PORTABLE LOW-COST MEASUREMENT SYSTEM DEVELOPMENT FOR SELF-POTENTIAL (SP) MONITORING IN SEVERE ENVIRONMENTAL CONDITIONS

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Introduction. In the field of environmental sciences self-potential (SP) data are generally considered as promising and reliable to investigate subsurface properties, especially for their ease of acquisition and simplicity in making qualitative interpretations (Revil and Jardani, 2013). Although it is one of the oldest geophysical method, the self-potential technique is currently adopted in a broad range of both qualitative and quantitative applications such as localizing and quantifying groundwater flows (Revil *et al.*, 2006; Jardani *et al.*, 2007; Jouniaux *et al.*, 2009), characterizing volcanic areas (Fournier, 1989; Di Maio *et al.*, 1996; Zhang and Aubert, 2003), monitoring contaminant plumes (Weigel, 1979; Naudet *et al.*, 2003), studying landslides (Perrone *et al.*, 2004; Naudet *et al.*, 2008) and geothermal exploration (Corwin and Hoover, 1976).

Self-potential is a passive method consisting in the measurement of the electric potential at a set of measurements stations. SP anomalies usually indicate the presence of a source of current in the ground due to subsurface disturbances (e.g. ground waters, geochemical phenomena). Three main contributions are widely recognized as a source of occurrence of SP signal (Revil and Jardani, 2013): the reduction-oxidation (redox) potentials, the diffusion potentials and the electrokinetic effect. The presence of an electronically conductive body creates an oxidizing area acting like an anode, and a reducing area acts like a cathode. This source of electrical potentials is referred to as the redox potential. Besides, the diffusion potential is related to the concentration gradients of ionic species in pore water. The electrokinetic effect (or streaming potential) is associated with the drag of excessive charge by the flow of water in porous rocks, causing a net source current density.

The SP method can also be applied as a monitoring method (Perrier *et al.*, 1998; Trique *et al.*, 2002) where a multi-electrode array is used to track the changes of the subsurface variables with time.

Monitoring strategies are generally required to evaluate the performance of engineered environmental control systems (e.g. remediation systems, leachate in landfills), to assess potential environmental impacts and public health risks from contaminant releases or to characterize environmental processes including chemical transformations, diffusion and advection phenomena or biological reactions, occurring in natural or engineered systems. Measuring the temporal variations of the electric potential is an effective tool to characterize and monitor these phenomena especially with regard to hydrogeological fluxes and electrochemical processes in the subsoil.

In several occasions the monitoring instrumentation is required to operate unattended or is exposed to environmental condition in which a degradation/oxidation of electromechanical parts is expected. In such situations the investment for the equipment could be economically unfeasible. In order to fulfill such requirements we developed a measurement setup with the main advantages of being portable, low cost, rugged, sufficiently accurate and optimized for low power consumption.

The measurement setup was first checked in laboratory for reliability and accuracy then was evaluated during a data acquisition campaign in Kenya to measure the SP variation linked to the fluctuations of the sea level during tidal events.

Apparatus.

Measurement system. The measurement system (Fig. 1a) was designed to monitor electrical potential in soil and sediments in locations where rugged instrumentation is required because of the harsh environmental conditions or when instrumentation security is critical.

