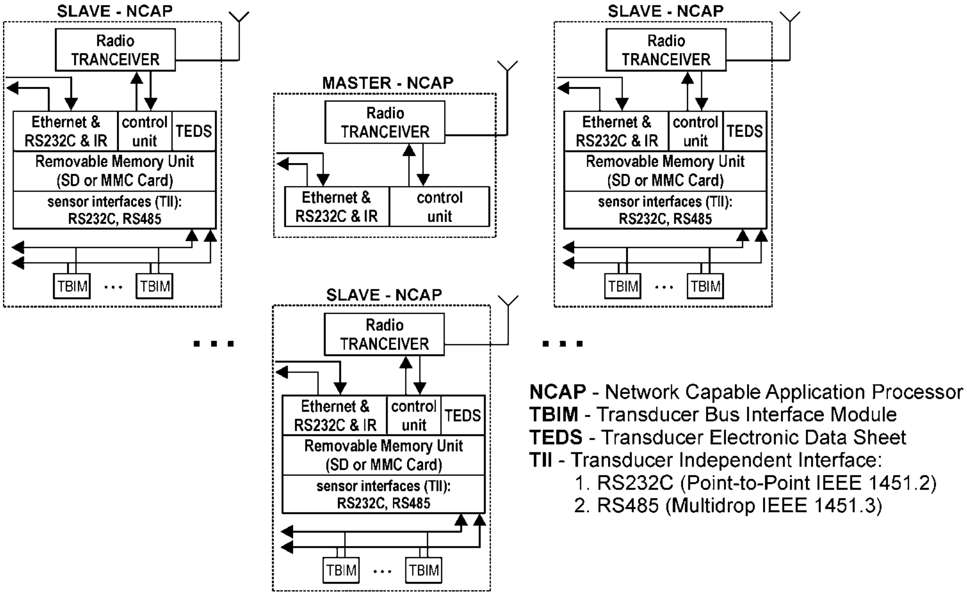


Fig. 6. System under development in IAPAS for the measurement of agrophysical properties, working in compliance with the IEEE 1451 standard

The main technical features of the soil physical parameters monitoring system with wireless communication link are as follows:

- radio communication in the license-free ISM (Industrial, Scientific and Medical) frequency bands 433 MHz,
- the hardware and software of the communication system is designed with the following major criteria:
  - minimize the transmission errors;
  - maximize the radio link range;

    - minimize the current consumption (SLAVEs are battery operated),
- each SLAVE device has facilities to connect it directly to the Ethernet network, as a Plug-and-Play device, with unique identification parameters (TEDS),
- sensors, smart sensors-transducers, measuring devices from various vendors (i.e. TDR units, tensiometers, temperature sensors, etc.) are connected to the SLAVEs by the sensor interfaces,
- SLAVEs are equipped with memory cards (Secure Digital or MultiMedia Cards) to store collected data (memory capacity is up to 128 MB).

Basic functional features of the wireless communication system:

- MASTER device works as a converter of radio data 433 MHz (other frequencies in ISM bands: 868 MHz and 2.4 GHz are planned for implementation) to Ethernet data accessible from any personal computer (PC) connected to Internet. It mediates between PC computer and SLAVE devices in data and commands transfer.
- The SLAVE device executes commands from a text script file stored in a memory card. After execution the last command in the script file, the sequence starts from the first command.
- The commands in the script file allow the SLAVE to:
    - change the parameters of the serial interfaces;
    - send commands and receive data by the sensor interfaces;
    - create an output file in the memory card and store data from the sensors in it;
    - change the format of data output file (insert time or data, number of the script executions, name of the script file executed currently);
    - initiate the sleep mode of the SLAVE (with minimized power consumption) for a fixed time (in seconds).
- Configuration and control of SLAVE device is performed by radio communication (default), Ethernet or serial interface RS232C and it enables to:
    - read the state of the SLAVE device (local real time clock, battery voltage, temperature, free memory card area, number of the script executions, the name of the current script);
    - read whole or partial files from the memory card;
    - write a new script file to the memory card;
    - stop the script execution and start it again;
    - give an unique identification number of the SLAVE.

- The application software is an Internet browser (*eg* Internet Explorer or Netscape) running on any PC computer connected to Internet accomplishes the control of the measurement system. The individual IP number and password guard the access to the selected SLAVE.

3.4. **Results and discussion**

The presented system of wireless communication was tested by connecting seven temperature sensors to the SLAVE unit, one of which measured the ambient temperature, the others were placed in the soil at the depths: 5, 10, 15, 20, 30 and 40 cm below the ground level. The SLAVE unit was placed in metal enclosure, protecting the electronics from rain, in a field plot at the distance about 70 m from the building with the PC computer controlling the MASTER unit. Detailed description of the experiment and the wireless communication protocol is presented in [74].

The experimental setup worked several days measuring and transmitting the temperature data by the radio link. The quality of the link is presented in **Fig. 7**. Totally there were 2772 radio connections with 97% performed in the first attempt. Only 3% connections were repeated; 11 1-time, 74 2-times and 1-time the attempt of radio connection had to be repeated 3 times to succeed.

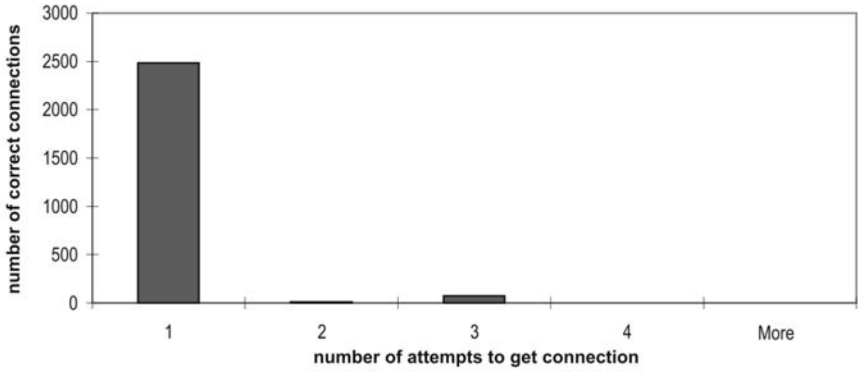


Fig. 7. A histogram presenting the frequency of successful data transfer between MASTER and SLAVE devices

The developed transmission protocol allows 10-times repetitions of sending the data or command frame. If the connection is not established the PC computer registers this event and records it in a text file, and then the system continues the operation. It was experimentally checked that the SLAVE unit worked well enough at distance about 500 m from the MASTER unit, provided that there was no obstacle (trees, buildings, etc.) between them. In other words the devices have to see one another.

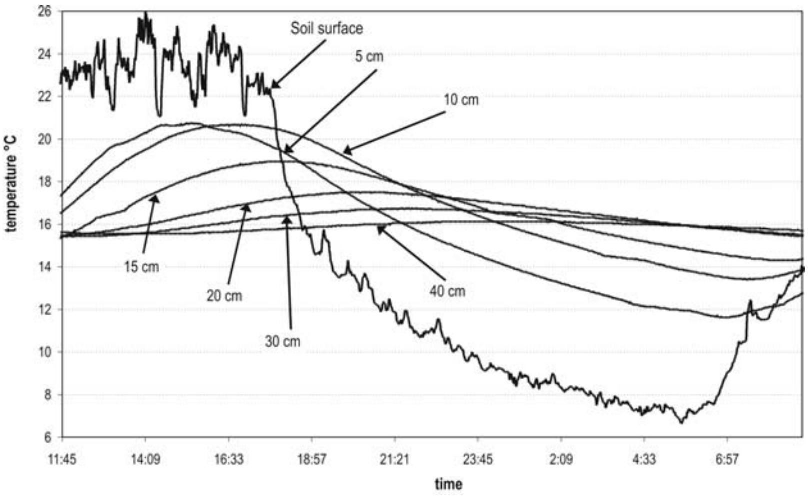


Fig. 8. Example readout of temperature sensors located on different depths of soil profile

The readouts from the temperature sensors placed on various depths in the soil profile are presented in **Fig. 8**. As expected, the sensor that measured the ambient temperature had the shortest response time to the temperature change. The deeper the sensor was located, the slowest reaction on the temperature change was observed. Additionally, the reaction of the sensors to temperature changes was shifted in time because of the limited speed of temperature change in the soil profile [64].

The main motivation for the measurement system (**Fig. 6**) design and implementation was the need to modernize the existing monitoring system of soil physical parameters: moisture measured by Time Domain Reflectometry method [34,61], water potential, salinity, and temperature. Such a system has been manufactured in IAPAS (http://www.easytest.lublin.pl) and used in many research centres in the world for soil physical properties analysis. It enables to verify the models of mass and energy transport in the soil in field conditions. Also, it may be applied for analysis of other porous media: building materials, food products, etc. as well as their storage and transportation. Particularly important parameter for monitoring is water content directly influencing the physical and chemical processes in these media.

New technical developments concerning the implementation of smart sensors and data transfer enhance the functionality of the measurement system. The applied ISM frequency band of 433 MHz in many cases does not provide the required speed for data transfer, which is limited to 9600 kbit/sec. However at the design stage the electronic components for wireless data transmission assuring the assumed criteria existed only for this frequency band. Being aware of new telecommunication developments this part of the system can be the most easily modified to fulfil the lowest power consumption and highest speed data transfer. The measurement system will be enhanced by other existing and popular sensors that are applied in soil physics and chemistry as well as environmental protection (psychrometric sensors, porous blocks, wind gauges, solar gauges, redox potential, oxygen diffusion rate sensors and pH sensors, ion selective electrodes, etc.). These sensors with additional electronics as an element of control and computation are intended to form Plug-and-Play smart sensors working according to IEEE 1451 standard.

3.5. Conclusions

The presented monitoring system for the measurement of soil physical parameters is intended to be equipped with smart sensors and wireless communication in the ISM (Industrial, Scientific, Medical) frequency band 433 MHz.

Partial implementation of the system in the form of two-point communication for the temperature measurement in a soil profile proves that the availability of advanced technology enables to enhance the existing measurement systems and sometimes only the sensors with functional and not expensive radio communication the distance of several hundred metres.

The developed hardware and software can be adapted to more complex monitoring systems working in compliance with IEEE 1451 standard and covering larger areas including air-borne or satellite remote sensing and serve as a source for ground reference measurements.

3.6. List of symbols and abbreviations

IAPAS	Institute of Agrophysics of Polish Academy of Sciences in Lublin, Poland
IEEE 1451	Set of smart sensor network standard under development by the Institute of Electric and Electronic Engineers
ISM band	Industrial, Scientific and Medical licence free frequency band
MEMS	Micro-Electro-Mechanical System

MMC	Multi-Media memory card
NCAP	Network-Capable Application Processor
NIST	National Institute of Standards and Technology
ODR	Oxygen Diffusion Rate
SD	Security Digital memory card
STIM	Smart Transducer Interface Module
TBIM	Transducer Bus Interface Module
TDR	Time Domain Reflectometry
TEDS	Transducer Electronic Data Sheet
TII	Transducer Independent Interface

4. EXAMPLES OF MONITORING SENSORS AND SYSTEMS FOR VERIFICATION OF MASS AND ENERGY TRANSPORT MODELS IN POROUS MEDIA

4.1. **TDR soil water content and salinity measurement**

4.1.1. *Status of water as significant issue of agrophysics*

Increasing demands of water management result in the continuous development of its tools. One of the most important, beside the simulation models of water balance [65], is monitoring of water status in porous materials defined as a space-temporal recording of the water properties that stimulate the phenomena and processes observed in the soil-plant-atmosphere system.

Concerning agrophysics, water status in porous materials is the issue of first priority, because each phenomenon or process examined in its scope depends on water status.

Monitoring of water status is accomplished using digital systems. The digital data acquisition systems react only on electric signals and the applied sensors must convert the measured value into the proportional electric signal.

Water status of soil, as a porous material should be expressed by minimum five variables: amount of water in the soil (i.e. soil moisture), soil potential, salinity, oxygenation and temperature [29].

The most difficult are the electric measurement of soil water potential and soil water content (soil moisture), therefore they are the subject of permanent research. It is assumed here, that the method successfully verified for soils will be also applicable for other porous agricultural materials because their structure is not so complex as soil.

The study discusses, on the example of soil, selected electric measurement methods applied for the monitoring of porous materials to determine the agrophysical variables. These methods have been elaborated and developed in IAPAS.

4.1.2. *Selectivity of the method*

The key feature of the applied method is the selectivity of the measurement, i.e. the lack of sensitivity of the conversion function (calibration) on the influence from the factors other than the measured one. Proper selectivity liberates the user from frequent, specific for each soil, *in situ* calibration measurements.

The solution to the problem of electric measurement of the physical quantity in selective way is to find such an electric property of the medium conditioning it, that is specific to the considered medium. For example, the specific property of molecular oxygen in electrolyte ("soil water") is small activation energy of electrode reaction of its reduction. It can be concluded that electric measurement of oxygenation may be based on the amperometric measurement of the current of electrode reaction of oxygen molecules reduction [30].

Concerning the problem of electric soil moisture measurement, the medium conditioning moisture is water and its specific property is the polar structure of water molecules (a water molecule has a permanent dipole moment of 1.87 D). Polarity of water molecules is the reason that dielectric permittivity (dielectric constant) of water is much higher than permittivity of soil solid phase (the relative dielectric constant of water in the electric field of frequency below 10 GHz and 18ºC temperature is 81, while the relative dielectric constant of solid phase is 4÷5 at the same conditions). The dielectric constant of soil strongly depends on its water content, therefore it may be concluded that electric measurement of soil moisture should be based on the measurement of its dielectric constant.

Similarly, concerning the issue of electric measurement of soil salinity, the media conditioning salinity are salts present in soils and the specific property is their ionic form. The ability to transport electric charge by the ions in "soil water" allows the soil to conduct electric current. Therefore the electric measurement of soil salinity should be based on the measurement of its electric conductivity.

4.1.3. *Electric measurement of soil moisture*

When the considered porous material is a moist dielectric (isolator), the measurement of its moisture is not a problem because it is enough to measure electric capacitance of the capacitor filled with the considered material and then recalculate the received value into moisture on the base of the conversion function (calibration).

In the case of materials conducting electric current, such as moist soil, the selective electric measurement of moisture on the base of dielectric permittivity is complicated because soil has features of dielectric and conductor simultaneously. The soil dielectric constant, ε, is a complex value [26]:

$$\varepsilon = \varepsilon' - j\left(\varepsilon'' + \frac{\sigma}{\omega\varepsilon_0}\right), \tag{10}$$

where:

$$\mathrm{Im}(\varepsilon) = \left(\varepsilon'' + \frac{\sigma}{\omega \varepsilon_0} \right) \tag{11}$$

is imaginary part of the relative complex dielectric permittivity of the soil, ε' – real part of the relative complex dielectric permittivity of the soil, ε'' – negligible contribution from the soil dielectric loss connected with dielectric polarization (mutual friction of permanent and induced dipoles), ρ - dry bulk density of soil [gcm^{-3}]), σ - electric conductivity of electrolyte [Sm^{-1}], ω - electric pulsation of external field stimulating the sensor, equal to $2\pi f$ [s^{-1}], f – frequency of electric field [Hz], ε_0 – dielectric permittivity of vacuum [Fm^{-1}], j – operator equal to $\sqrt{-1}$.

Practically the real part, ε', of the complex dielectric constant depends solely on its moisture, θ, and soil dry bulk density, ρ. The imaginary part depends on electric conductivity of the soil, σ, as well as the frequency of electric field, f. The bigger the value of the imaginary part (practically the bigger the value of soil electric conductivity), the more visible are conductive features of the soil.

From Eq. (11) it comes that the value of the soil complex permittivity depends also, besides its moisture, on the electric conductivity (that changes with moisture and salinity), as well as the frequency of electric field, f, applied to the sensor. It was found [37], that the imaginary part of ε is negligible above the sufficiently high frequency of the electric field, $f = f_{prog}$:

$$\lg f_{prog} = 8.87 + 1.06 \lg \sigma . \tag{12}$$

Equation (12) helps to evaluate the minimal frequency of alternative electric voltage polarizing the sensor, f_{prog}, which should be applied for the defined soil electric conductivity (salinity), to minimize no selective feature of dielectric measurement of examined material moisture.

If the applied frequency increases, the polarizing current (dependent on dielectric polarization) dominates the conductive current (not dependent of frequency, dependent on electric conductivity). Therefore the electric field applied to the sensor recognizes the soil as an insulator and the measurement becomes selective.

Considering that the electric conductivity of soils reaches values of 1 Sm^{-1}, the electric method of moisture measurement should apply the electric field of frequency not lower than 1 GHz. However the wave length in the frequency range

1 ÷ 10 GHz is 30 ÷ 3 cm, and is comparable with the size of the sensor electrodes. In such conditions the sensor generates standing waves of significant amplitude, which mask its own response. This measurement method is known as microwave interferometry. At every point of the measurement setup there are several discontinuities of impedances and the voltage standing wave ratio (VSWR) summarizes the interference effect, therefore interferometry cannot distinguish the individual effects of different impedance discontinuities of the generator-sensor system. This disadvantage does not exist in time domain reflectometry (TDR).

4.1.4. *Time domain reflectometry application in electric moisture measurement*

Time domain reflectometry (TDR) known also as cable radar method consists in actuating the tested transmission line by the voltage pulse and registering the time instants of the reflections from the impedance discontinuities encountered along this line (i.e. the line failures).

The electric voltage pulse is the result of interferences of infinite number of sine waves having different frequencies. Its edge is composed of sine waves of the highest frequencies in the wave bandwidth. Arbitrary setting the right limit of the bandwidth, f_{max}, the estimated rise time of the pulse edge, t_r, is [59]:

$$t_r = 0.35 f_{\max}^{-1}. \tag{13}$$

For example: to accomplish the condition $f_{max} > f_{prog} = 1.75$ GHz the required rise time, t_r, of the pulse should be not longer than 200 ps.

4.1.5. *The principle of electric measurement of moisture*

It has been found that the dielectric constant, ε, of examined soils and other porous materials depends on volumetric water content, θ, and density, ρ [34]:

$$\sqrt{\varepsilon} = 0.819 + 0.168\rho + 0.159\rho^2 + \theta(7.17 + 1.18\rho). \tag{14}$$

Relation between the square root of dielectric constant and moisture for 61 different porous materials of densities from 0.086 ÷ 1.77 g cm^{-3} is presented in **Fig. 9**. The examined samples included mineral and organic soils, sawdust and wood shavings, wood, artificial soil substrates and others

$$\theta = \frac{\sqrt{\varepsilon} - 0.819 - 0.168\rho - 0.159\rho^2}{7.17 + 1.18\rho}. \tag{15}$$

Converting (14) leads to a new formula for determination of moisture from dielectric permittivity and density, which represents the equation (15).

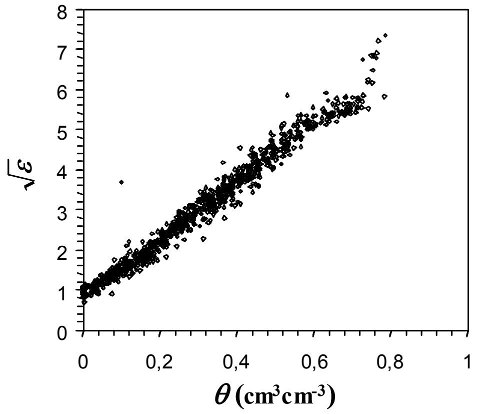


Fig. 9. Relation between dielectric constant and moisture for 61 different porous materials of densities from 0.086 ÷ 1.77 g cm^{-3}. The examined samples included mineral and organic soils, sawdust and wood shavings, wood, artificial soil substrates and others

The dielectric constant, ε, is calculated from the measurement of the propagation velocity, v, of electromagnetic pulse in the examined medium, for example in soil according to:

$$v = \frac{c}{\sqrt{\mu\varepsilon}}, \tag{16}$$

where: c is the velocity of propagation of light in vacuum. Assuming that for majority of considered materials the magnetic permittivity, μ=1, and transforming (16) we can find the formula for the electromagnetic wave refractive index, $\sqrt{\varepsilon}$:

$$\sqrt{\varepsilon} = \frac{c}{v} = \frac{c}{2L} t, \tag{17}$$

where: c is the velocity of light in vacuum, L – the length of the sensor rods, t is the time necessary for the pulse to travel the double length of the sensor rods, presented in **Fig. 11**.

4.1.6. *The principle of the measurement of electromagnetic wave propagation velocity by reflectometric method*

The principle of measurement of electromagnetic wave propagation velocity in soil (or other porous materials) is presented in **Fig. 10**. A section of transmission line, called the sensor, is constructed from two parallel, non-isolated metal rods. Another transmission line (for example coaxial line), called the feeder, connects the ending of the sensor with an electric voltage pulse generator. The voltage step travelling along the feeder reaches at instant t_1 the beginning of the sensor and propagates further in the soil to reach the sensor ending at the instant t_2.

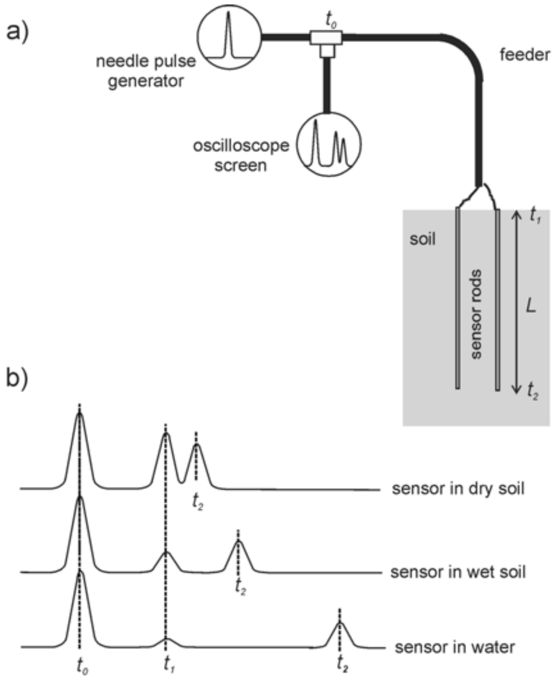


Fig. 10. Principle of the reflectometric measurement of soil moisture: a) basic components of the system, b) the pulse and its reflections as seen on the screen of the oscilloscope.

There is a discontinuity of impedance (feeder impedance differs from the sensor impedance) at the feeder/sensor connection, and a part of energy of the pulse is reflected at the instant t_1 and returns to the generator. The remainder continues to propagate further (in the soil) to reach the end of the sensor at the instant t_2 and reflects again towards the generator because of the impedance rise at the end of the sensor.

Fig. 10b shows the picture of the pulse and its reflections as is recorded on the screen of an oscilloscope connected to the feeder. The initial pulse reaches the T-adapter at the instant t_0, propagates further and is subjected to described reflections at the instants t_1 and t_2. The higher the soil moisture, the higher is the dielectric constant, ε, and the smaller propagation velocity, v, of the pulse in the soil, and the longer the time interval $t_2 - t_1$. The measurement of $t = t_2 - t_1$ between the reflections from the beginning and the end of the sensor and knowing the sensor length, L, allows to calculate, according to (14) the value of $\sqrt{\varepsilon}$ and then, according to (15), the corresponding volumetric water content, θ.

Sphere of influence of the sensor is a cylinder circumscribed on the sensor rods, with the height equal to 1.1L and the diameter about three times the distance between the rods (**Fig. 11**).

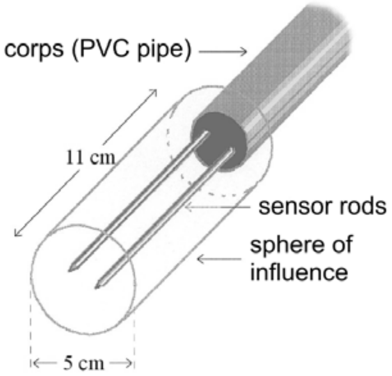


Fig. 11. Sphere of influence of the TDR sensor sensor

Fig. 12 shows comparison of the soil moisture measurement results carried out by reflectometric method, θ_{TDR}, with the ones by thermogravimetric method, θ_{grav}, for 61 different mineral and organic soils of densities in the range $0.086 < \rho < 1.78$ g cm^{-3} [34].

Small scatter of data proves the TDR method of soil moisture measurement to be satisfactory. It should be noted that this method has been also proved in applications to grain and wood [32,33].

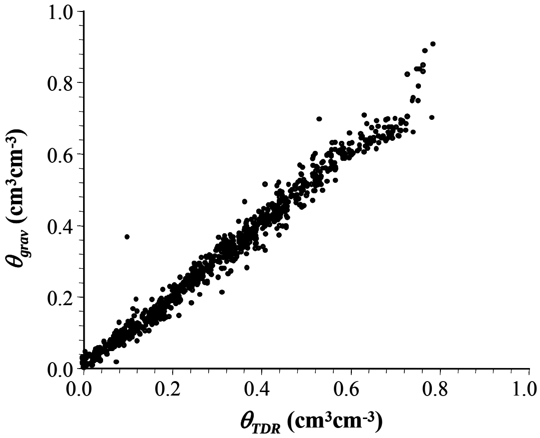


Fig. 12. Comparison of soil moisture data obtained using TDR, θ_{TDR}, with data obtained using the oven-drying method, θ_{grav}, for samples having bulk densities $0.086 < \rho < 1.78$ g cm^{-3}.$\theta_{TDR} = 0.0001 + 1.00\ \theta_{grav}$, $R^2 = 0.9801$, $SD = 0.028$ (SD is standard deviation).

4.1.7. *TDR meters for soil water content from the Institute of Agrophysics Polish Academy of Sciences in Lublin*

Below there is a selection of TDR meters for soil water content elaborated and developed in the Institute of Agrophysics PAS in Lublin. Short comments can be found in the figure captions.

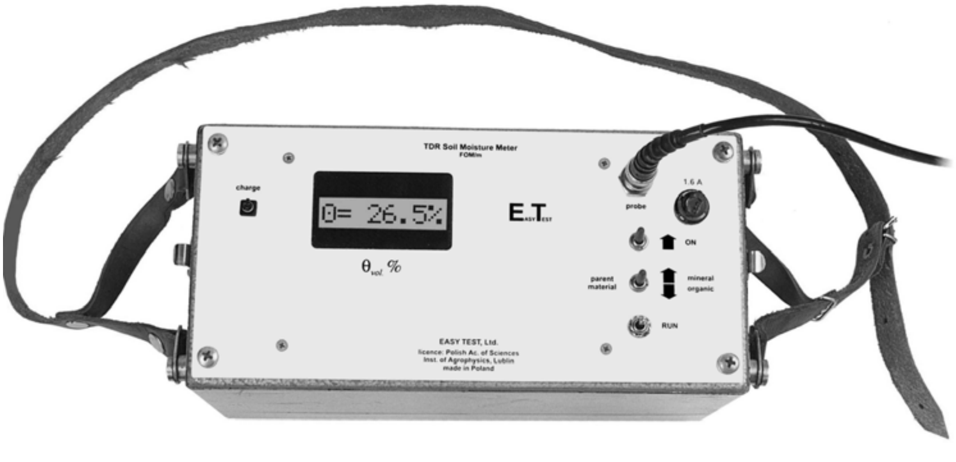


Fig. 13. FOM/m, Field Operated Meter for determination of soil moisture

FOM/m (**Fig. 13**) is a portable, battery operated, microprocessor controlled device designed for *in situ* field measurements of soil moisture by means of TDR (Time-Domain Reflectometry) technology. It is designated for periodic measurements at random and/or fixed locations where water content distribution is to be determined by readings taken at various levels of the soil profile. It utilizes the FP/m-type probes. FOM/m is equipped with a 15 mm high 3.5 digit LCD to display moisture and provides a Mineral/Organic option switch for soils originated from mineral or organic parent material, thus no user calibration is needed to read the soil moisture.

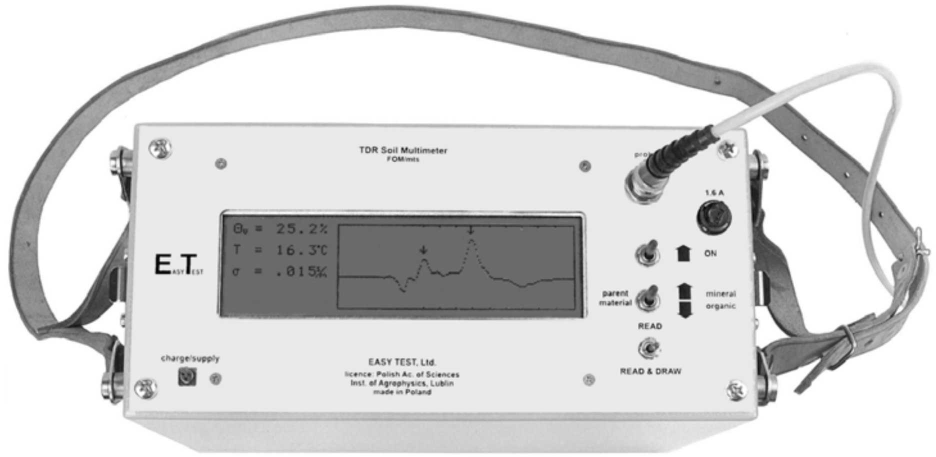


Fig. 14. FOM/mts, Field Operated Meter for determination of moisture, temperature and salinity of soils.

FOM/mts (**Fig. 14**) is a TDR (Time-Domain Reflectometry) based, portable, battery operated, microprocessor-controlled device designed for *in situ* field measurements of soil moisture, temperature and salinity (bulk electric conductivity) from the same probe. It is designated for periodic measurements at random and/or fixed locations where moisture, salinity and temperature distribution is to be determined by readings taken at various levels of the soil profile. It utilizes the FP/mts-type probe. FOM/mts is equipped with a 256 by 64 dot matrix graphic LCD to display data and TDR trace simultaneously. The TDR trace is a voltage-versus-time record of the voltage pulse round-trip along the probe. It is helpful to check the probe status during (break, short) and after its installation (excessive attenuation of the pulse). FOM/mts provides a Mineral/Organic option switch for soils originated from mineral or organic parent material, thus no user calibration is needed to read the soil moisture directly. Also FOM/mts-RS equipped with the RS-232C serial port is offered. This makes it possible to operate the meter under control of any IBM compatible PC.

FP presented in **Fig. 15** is a Time-Domain Reflectometry (TDR) probe for momentary or semipermanent installation. Thin-wall PVC body of the probe provides ultimate low heat conductivity, thus allowing avoiding the parasite "thermal bridge" effects on distribution of soil moisture in the probe’s sensor vicinity. Through a preaugered pilot hole it can reach any depth without destroying either the soil structure or disturbing the heat and mass transport in the soil. For semi-permanent installation the probe can be inserted horizontally through a sidewall of a soil pit or slantwise, from the soil surface. The probe installed once may be left intact in the soil for as long as necessary, then drawn out at the end of the experiment.

Fig. 15. FP/m, FP/mts, the Field Probe for moisture, temperature and salinity of the soil

FP/m is a probe for *in situ* field measurement of the soil moisture whereas FP/mts is its version for simultaneous measurement of moisture, temperature and salinity conductivity) of the soil from the same sampling volume

The shortest available probe is 15 cm long. Its supporting pipe does not have any bending. To place the probe at 5 - 15 cm depth it can be inserted horizontally through a sidewall of a shallow soil pit. The longest possible probe is 400 cm long (probes longer than 150 cm are delivered as a kit to be assembled by the user). In order to install FP in the soil, a pilot hole has to be preaugered from the soil surface, deviated out of vertical of an appropriate angle, *a*. The probe length, *L*, and the depth, *D*, the sensor rods are meant to reach in the soil profile (the installation depth) are related as follows:

$$L = D/\cos\alpha - 5 + a\,, \tag{18}$$

where: L, D and a in cm and α is the out of vertical deviation angle. The length, L, is the distance between the base of the sensor rods and the bending point of the plastic support pipe and a is length of the part of the probe body sticking out the soil surface. Different combinations of L, α and a allow to reach the intended depth, D. Suggested magnitude for α is 30° (**Fig. 16**).

Both probes are suitable for periodic measurements at random and/or fixed locations, where instantaneous profiles of water content, temperature and salinity are to be determined by readings taken at various levels of the soil profile. Each of them may also be applied as a mobile probe (FP/m/m or FP/mts/m) for momentary measurements in surface layer of the soil, by walking over the field and inserting the probe in the soil surface layer at chosen sites.

An example minimum set of probes consists of 7 probes for different depths of installation: 3 probes of L = 15 cm for D = 5 - 15 cm, 1 probe of L = 50 cm for D = 30 cm, 1 probe of L = 84 cm for D = 60 cm , 1 probe of L = 154 cm for D = 120 cm, 1 probe of L = 188 cm for D = 150 cm.

The shortest probes (L= 15 cm) can be placed horizontally. The remaining probes are calculated for α = 30° and a = 20 cm.

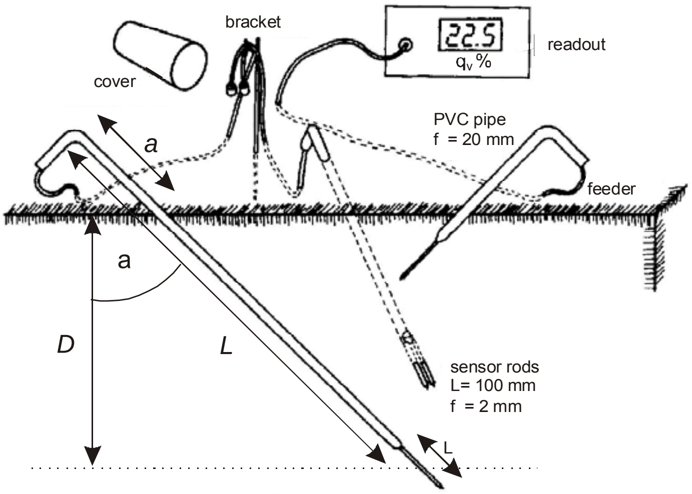


Fig. 16. The principle of installation of the FP-type probes. In order to minimize disturbances in the soil structure the probes are inserted into the soil via pilot holes, circularly distributed over the soil surface. The holes run slantwise and converge along a chosen vertical line. The cables are buried below the soil surface to protect them against the UV sun radiation as well as against rodents.

LOM (**Fig. 17**) is a TDR (Time-Domain Reflectometry) technology based, computer aided instrument, designed to record mass and heat transport data. It is suitable for controlling long-term laboratory experiments on soil columns, which require monitoring of water, heat and salt transport. This is achieved by means of periodic recording of instantaneous profiles of moisture, matric potential (capillary water pressure, "suction force"), temperature and electric conductivity in chosen time intervals. To record moisture, θ, a factory installed conversion equation $\theta(\varepsilon)$ for mineral soils is implemented.

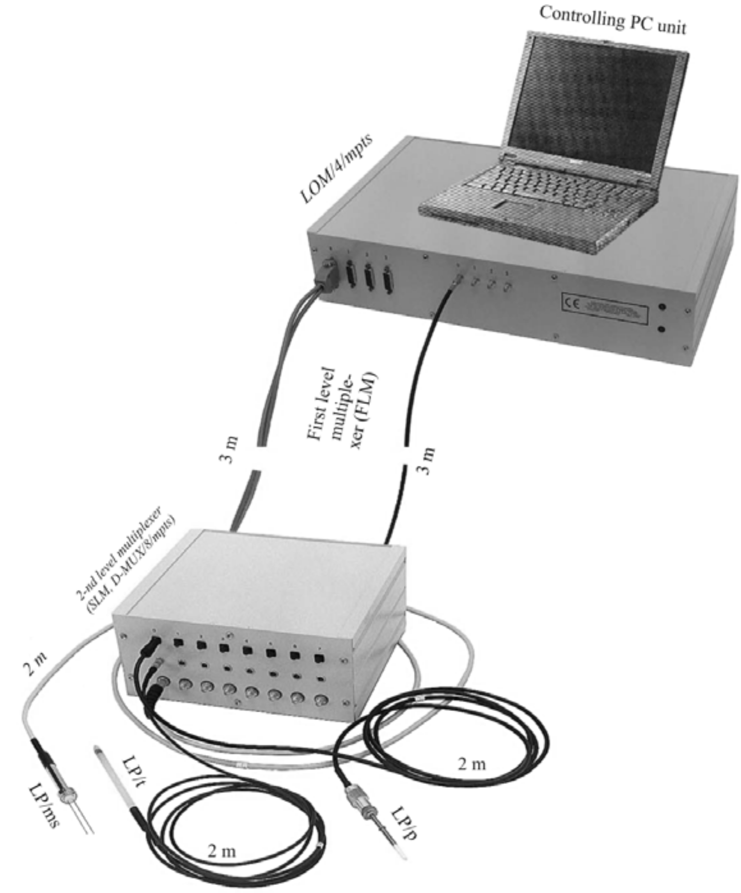


Fig. 17. Example of structure of a LOM/4/mpts based stand for recording instantaneous profiles of soil moisture, capillary pressure of soil water, temperature and salinity (bulk electric conductivity) from soil column(s), with application of a single MUX/8/mpts.

Several LP type miniprobes of selected type (or of all types) can be inserted through the side wall of a soil column or a steel sampling cylinder, thus allowing for vertical scanning of instantaneous profiles of moisture, capillary pressure (matric potential, suction force), temperature and salinity (bulk electric conductivity).

This makes it possible to collect a set of corresponding data from transition of the soil solute (and temperature) front. From this, after processing, one can obtain a complete set of unsaturated water flow characteristics of the soil such as the water retention (PF) curve, the unsaturated water conductivity (k-function), the differential water capacity and the unsaturated water diffusivity as well as the solute transport data. Also the heat flow parameters (thermal conductivity, thermal diffusivity, specific heat) can be determined if a temperature gradient is applied and a heat flux meter is installed in the soil column.

Probes are switched in two levels. For instance the LOM above is provided with a 3-pole-4-throw first level multiplexer (FLM) to switch between 1 to 4 second level multiplexers (SLMs). To switch between the probes 3-pole-8-throw multiplexers can be applied as the SLMs, as shown in the picture. For such configuration up to 32 LP/ms, 32 LP/t and 32 LP/p probes can be switched. Other options are also possible. The TDR LP/ms probes for moisture and salinity use special microwave switches. Remaining probes (LP/p, LP/t) are switched using common solid-state switches and/or reed relays.

Fig. 18. LP/ms, Laboratory miniProbes for soil moisture and salinity

LP/ms (**Fig. 18**) is a laboratory miniprobe designed for monitoring changes in water and salt distribution in soil columns or in soil cores sampled with standard sampling equipment. Several LP/ms can be inserted through the sidewall of a soil column or a steel sampling cylinder (**Fig. 19**), thus allowing for vertical scanning of the instantaneous moisture and electric conductivity profiles.

Such an array, when combined with similarly installed minitensiometers (LP/p), makes it possible to collect a set of corresponding water content and matrix potential gradient data from drying or wetting front transition. From this one can obtain a complete set of the soil unsaturated water flow characteristics, i.e.: water retention (PF-curve), water conductivity (k-function), differential water capacity and unsaturated water diffusivity.

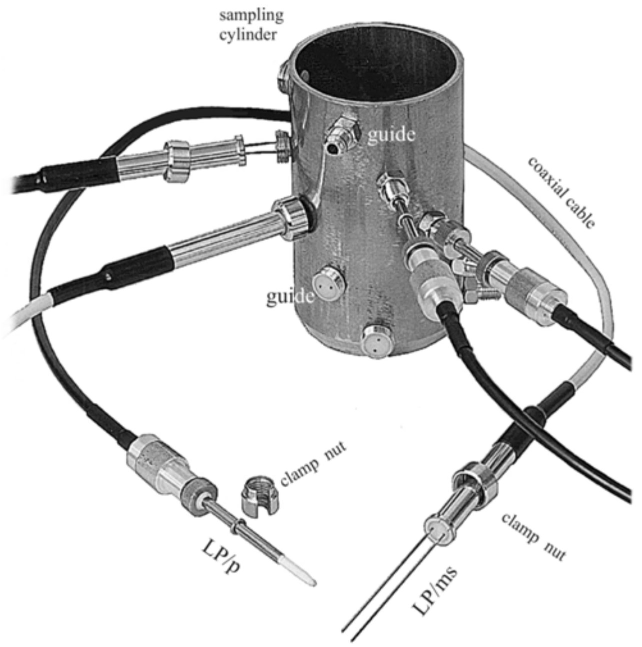


Fig. 19. A set of LP/ms and LP/p LOM controlled miniprobes inserted through a 2.75 mm thick wall of a sampling steel cylinder, having height of 100 mm and 55 mm inner diameter. The wall of the cylinder is provided with tapped holes equally distributed along the cylinder height in order to monitor independent layers of the soil. The holes are aligned spirally to minimize mutual shadowing in the vertical.

D-LOG/mts (**Fig. 20**) is a TDR (Time-Domain Reflectometry) technology based, computer aided instrument, designed for periodic recording of instantaneous profiles of soil moisture, temperature and salinity (bulk electric conductivity) in chosen time intervals. It is suitable for long-term lysimeter-based investigations and also for field experiments, when monitoring of water, solute and heat transport is required.

D-LOG is equipped with a built-in local computer having an RS232C serial port. It serves for:

- controlling pulse circuitry action;

- recording voltage-versus-time traces;
- calculating pulse attenuation and velocity of propagation;
- calculating the soil dielectric constant, moisture and electric conductivity;
- communicating with a master PC via the RS232C serial port.

Fig. 20. An example of the D-LOG/10/mts-controlled stand incorporating six D-MUX/10/mts 2-nd level multiplexers. Maximum amount of the controlled FP/mts (or FP/m) probes is 60. For clarity only a single D-MUX was linked with the D-LOG and a single probe was connected to each D-MUX when taking the picture.

D-LOG uses probes type of FP/mts for moisture, temperature and bulk electric conductivity. Also FP/m probes can be applied if only moisture is of concern. To calculate moisture a factory-installed conversion equation can be used and/or a user-determined calibration function can be applied as well.

To switch between FP/mts or FP/m probes D-LOG is provided with an inherent 1-st level switch and optional amount of standing alone 2-nd level switches (D-MUX/n/...), as shown in figures. Each 2-nd level switch contains moisture, temperature and salinity control circuitry and also a single-pole-n-throw microwave switch, where $2<n<16$.

To protect against rainfall the D-LOG as well as D-MUXes are kept in metal, rainproof exhausting boxes.

4.1.8. *Summary*

1. Reflectometric method, TDR (Time Domain Reflectometry) has been verified in comparison to other electric (dielectric) methods of soil moisture measurement as the best one.
2. TDR is especially useful for measurements in salty soils because the frequencies of the sinusoidal components forming the pulse edge fall in the range of 0.5 ÷ 5 GHz, whereas for soil conductivity below 1 Sm^{-1} the parasite influence of conductivity current is negligible (the frequency dispersion of soil electric permittivity does not, practically, appear).
3. TDR is convenient in applications to parallel measurements of soil dielectric constant and electric conductivity from which the soil water content and salinity can be estimated. The readings of both variables refer to the same soil sample (the sphere of influence of TDR sensor is common for the both variables).
4. The TDR as applied to water monitoring systems should be developed in the direction of an independent, single-unit “intelligent sensor” to make the systems immune to global collapse in data collection (even if only few sensors break, the system will still work using the remaining sensors).

4.2. Soil water potential measurements using Peltier psychrometers

Soil water potential measurements in field condition cannot be acceptably performed by one method in the full range of variability, i.e. from 0 MPa to the wilting point water potential –1.5 MPa, and below. Tensiometers work from 0 to about –0.09 MPa and respond only to soil matrix potential, porous gypsum blocks are available in the full range of interest but they respond also to soil salinity and therefore need site-specific calibration. Psychrometric sensors seem to be the ideal solution because they measure the humidity of air that remains in equilibrium with a sample of material containing moisture and they respond to total soil water potential. However in contrary to tensiometers, they work in the range from about –0.3 to –6 MPa. Therefore in field condition there is no reliable sensor covering the range of soil water potential from –0.09 to –0.3 MPa. The thermocouple psychrometry is reliable method of water potential measurement [3,50] provided that proper precautions are applied to sensors. This includes careful cleaning, handling and calibration of the sensors that are susceptible to acid environment. Special attention should be paid to eliminate the temperature gradients in the sensor during measurements. The current state of the thermocouple psychrometry is presented in [3], therefore the description of the measurement principle will be limited here to basics. The psychrometers are commercially available [13,71] but the complexity of measurements and rigid temperature conditions forced on the measurement process make this method not convenient.

The relation between water potential and relative humidity is theoretically expressed by the equation:

$$\Psi = \left(RT / V_w\right) \cdot \ln\left(e / e_0\right), \tag{19}$$

where: Ψ is the water potential in Pascal, R is the universal gas constant (8.3143 $\mathrm{J \cdot mol \cdot K^{-1}}$), e/e_0 is the relative humidity expressed as a fraction, T is the absolute temperature (in Kelvin degrees), V_W is the molar volume of water ($1.8 \cdot 10^{-5}$ $\mathrm{m^3 \cdot mol^{-1}}$).

Since the publication in [57] on the measurement of the water potential using Peltier effect, thermocouple psychrometers are widely used for measuring water potential of soils and plants.

The Peltier and Seebeck effects are two physical phenomena describing the psychrometric method of water potential measurements. The Peltier effect happens when a thermocouple junction is cooled or warmed by passing an electrical current through it in different directions. The Seebeck effect consists in the current flow in the loop of two dissimilar wires connected together when the junctions are at different temperatures. When the current generating the Peltier effect stops flowing, the water condensed on the junction evaporates and cools down this junction. The temperature depression between the thermocouple junction and the ambient air caused by condensed water film evaporation is observed as the voltage drop on the thermocouple. The temperature of the thermocouple during water evaporation depends on the relative humidity of ambient air, the higher the humidity, the bigger the temperature difference and the voltage drop.

4.2.1. *Meter and sensor descriptions*

The construction of a typical psychrometer sensor and its connection to the prototype meter are presented after [71] in **Fig. 21**. Very thin chromel and constantan wires (25 µm diameter - so that cooling of their junction will not significantly change the temperature of the larger reference junction) form the welded thermocouple used for the measurement of the equilibrium relative humidity/water potential.

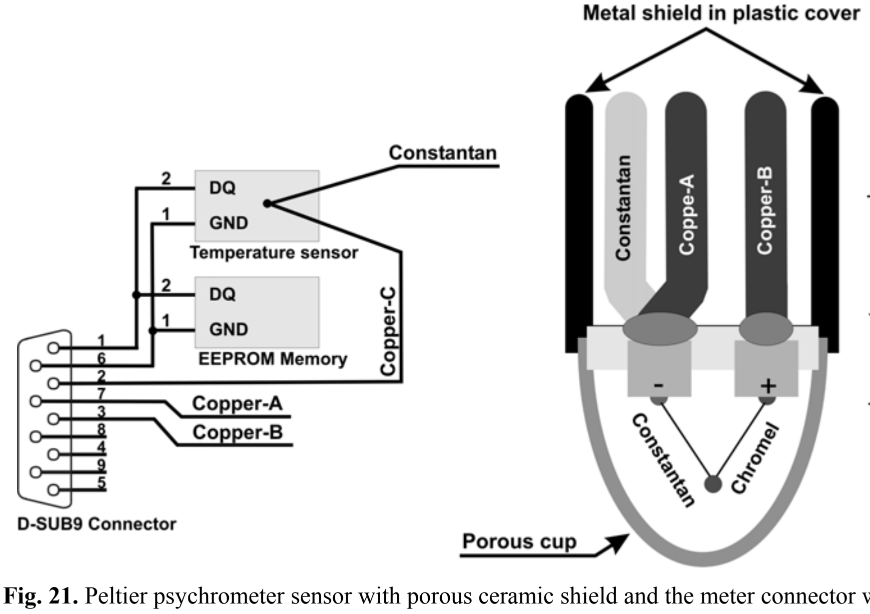


Fig. 21. Peltier psychrometer sensor with porous ceramic shield and the meter connector with installed electronics for cold junction compensation and storage of the sensor individual parameters.

Two copper wires, Copper-A and Copper-B, allow to feed the fine Constantan/Chromel thermocouple junction with appropriate cooling current and then make readout of psychrometric voltage difference associated with the water potential. Copper-C/Constantan thermocouple junction is used for the readout the psychrometric sensor temperature. The cold junction compensation of this thermocouple is done by the measurement of its temperature by means of semiconductor temperature sensor Dallas DS18B20 (Data Sheet available on www.maxim-ic.com). This very convenient 12-bit temperature sensor measures with ±0.5°C accuracy and 0.0625°C resolution and is integrated with digital circuitry for 1-Wire communication with the master microcontroller. The Copper-C/Constantan reference junction is thermally connected with DS18B20 by means of a special adhesive of small thermal resistance. The junction and the body of the DS18B20 temperature sensor are fixed together by epoxy resin to increase the thermal inertia of the whole construction that is placed in the housing of the D-SUB9 connector. Inside it there is also another 1-Wire device, Dallas DS2430A EEPROM memory, connected in parallel with the DS18B20 temperature sensor. Each psychrometer sensor may have its characteristic parameters, i.e. DS18B20 temperature correction, thermocouple cooling coefficient [12], probe unique identification number, written to the EEPROM memory so as to increase the accuracy of the measurement and for the sensor identification. The fine Constantan/Chromel welded junction is covered with a porous cup (or ultra fine weave stainless steel screen shield) that provides necessary cover while allowing the internal air to equilibrate with the ambient.

The main difficulties to overcome in the construction of the developed device are twofold: the resolution and stability of the readout device has to be very high (below 50 nV) in order to allow the measurement of relative humidity in the range of 99.99-95% with acceptable accuracy. This has been solved by the selection of advanced electronic analog and digital components. The other difficulty is to keep the measuring Constantan/Chromel junction at the same temperature as the reference junction. From (19), a change in the vapour pressure ratio of about 0.01 at 25˚C corresponds to about 1.4 MPa difference in water potential. It would be therefore necessary to limit the change in reference junction temperature to about 0.001˚C to maintain precision of 0.01 MPa [8]. This is especially challenging for measurements in field conditions. The most critical range is close to 100% humidity corresponding with the soil water potential range adequate with natural conditions of plants growth.

The measurement cycle consists of steps that are controlled by the microcontroller and electronic circuitry of the meter. These steps may vary according to the water potential to be measured, temperature, required accuracy and time interval of measurements. Optimisation of measurement process with respect to different restrictions may lead to various measurement procedures. The measurement sequence taking place to determine psychrometric water potential value is as follows:

The Constantan/Chromel thermocouple should not have water condensed on the fine wires. This is assured by passing the appropriate value warming current through the junction and then, after stopping the current, the junction should attain the temperature equilibrium with the air space surrounding it. Also the air space must be in the temperature and vapour equilibrium with the measured sample.

1. The Peltier cooling current is passing through the Constantan/Chromel thermocouple junction. The magnitude and duration of cooling current must be sufficient to cool the junction below the dew point temperature of the equilibrated air. When the temperature of the junction is below the dew point, water condenses on the junction from the surrounding air.
2. The Peltier current is discontinued and the thermocouple output voltage starts to be monitored (**Fig. 22**, point A). During the evaporation of water condensed on the thermocouple junction its temperature does not change rapidly (part A-B in **Fig. 22**). This temperature - the wet bulb depression temperature, depends of relative humidity of the air surrounding the sensor. The wet bulb depression lasts until all water evaporates from the junction and the thermocouple temperature returns to the ambient (part B-C in **Fig. 22**).

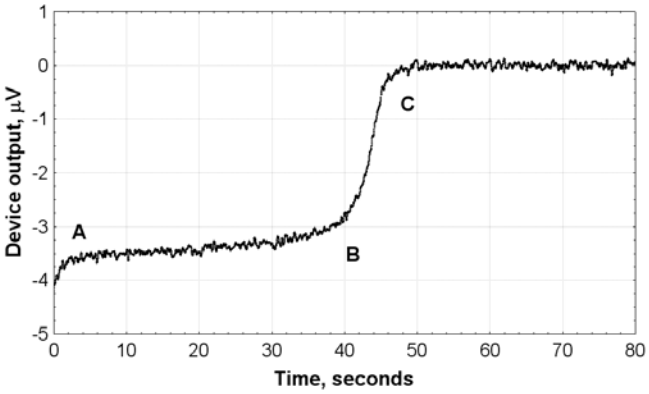


Fig. 22. Recorded output of the thermocouple psychrometer

The schematic picture of the prototype thermocouple psychrometer is presented in **Fig. 23**. The meter is controlled from PC compatible computer, by the application program written in Visual Basic, equipped with RS232C asynchronous serial port for sending commands and receiving raw data. The raw data from the meter consist of several hundreds, three-byte long data words representing values of voltage drop on the fine wires Constantan/Chromel or the thick wires Copper-A/Constantan thermocouples.

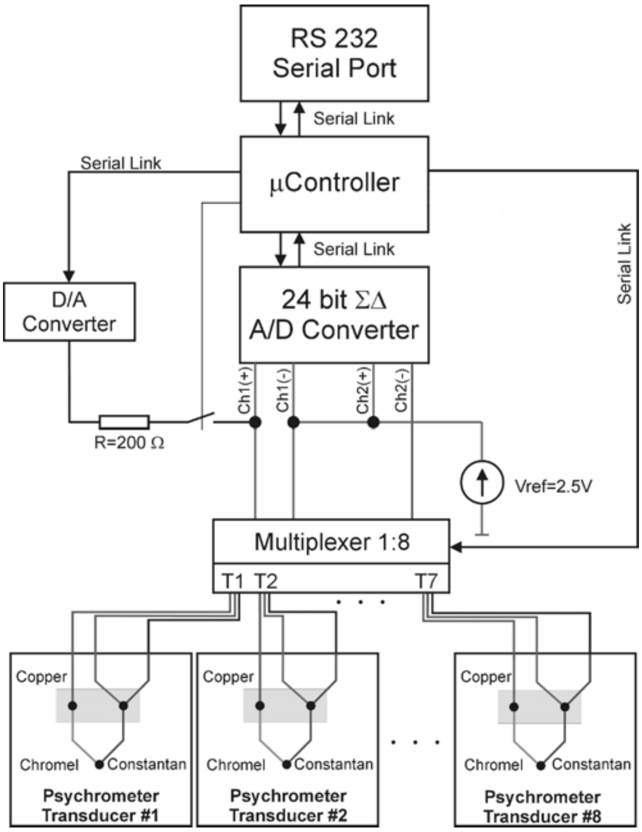


Fig. 23. Basic modules in the prototype thermocouple psychrometer

The input multiplexer enables to connect up to eight thermocouple sensors to the Analog Devices AD7730 24-bit Sigma-Delta Analog to Digital (Data Sheet available on www.analog.com). This is a very flexible device with a input programmable gain amplifier (PGA) for bipolar input ranges from ±10 mV to ±1.25 V or unipolar input ranges from 20 mV to 2.5 V. The presented meter is set for ±10 mV bipolar mode that enables to sample the input voltage with 1.2 nV resolution. This is a theoretical value, impossible to achieve in practice because of noise introduced by the measurement system. The device has a digital filter with the nodes that can be configured for 50 Hz for European and 60 Hz for American areas. The internal circuitry includes system and device calibration registers enabling to make corrections for zero and gain drifts. The device calibration registers can be loaded with appropriate values after switching the internal input PGA to ground or to the voltage equal to the selected measurement range. Each subsequent measured value is automatically corrected for the device zero and gain drift. System calibration requires manual switching of the meter input to the system ground and the selected voltage range. The presented meter uses only the device calibration feature before recording each response from the psychrometer sensor.

The 8-bit Digital to Analog (D/A) converter with the output voltage swing 0-5V, current limiting resistor R, the switch and the low noise precision 2.5V reference, Vref, are applied to control the value of warming or cooling current that is injected into the Constantan/Chromel junction. The both converters and the multiplexer are controlled by means of a three wire fast synchronous serial link from the microcontroller PIC 16F876 (Data Sheet available on www.microchip.com). The input values of the D/A converter in the range of 128-255 produce warming currents flowing in one direction, while the input values from the range 0-127 produce cooling currents flowing in opposite direction across the Constantan/Chromel junction. The current resolution is about 0,39 mA and the maximum value about 7 mA.

The cold junction compensation of Copper-A/Constantan thermocouple that measures the temperature of the Psychrometer sensor is done by the measurement of its temperature Ti (**Fig. 23**). The value of cooling current has to be determined experimentally so as to receive the temperature depression and the corresponding voltage swing in the fine Constantan/Chromel measuring junction somewhere in the middle of the 80 seconds time period when this voltage is sampled by A/D converter. The voltage of the measuring thermocouple is sampled with the frequency of 50 Hz, giving 4000 data points consisting of 3-byte words that are sent to PC computer by serial asynchronous link for further processing.

4.2.2. *Calibration of the psychrometric probes*

The calibration of the psychrometric sensors is performed by immersing them into the solutions of NaCl of known water potential (or relative humidity). The relationship between water potential and molality is presented after [27] in tabularized form (**Table 2**). The containers filled with NaCl solutions were placed in a water bath of constant temperature 25±0.3°C.

Table 2. Relation between molality, water potential and relative humidity for NaCl solutions at 25°C

molality	water potential in MPa at 25°C	relative humidity
0.05	-0.234	0.998
0.10	-0.462	0.997
0.20	-0.915	0.993
0.40	-1.823	0.987
0.60	-2.744	0.980
0.80	-3.682	0.974
1.00	-4.640	0.967
1.20	-5.620	0.960

There is an influence of temperature on the psychrometer readout reported [10,19] which can be adjusted to the values in 25ºC using the formula:

$$U_{corrected} = U_{measured} / (0.325 + 0.027 \cdot T) \tag{20}$$

where: T is the temperature in Celsius at which the reading was made. This temperature is calculated as $T = T_{reference} + T_{thermocouple}$, where $T_{reference}$ is the reference temperature of the Copper-C/Constantan junction measured by the 1-Wire DS18B20 temperature sensor (**Fig. 21**) and $T_{thermocouple}$ is calculated from the voltage U measured on this junction using the polynomial:

$$T_{thermocouple} = d_0 + d_1 \cdot U + d_2 \cdot U^2 + \ldots + d_n \cdot U^n \tag{21}$$

The coefficients $d_0 \ldots d_n$ for Copper/Constantan thermocouple (type T thermocouple) are [6]: d_0=0.000000E+00, d_1=2.592800E+01, d_2=-7.602961E-01, d_3=4.637791E-02, d_4=-2.165394E-03, d_5=6.048144E-05, d_6=-7.293422E-07, d_7=0.000000E+00. The accuracy of temperature determination by (21) is ±0.03ºC in the temperature range 0-400ºC.

The example calibration readouts from the same probe for different NaCl solutions are presented in **Fig. 24**. When molality of the NaCl solution decreases, the cooling time necessary for vapour condensation on chromel-constantan thermocouple decreases, too. To condense vapour on the thermocouple sensor inserted in 1.2 mole NaCl solution it is necessary to provide 7 mA current for 50 seconds while for the 0.2 mole solution the cooling time is 4 seconds and the current value is 5 mA. For each solution presented in **Fig. 24** the effect of evaporation of water condensed on the thermocouple is distinctive and is represented by fast voltage change. The higher molality of the solution, the lower is relative humidity of the air inside the shield of the sensor and the bigger is the voltage drop on the thermocouple. The applied cooling time is in direct proportion with the time necessary for the water to evaporate from the cooled junction. This phenomenon can be used also in water potential determination. The current and time values in the legend in **Fig. 24** refer to the cooling currents flowing across the Constantan/Chromel junction for the defined time. The chosen values depend on molal concentration of the particular NaCl solutions used for calibration. The voltage representing the temperature equilibrium state is zero on **Fig. 24**. Actually this value differs from zero because the distance from the Chromel/Constantan fine thermocouple to the input of the A/D converter includes connections of different wires generating thermocouple voltages themselves. Therefore the data in **Fig. 24** are adjusted to take account the zero drift of the system. This is done by subtracting the average value of 100 last points from each point of the curve. If the whole measuring system is in stable temperature state when the measurement process takes place, the only change of the output curve will result from the temperature depression caused by evaporation from the wet thermocouple junction.

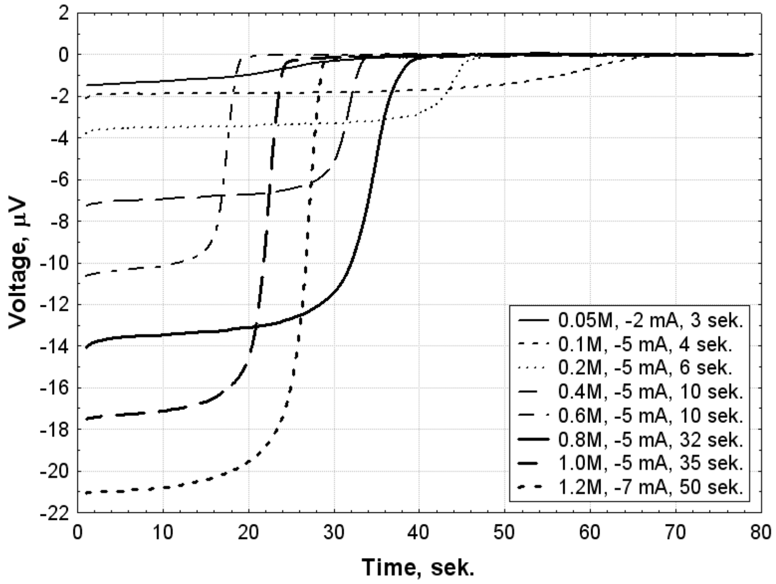


Fig. 24. Voltage generated by presented Peltier psychrometer as a function of time for different NaCl solutions representing different water potentials (each curve is generated for specific cooling current in the Constantan/Chromel junction).

Each curve from **Fig. 24** is a fitted trend line into the observed data, calculated as a moving average from ±50 points. This smoothing procedure is not necessary for low water potentials, but for water potentials above –0.4 MPa the interpretation of the curve is more reliable because of the scatter of the collected data. Determination of the voltage depression as well as the scatter of data readout from the meter is presented in **Fig. 25**.

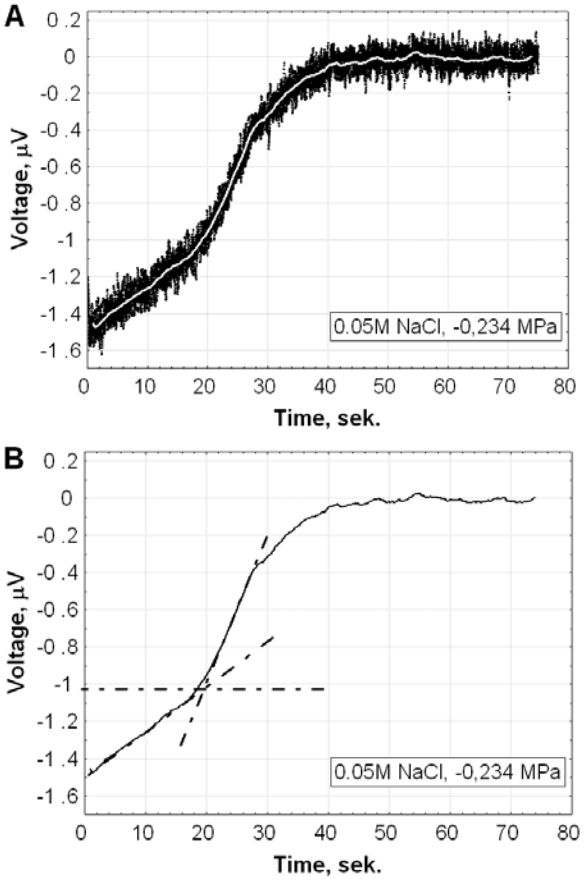
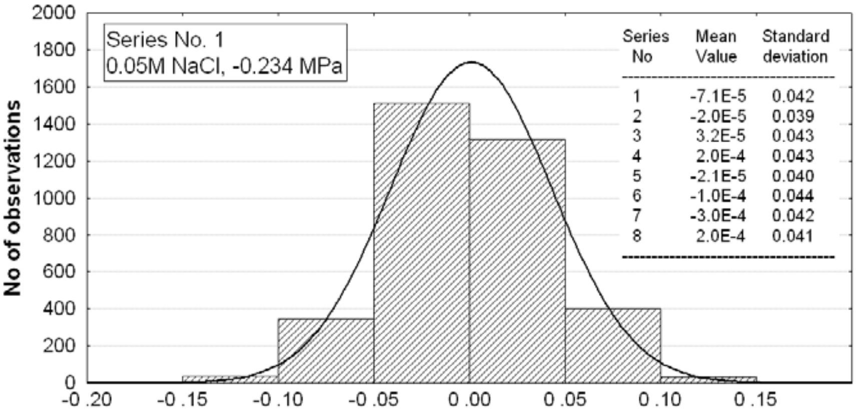


Fig. 25. Scatter of data from the meter readouts produced by eight consecutive curves grouped together with the ±50 points moving average (white curve) – A, determination of the voltage depression value on the psychrometer thermocouple – B.

The white curve in the **Fig. 25A** shows the average from eight readouts of the meter in the case when psychrometric sensor was in NaCl 0.05 molal solution. The points along the white curve represent eight data readouts received from the meter one after the other. The value of the depression voltage is determined as a crosscut of tangent lines, one of which is placed along the points representing the state when there is still some water condensed on the fine wires of the psychrometric sensor, the other line represents the state of sudden temperature increase of the junction reaching the ambient temperature (**Fig. 25B**). The first tangent line is not horizontal which means that the wet junction temperature is still slowly increasing as the condensed water is evaporating.

The resolution of the presented meter is determined from the distribution of error calculated as the difference between the observed values and the fitted ones, using the ±50 points moving average. The histogram of this error is presented in **Fig. 26**. For the psychrometric sensor inserted into the 0.05 molal solution of NaCl (the corresponding water potential is 0.234 MPa) the mean value of the error is close to zero and the standard deviation, describing the noise and also the measurement resolution produced by the meter and the sensor, is about 0.04 μV. The readout is repeated seven times for the same psychrometric sensor and similar values of error distribution are reported.



Series No	Mean Value	Standard deviation
1	-7.1E-5	0.042
2	-2.0E-5	0.039
3	3.2E-5	0.043
4	2.0E-4	0.043
5	-2.1E-5	0.040
6	-1.0E-4	0.044
7	-3.0E-4	0.042
8	2.0E-4	0.041

Fig. 26. Distribution of the meter error between the observed voltages (series No. 1) and the corresponding values from the fitted ±50 points moving average.

The calibration function of a psychrometric sensor as the relation between the device readout and examined water potential is presented in **Fig. 27**. The straight trend line shows that the calibration can be simplified to only two-point measurement. The calibration formula presented in **Fig. 27** refers only to the specific psychrometric sensor. Each sensor should be calibrated independently to obtain as high accuracy of measurement as possible.

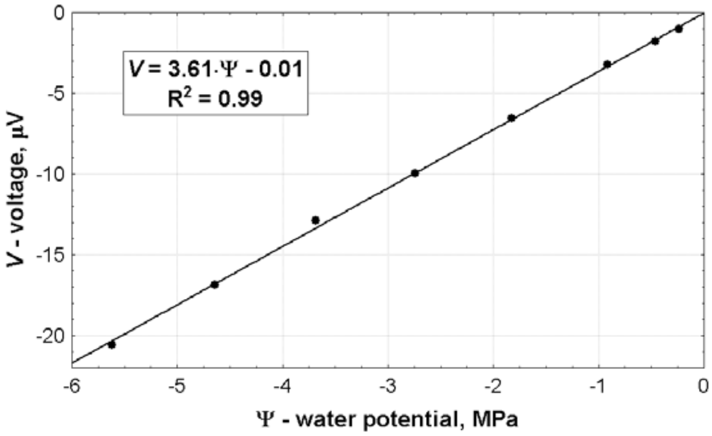


Fig. 27. The calibration function as a trend line for a Peltier psychrometer sensor.

The total number of eight psychrometric sensors (type PST-55 from Wescor Inc., with ultrafine weave stainless steel screen shield) were calibrated on NaCl solutions, according to the procedure described above. All the sensors had linear characteristic similar to the one in **Fig. 27**, although the slope differed slightly from 3.5 to 3.7 µV/MPa at 25ºC.

4.2.3. *Conclusions*

The presented thermocouple psychrometer is a convenient computer controlled device that enables the user to measure water potential simultaneously from up to eight sensors. The collected data may be analysed using various statistical tests as they have numeric form. The flexible construction of the meter enables the user to treat the sensor with heating and cooling currents of various values so as to determine the water potential in the range –6 to –0.2 MPa that correspond to the relative humidity range from 0.96 to about 0.998. The presented device can be applied not in soil physics for water potential determination, but also in building industry or food industry to determine properties of tested materials in the relative humidity range of 95-100%.

4.3. Ion-selective electrodes for the determination of selected ion concentration in soils

4.3.1. *Ion-selective electrodes basics*

Chemical sensors are miniaturized analytical devices, which can deliver real-time and on-line information on the presence of specific compounds or ions in complex samples [11,23]. Usually an analyte recognition process takes place followed by the conversion of chemical information into an electrical or optical signal. Chemical sensors have been known as the well-established tools for the determination of analytes after the separation from their native environment. Ion-selective electrodes play an important role as detectors commercially available clinically relevant electrolytes/gases analysers [40,41,58]. The studies on flow systems for water quality monitoring have also been carried out [16,17]. Recently, the possibility of an application of potentiometric sensors for environmental monitoring based on controlling of chosen components of soils [1,2,70] and [4,5,9]. These latest reports prompted us to initiate research studies in this field, especially that there is a need for the instrumentation that would allow the control of the soil condition in Poland. At this point it should be mentioned that this type of studies haven't been carried out yet in Poland.

Chemical sensors consist of two basic elements: receptor layer that exhibits chemical selective and integrated with sensing receptor a transducing element. Among various classes of chemical sensors ion-selective electrodes (ISE) are one of the most frequently used potentiometric sensors during laboratory analysis as well as in industry, process control, physiological measurements, and environmental monitoring. The principle of ion-selective electrodes operation is quite well investigated and understood [11]. Historically the first developed and implemented ISE was a membrane pH glass electrode (in the year 1909) [20,24]. pH electrodes are constructed from a special composition glass which senses the hydrogen ion concentration. This glass is typically composed of alkali metal ions. The alkali metal ions of the glass and the hydrogen ions in solution undergo an ion exchange reaction, generating a potential difference. In a combination pH electrode, the most widely used variety; there are actually two electrodes in one body. One portion is called the measuring electrode, the other the reference electrode. The potential generated at the junction site of the measuring portion is due to the free hydrogen ions present in solution.

An ion-selective membrane is the key component of all potentiometric ion sensors. It establishes the preference with which the sensor corresponds to the analyte in the presence of various interfering ions from the sample. If ions can penetrate the boundary between two phases, then electrochemical equilibrium will be reached, in which different potentials in the two phases are formed. If only one type of an ion can be exchanged between the two phases, then the potential difference formed between the phases is governed only by the activities of this target ion in these phases. When the membrane separates two solutions of different ionic activities (a_1 and a_2) and provided the membrane is only permeable to this single type of ion, the potential difference (E) across the membrane is described by the Nernst equation:

$$E = \frac{RT}{zF} \ln\left(\frac{a_2}{a_1}\right). \tag{22}$$

If the activity of the target ion in phase 1 is kept constant, the unknown activity in phase 2 ($a_2 = a_x$) is related to E by:

$$E = \frac{RT}{z_x F} \ln\left(\frac{a_x}{a_1}\right) = const. + S \log(a_x), \tag{23}$$

where: R, T and F are the gas constant (8.314 J mol^{-1} K^{-1}), temperature (in K) and Faraday constant (96485C) respectively, S=59.16 [mV] at 298 K for single charged ions (29.58 for double charged ions), and z_x - the charge of the analyte.

The potential difference can be measured between two identical reference electrodes placed in the two phases. In practice the potential difference, *ie* the electromotive force is measured between an ion selective electrode and a reference electrode, placed in the sample solution. It is important to note that this is a measurement at zero current, *ie* under equilibrium conditions. An exemplary setup for the measurement of electromotive force is presented after [11] in **Fig. 28**. Equilibrium means that the transfer of ions from the membrane into solution is equal to the transfer from the solution to the membrane. The measured signal is the sum of different potentials generated at all solid-solid, solid-liquid and liquid-liquid interfaces.

The most important part of ISE is the polymeric membrane containing compounds (known as ionophores) that are able to form complexes with ions in a fast and reversible mode. The presence of ionophores and other active additives within the membrane phase determines the membrane selectivity and its working characteristics such as linear range of the calibration curve, response time, life-time, etc.. This is the reason why the optimisation of the composition of the ion-selective membrane is such an important matter.

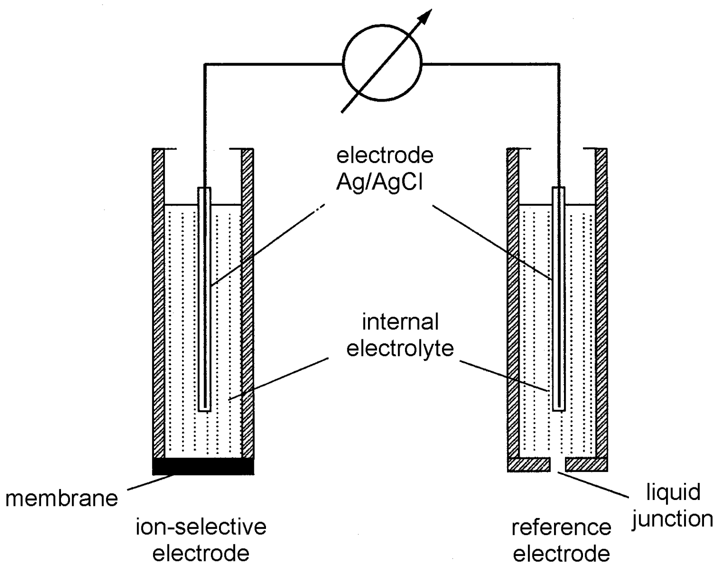


Fig. 28. Ion-selective electrode measurement setup

4.3.2. *ISE application is soil testing*

Continuous or periodic control (monitoring) of the chemical substance concentration including ions is the basic need in modern process control in industry, environmental protection and agriculture. Classical methods of analytical chemistry are not useful in conditions where speed and ability to automatize of measurement are required. Automatic analytical control implies increasing reliability and multifunctional work connected with minimal interference with the tested medium. Chemical sensors fulfil the above requirements.

The efforts to use ISEs for soil/ground tests are limited mainly to the tests of soil solution extract or a mixture (in different ratios) of distilled water or other solvent with soil [9,70]. Measurements performed on such a sample although quite precise, are not practical in the application with automatic acquisition systems or mobile devices connected with GPS systems used in precision agriculture. However there are experiments [2,55] showing the possibility to monitor the electrolyte concentration with ISEs in field condition.

The potentiometric method with the application of ISEs seems to be ideal due to the fact that the concentration ranges of ions (*eg* K+, Ca++, NO_3- or pH) that exist in the soil fit nicely to the linear response ranges of respective ISEs.

However, soils are very difficult analytical objects and the composition of polymeric membranes and the construction of indicator as well as reference electrodes must be chosen very carefully to make it compatible with a measuring system.

4.3.3. *Interdisciplinary cooperation for the measurement of selected ions concentration in the soil*

The Institute of Agrophysics PAS in Lublin develops systems to monitor soil moisture and soil salinity by the measurement of soil electrical conductivity [31,39] (which together with soil moisture is the base to calculate the electrical conductivity of soil extract, being the measure of soil salinity), that is without the possibility to determine selectively which ions influence the determined soil salinity. The measurement equipment [30,36,38,51,67] for tests of physical soil and plant material properties developed in the Institute of Agrophysics PAS and produced on its licence [21] is used in many agrometeorological stations. The current need is to enhance these stations with the sensors to monitor the dynamics in concentration of selected ions.

Research related to designing of various type of ISEs has been carried out at the Department of Analytical Chemistry, Warsaw University of Technology. Research interests that focus on the improvement of the selectivity of polymeric membrane-based ISEs, IS-FETs or miniaturized potentiometric transducers [11,16,17,] and [46,47,76,77]. It creates the possibility to extend their application in monitoring of soil under various moisture conditions without preparatory mixing with solvents. The schedule of the planned research should include: potentiometric studies on polymeric membrane sensors, development of the measurement system of selected ion concentration with the application of manufactured ion-selective electrodes, validation of the measurement method of selected ion concentration in the soil.

4.3.3.1. Potentiometric studies on polymeric membrane sensors.

One of the goals of this project will be development of ion-selective sensors for a group of chosen ions. Ionophores for membrane preparation will be selected based on literature data. Their complex formation ability and lipophilicity will be consider in order to prepare membranes of good selectivity and long-term stability. During the preliminary studies, a series of classical electrodes will be prepared and their working parameters will be evaluated at the laboratory conditions in order to find the optimal membrane compositions. The work on sensor's receptor layers (membranes) will include the selection of the appropriate ionophore and its amount, the amount of ionic additives in the membrane as well as the type of polymeric matrix and plasticizer. The following working parameters of electrodes will be taken into account: selectivity coefficients, the linear response range and slopes of calibration curves, response time and lifetime.

4.3.3.2. Measurement system of selected ion concentration in soil/ground with the application of ion-selective electrodes

Another, parallel goal is to develop the methodology of measurement which will be adapted to soil samples. It is planned to prepare a procedure of system calibration and sample measurement for a model setup, as well as to optimise the construction of ISE and reference electrodes taking into account field measurements.

4.3.3.3. Validation the method of measurement of selected ion concentration

The electrodes and measurement system, developed earlier, will be verified by the measurements of soil samples. Special attention will be paid on comparison of the results obtained this way with the ones obtained using traditional methods. Also the "edge" soil moisture values giving reliable ion concentration data will be determined.

Electrodes for the measurement of selected ion concentration specially constructed to enable installation in soil/ground and continuous measurement and recording the results in digital form. Monitoring system (**Fig. 29**) of soil physical (soil/ground moisture, electrical conductivity as the indicator of soil salinity, temperature) and chemical (concentration of selected ions) parameters of soil/ground, which will enhance the existing local meteorological and agrometeorological stations. Such a complete system will enable to register the climatic parameters, i.e. the elements of heat and water balance, radiation, wind speed, vapour pressure as well as physical and chemical parameters in soil/ground profile. It will present the complete image of processes describing the exchange of mass and energy in soil-plant-atmosphere system and enable to examine the environmental state as well as model verification (simulation and prognostic models) describing this state.

A simplified scheme of the system measuring soil/ground physical and chemical parameters is presented in **Fig. 29**. The similar systems, developed in the Institute of Agrophysics PAS in Lublin have been working for many years in different parts of the world. The system is modular and the communication between the main module MASTER and measurement modules SLAVE will be done by wireless radio link in the unlicensed frequency band 433 MHz.

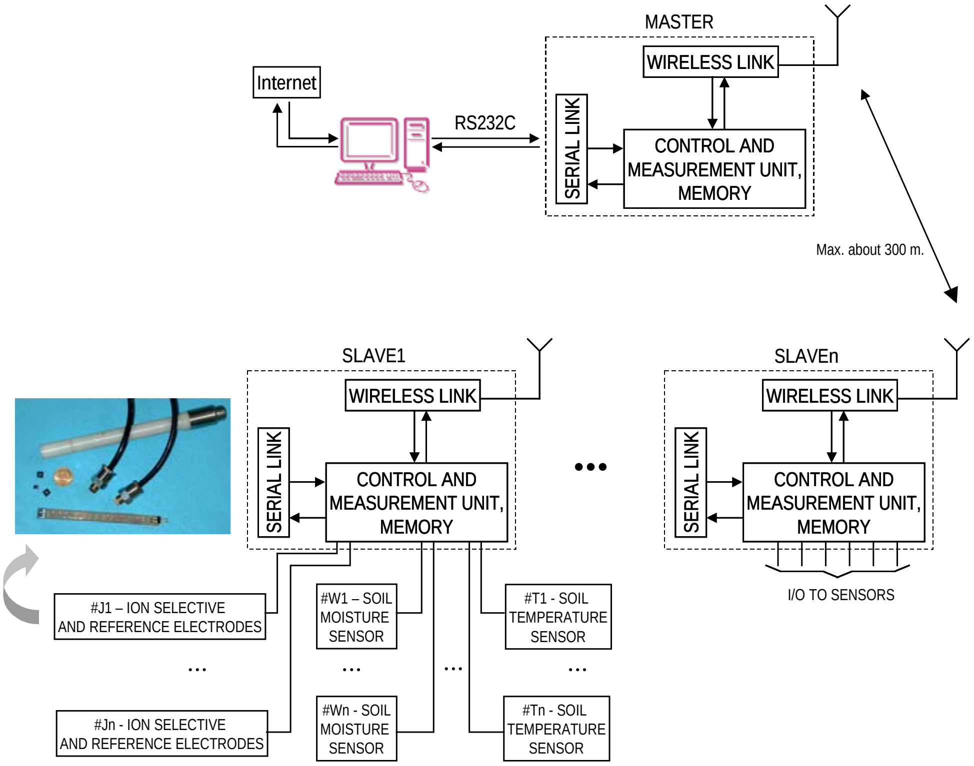


Fig. 29. Simplified scheme of soil/ground physico-chemical.measurement system enhanced by the set of ion selective electrodes

The user, having configured the time sequence of measurements, will collect the data from the module memories using a portable computer. It will be possible to connect the measurement system with Internet and sending the data directly to the personal computer of the user to monitor the system as well as to process the data.

The detailed description of the measurement system from simplified scheme in **Fig. 29** is presented in the following section.

4.4. **Multi Interface Data Logger as a part of a soil monitoring system**

Selective measurements, without destructive interference to the measurement process and measured medium from unpredictable reasons are easy for interpretation but practically hard to accomplish. The unwanted sources of error when identified can be eliminated by application of a physically good model of the observed process or by empirical correction based on reference measurements. A lot of measurement errors happen during the wire-transmission of an analog signal from the sensor equipped by an appropriate transducer, converting the usually non-electrical signal to its electrical representation, to the measuring unit. To avoid wire-transmission errors modern measurement systems combine the measuring unit with the sensor-transducer element in the form of a smart transducer or smart sensor. Smart sensors are equipped with microcontrollers or digital signal processors capable to convert the measured signal to the digital form, performing individual calibrations and necessary corrections. Thus most of the data processing is completed at the sensor and the command and data communication with it usually performed in wireless way.

The main reasons for the development of automatic measurements systems are: the requirement objective readouts, without the unwanted interference from error sources including the influence of an experiment operator and economical reasons. The integral part of such a system is a data logger for autonomic data collection and storing. The recent development of telecommunication and associated electronics gives the new tools and means for the idea of automatic measurement of environmental physical and chemical properties, especially low power converters of non-electrical signals to easy for processing electrical signal, powerful microcontrollers integrated with analog-to-digital and digital-to-analog converters, timers, digital interfaces and abundant non-volatile memory.

The presented study shows the potential of the MIDL (Multi Interface Data Logger) data logger, its functional features and the function in the automatic measurement system of physical and chemical parameters of soil and ground. The system has been developed in the Institute of Agrophysics in Lublin, Poland, as the direct answer for the need to collect data from ion-selective electrodes that measure the concentration of selected ions in the soil (Research Project 2 P04G 032 26 financed by the State Committee for Scientific Research). Also, the measurement devices developed, produced by the Institute of Agrophysics and used by a number of scientific soil laboratories [21] need a modern and hardware as well as software compatible data logger. The detailed description of functional and technical parameters of this system as well as the details of start procedures are presented in [42, 43,44].

It has been assumed that the MIDL data logger should provide:

- Ethernet 10Base-T Internet communication features,
- radio communication in the non-licensed 433 MHz frequency band [74],
- supply by an external power source 6-12 VDC,
- limited power consumption below 2 W in the continuous work mode,
- communication interfaces for monitoring and configuration the device by means of a PC compatible computer, *ie* serial RS232C and infrared (IRDA) wireless digital data transmission,
- serial RS232C and RS485 work interfaces for connecting measurement devices,
- 4-bit output parallel port in TTL standard (to be compatible with the old measurement devices developed in the Institute of Agrophysics),
- user accessible universal connector for MMC (MultiMedia Card) memory card with the capacity up to 128 MB memory,
- internal temperature sensor and real time clock,
- limited power consumption in the standard in the standard work mode, *ie* the energy used from 12 VDC power source during 90 days should not exceed 2 Ah, when the total script execution time is 3.6 hours (including 0.33 hours of RS232C or RS485 operation), the total radio communication – 7 hours, the total time of the device in the watch mode (with the radio access periods of minimum 2 seconds) – 2000 hours.
- Temperature range of work –25°C to 85°C.

4.4.1. *Functional description*

MIDL data logger consists of two functional versions, *ie* MASTER and SLAVE. The both versions are built on the base of the same hardware; SLAVE uses the whole hardware features while MASTER only the part of it. The functional features are distinguished by software automatically identifying the version.

MIDL can operate in various modes and **Fig. 30** presents the most complex mode where the system consists of a number of MASTER devices controlled by via Internet by PC compatible computers.

MASTER modules are wireless transceivers (receivers and transmitters) of signals from Internet to radio signals between PC and the addressed SLAVE module. The wireless radio link works according to the accepted assumptions in the non-licensed frequency band of 433 MHz [74]. The SLAVE modules together with the connected measurement devices (by means of the serial interface RS485) are complete data acquisition systems. Each of them contains all the elements necessary to control the measurement process by the connected probes, store the collected data and communicate with the MASTER device to transmit the whole or a part of the storage memory to the PC, *ie* a separate supply source, microcontroller, real time clock and abundant (up to 128 MB) nonvolatile memory.

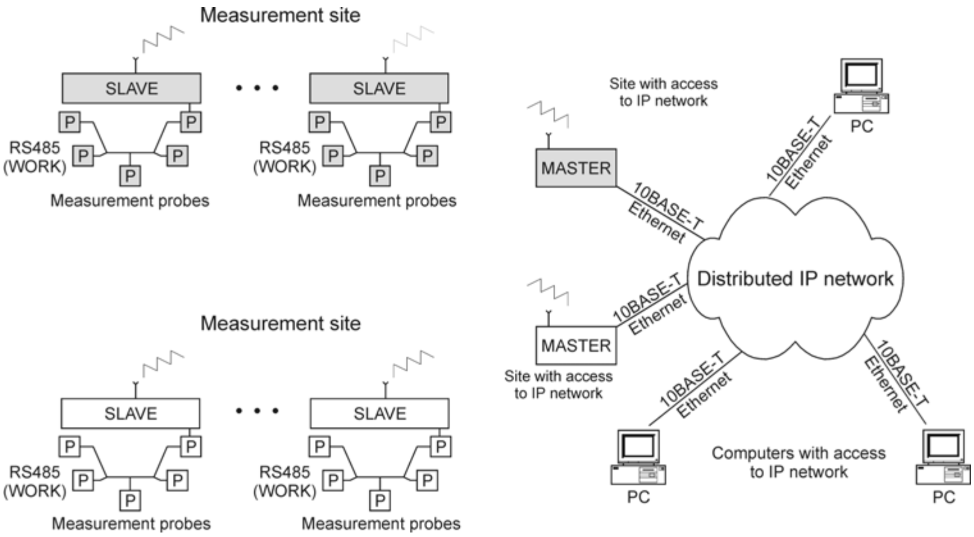


Fig. 30. Example setup of devices for soil and ground physico-chemical parameter monitoring system using wireless communication

The access to MASTER and SLAVE devices is possible from any place accessible by the IP network and in case of Internet network – from any place in the world. The devices are protected by unique Internet addresses and access passwords. The range of the applied radio link is limited to about 500 meters in the case when there are no physical obstacles between the transmitting and receiving antennas. The applied radio link in built from commercially available, completely assembled and tested electronic modules [15]. During transmission and reception they consume small power (about 100 mW), they can be completely disconnected for a defined period to save power and quickly connected again. The communication speed is 9600 bits per second, and in case of large file transmission, *ie* above 1 MB, is not economical due to limited energy in the supply battery. Another considered solution is to provide each SLAVE module with GPRS modem that enables much more fast connection with the Internet network. The basic drawback to apply GPRS modems is that they consume much more power than the presently applied 433 MHz modules. However it is possible to program the transmitting and receiving modems for short-time work, *ex* 10 minutes during 24 hours, to transmit the collected data to the base station (PC computer). Such a solution would guarantee large amount of data transmission and battery saving, which is a fundamental assumption of the presented data logger system. The described service of "wireless Internet" is presently provided by majority of mobile telecommunication providers.

Another example mode of operation of the MIDL system is the direct connection of the SLAVE modules to the cable Internet network, for example to perform measurements in a laboratory (**Fig. 31**). The access to the defined SLAVE module is possible from any computer connected with the Internet network and the software embedded in the SLAVE eliminates the conflicts that may occur by simultaneous access from many computers.

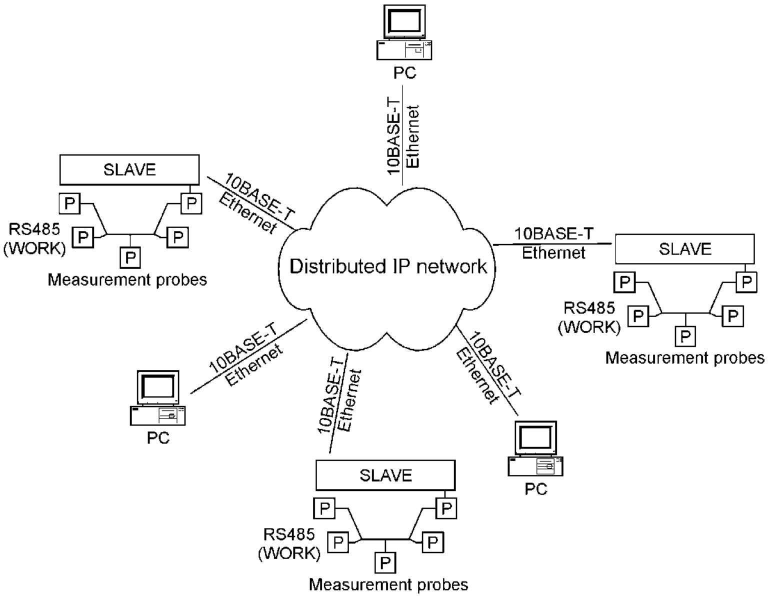


Fig. 31. Direct connection of SLAVE modules to Internet network

The simplest operation mode of the MIDL system is an autonomic mode. It consists in storing the experiment details (probes selection sequence, time distance between the measurements, format of data storage) in the MMC memory card by means of MMC read/write interface connected to PC computer, using script commands (the list of script commands is presented in the part 4.4.2.3). The access to the data is accomplished by the replacement of the MMC memory card filled with the collected data with an empty card. Due to large amount of memory available in MMC memory card its replacement is rare. The advantage of this mode of operation is small power consumption of the data logger.

4.4.1.1. SLAVE module

The basic version of MIDL data logger is SLAVE. Its simplified diagram is presented in **Fig. 32**.

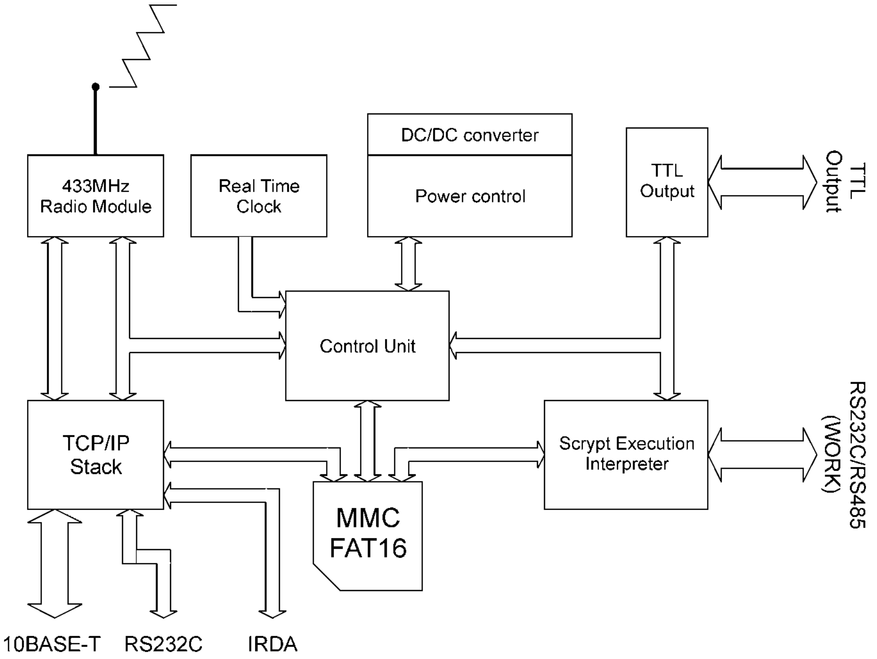


Fig. 32. Simplified functional diagram of the MIDL setup in SLAVE configuration

The central element of the device is Control Unit. It is responsible for the supply distribution and coordination of the work of the remaining units on the base of the sequence of events written in the script file. For example when the Control Unit finds the command to set the device into the sleep mode, it disconnects supply to each module introducing the device into low power mode of work (about 100 μA) when no sensor is activated. After the defined period of time the Real Time Clock module wakes-up the device, the Script Execution Interpreter reads the following commands, interprets them and executes sending commands to the work interface RS232C or RS485, setting the TTL outputs, reading the sensor data or storing the data into the MMC memory.

The access to data and to all configuration parameters of the device inscribed in the MMC memory card is possible by the 433 MHz radio link, RS232C serial and 10BaseT-Ethernet interfaces. All of them operates using IP protocol and the configuration of the device and the data access is the same for each interface.

The 433 MHz radio link enables a remote access to each SLAVE from the MASTER device. The remaining interfaces are activated by the operator directly at the device (*ex* by means of a notebook) after pushing the dedicated switch.

The characteristic features of the SLAVE device:

- cyclic execution of commands from the script file to control measurement from external probes,
- connection with the measuring probes by means of RS232C or RS485 interfaces,
- configuration, monitoring and readout of stored data by RS232C, 10BaseT-Ethernet and 433 MHz radio interfaces,
- the device management by means of TCP/IP network protocols,
- connection to the device by any FTP client and WWW browser,
- MMC memory handling using FAT16 file system (this means that MMC cards can be read directly by a PC compatible computer equipped with the MMC cars reader),
- the device works with minimal power consumptions for supply battery savings.

4.4.1.2. MASTER module

MASTER version of MIDL data logger is presented in **Fig. 33**.

MASTER serves as a bridge between the 10BaseT-Ethernet interface and the 433 MHz radio link. It is a mediator in the data and commands transfer between SLAVE devices communicating with the MASTER by radio and the base station (PC computer usually located in laboratory and performing data processing). The base station distinguishes A SLAVE device is as the next IP device in the network for remote configuration, monitoring or readout of the stored data.

The characteristic features of the MASTER device:

- serving as a bridge of network communication between 433 MHz radio link;

- possibility to configure and monitoring of the device by RS232 and 10BaseT-Ethernet interfaces.

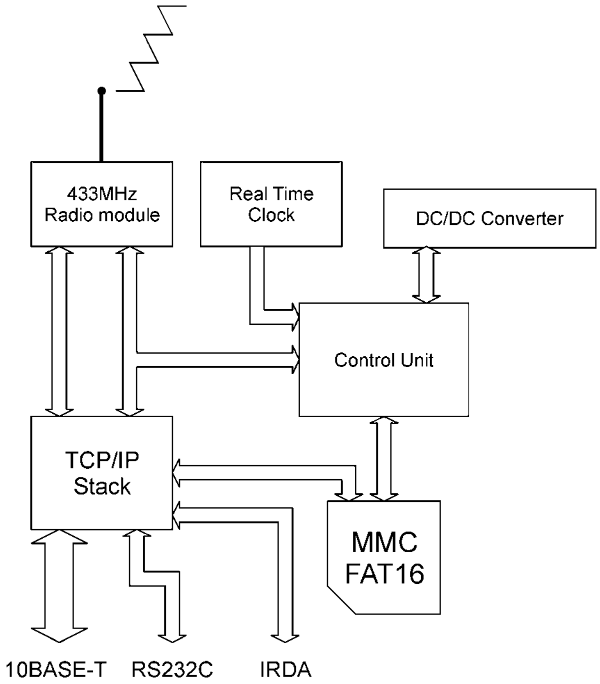


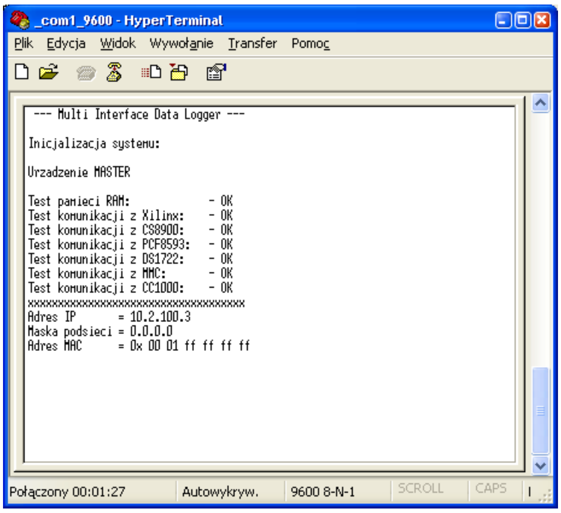
Fig. 33. Simplified functional diagram of the MIDL setup in MASTER configuration

4.4.2. *MIDL system handling*

The detailed description of MIDL system handling, including the description of user interface accessible from an WWW Internet browser, is presented in the Operation Manual [42].

After switching on the system performs checking of its basic functional elements and the tests results are transmitted by the RS232C configuration interface. Evaluation of the tests results can be done by connecting RS232 cable to between the configuration interface of the system and PC compatible computer. Then the user should run any RS232C terminal program on PC computer (*ex* Hyper Terminal in Microsoft Windows system), switch on the power supply and the computer display will present the tests results (**Fig. 34**).

All test communicates must be positive for the correct operation of the MIDL data logger. The window contains also network configuration parameters that are necessary to know for establishing connection with the system.



```
 --- Multi Interface Data Logger ---

Inicjalizacja systemu:

Urzadzenie MASTER

Test pamieci RAM:            - OK
Test komunikacji z Xilinx:   - OK
Test komunikacji z CS8900:   - OK
Test komunikacji z PCF8593:  - OK
Test komunikacji z DS1722:   - OK
Test komunikacji z MMC:      - OK
Test komunikacji z CC1000:   - OK
xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
Adres IP      = 10.2.100.3
Maska podsieci = 0.0.0.0
Adres MAC     = 0x 00 01 ff ff ff ff
```

Fig. 34. Serial RS232C port terminal window with the MIDL system initial tests

4.4.2.1. Configuration of basic parameters of the MIDL system

The correct operation of the system needs initial configuration of the Internet link. The configuration parameters are included in a system file ”server.ini” located on the MMC memory card. This file may be placed in the MIDL data logger in three ways:

- writing on the MMC card by means of an universal read/write device dedicated for MMC memory cards, connected to a PC computer, inserting the card into the slot in the MIDL device (MASTER or SLAVE) and switching on the power supply;
- accessing the cart in the device slot by WWW site;
- accessing the cart by means of FTP protocol to send the “server.ini” file by Internet.

Before accessing the card by WWW browser or FTP client the device must be connected to the computer by means of IP network.

4.4.2.2. System files

There is a number of file types in the MMC memory card. From a WWW site it is possible to access script files (“*.scr” file extension) and output data files (“*.txt” file extension). All files on the MMC memory card are accessible by FTP client or by reading the card in the universal card reader read/write device:

- files with „*.htm”, „*.css”, „*.js” extensions – files of graphical user interface used by a WWW browser;
- files with „*.scr” extensions – device executable script files;
- files with “*.txt” extension - output data files generated by executable scripts;
- files with “*.ini” – system files with the device configuration parameters.

The format and command of the executable script files are presented below.

4.4.2.3. Executable script files

Files with „*.scr” extension treated by the device as executable script files.

Table 3 below presents an example script file with commands that: fix the SLAVE RS232C serial port transmission speed to 9600 baud, give a name to the output data file where the data from the addressed sensor will be stored, send a command to the serial RS485 interface with the address activating the individual sensor, format the data received from the sensor and setting the SLAVE device into the sleep mode for a given period of time. The beginning of the script is marked by `[beg]` and the end by `[end]` directives.

Table 3. An example of the executable script file

```
[beg]
port(9600)
filename("RS485t.txt")
outp(RS485,"Command sent to the work interface RS485
\n\r")
fprintf("Result of the measurement received by RS485: ")
inp(RS485,14,4000)
sleep(120)
[end]
```

When the defined period of time, when the device is in the sleep mode, terminates, the script file executes from the beginning.

The script commands for autonomic, cyclic control measurements by the SLAVE device are presented in **Table 4**.

Each sensor connected to the SLAVE module should “understand” the script commands. This requires that each sensor is provided with an appropriate hardware and software interface. Therefore the term “sensor” means a device converting the analyzed signal (*ex* temperature, pressure, electrical conductivity, etc.) into the corresponding electrical signal.

Table 4. Script file commands

Command	Description
`port(baudrate, databits, stopbits, paritychecking);`	Setting parameters of the serial port
`outp(port, ”data”);`	Sending data by the working interface
`inp(port, length, wait);`	Receiving data from the working interface
`filename(”name”);`	Setting the file name where the data received from working interfaces will be stored
`sleep(sec);`	Bringing the MIDL into the sleep mode for defined number of seconds
`fprintf(”format”);`	Introduction of additional formatted data into the output file

Such a sensor integrated with a decision-making element, computation and communication facilities forms a smart sensor [54]. Smart sensors must be also identified and have means for storing individual calibration data.

4.4.3. *Testing the MIDL data logger*

The field system for monitoring physico-chemical parameters of soil and ground has been tested to verify its assumed parameters and performance. The MIDL system worked in the mode presented in **Fig. 30** using one MASTER and SLAVE modules. There were two measuring devices connected to the work RS485 serial interface: TDR soil moisture meter [21] with a single probe installed in the surface soil layer and a thermometer for environmental temperature measurement. The whole setup was installed in the field agro-meteorological station in the distance of about 70 meters from the building where PC computer controlled the experiment by means of the MASTER module. The transfer of configuration and data files between the SLAVE and the MASTER was by means of 433 MHz radio link. The SLAVE unit was supplied from 12V lead 7Ah capacity lead battery. The test lasted about 275 hours and the collected readouts are presented in **Fig. 35**.

The TDR soil moisture meter measures the propagation time of the electromagnetic pulse along the parallel metal rods of a TDR probe. It is expressed in picoseconds (10^{-12} s). According to the formula given by Malicki and Skierucha, 1989 [36], this time is converted to soil volumetric water content. The increase of the propagation time at the beginning of the test reflects the increase of soil moisture caused by precipitation. The temperature curve shows the temperature variations between day and night, which is reflected by corresponding variations of the propagation time of the TDR pulse along the probe rods inserted into the soil. The increase of environmental temperature and consequently the temperature of the soil top layer decreases the TDR propagation time.

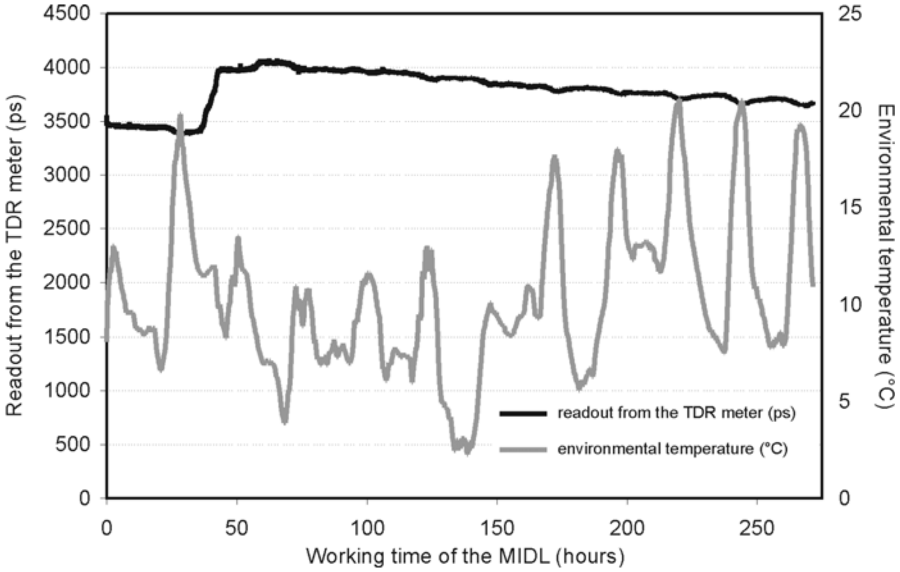


Fig. 35. Readouts of soil moisture and environmental temperature values collected by the MIDL Data Logger system

Totally the installed probes were measured about 65000 times. Each readout lasted about 1 second and then the SLAVE switched into the sleep mode for about 15 seconds and again the measurements were done. The collected data were stored in the SLAVE MMC memory card and the data from the card was sent to the PC computer via the MASTER unit by means of the described radio link.

The performed tests proved that the design and functional assumptions of the MIDL data logger system were fulfilled. The radio communication functioned correctly and the energy consumption was in the assumed limits.

4.4.4. *Summary*

The presented data logger system for collecting physical and chemical parameters of soil environment represents modern trends in the development of measurement systems that is manifested by low power consumption, high capacity of storage memory and possibility to control the measurement process from any place in the world using Internet connection or application of wireless radio connection in the case when the access to the monitored object is limited. Traditional sensors and measurement devices, such as soil thermometers, reflectometric soil moisture meters, soil tensiometers for water potential measurement, rain-gauges and others may be easily equipped with not expensive, intelligent communication interfaces enabling identification, addressing as well as hardware and software compatibility with the presented MIDL data logger. The system was designed in modular way for future modifications following the progress in the metrology of non-electrical quantities and the general technological development.

5. GENERAL SUMMARY

Mass and energy movement in the unsaturated soil at the soil-air interface, vadose zone, plays a central role in hydrology. The soil moisture at the land surface controls the transfer of precipitation into quick storm runoff and infiltration and the partition of the available energy into latent and sensible heat fluxes into the atmosphere. In addition, biological processes such microbial activity and plant growth depends on moisture and temperature status in the vadose zone.

The presented study shows the importance of the interdisciplinary work in the field of monitoring and modelling the processes in vadose zone. The new measurement equipment cannot be designed without the feedback from soil physicists and chemists, and they also should be aware of the advantages or disadvantages of applied measurement equipment and techniques. The continuous research for environmental sensors that should not influence the analyzed objects will never end because new technological developments and scientific efforts to understand nature will never end, too. The international scientific cooperation tools offered by the European Community can speed the process of application of physics in sustainable agriculture and sustainable development.

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7. INDEX OF FIGURES