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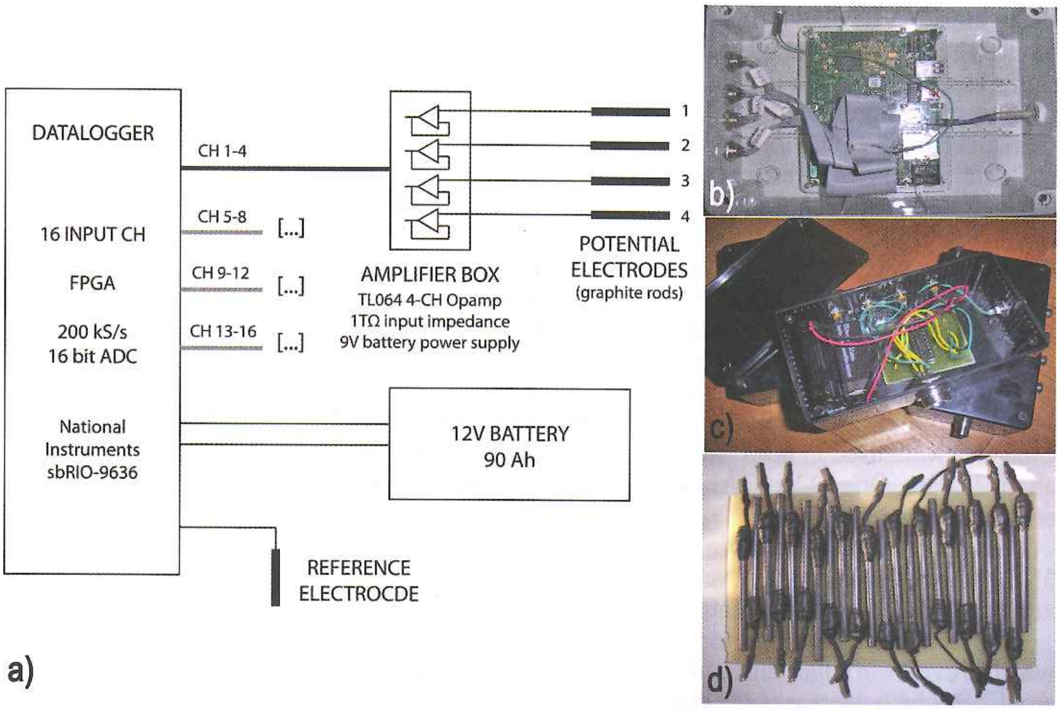

Fig. 1 – a) Block diagram of the measurement system designed for the self-potential monitoring; b) the data acquisition device NI-sbRIO-9636 by National Instruments; c) the amplifier boxes with the four-channel JFET-input operational amplifier (Texas Instruments TL064); d) the graphite electrodes.

The system consists of up to 16 channels to measure the voltages between the potential electrodes and a reference electrode connected to the system ground. The potential electrodes (Fig. 1d) are connected to 4 amplifier boxes (Fig. 1c) with a 4-channel buffer amplifier within each box and then the signals are fed to the acquisition device (Fig. 1b), powered by an external battery.

The data acquisition device is a NI-sbRIO-9636 by National Instruments. It features 16 single-ended (8 differential) 16-bit analog inputs at 200 kS/s, +/- 10V maximum input range, a real-time processor, a user-reconfigurable FPGA, 256 MB of DRAM for embedded operation and 512 MB of nonvolatile memory for storing programs and data logging. The 16-bit analog-to-digital converter allows to obtain a sensitivity (LSB) of 32 μV when the +/- 1V input range is selected, much higher than the minimum required of 0.1 mV (Revil and Jardani, 2013).

The sbRIO-9636 is hereby used as a standalone device and it is programmed for data logging and real-time data processing in LabVIEW programming environment. The acquisition is controlled by the FPGA and a sampling frequency of 1 kHz for each channel is chosen. The signals are then filtered and downsampled to 1 Hz by the real-time processor and data is stored on the internal nonvolatile memory.

Measurements of self-potential are subject to a number of errors such as the instability of the measuring electrodes and near surface noise due to anthropogenic activities (e.g. power lines, electromagnetic interference), telluric currents, meteorological effects or natural processes associated with soil electrochemical reactions or root activities (Perrier and Pant, 2005).

Other common sources of error are related to the measurement of voltage sources with high internal impedance (i.e. high contact impedance between electrode and soil). In this case the measurements are subject to loading errors and offset current errors occurring at the input of the acquisition device. In order to avoid these errors the input impedance of the acquisition device should be much higher than the source impedance (Keithley, 1998).

A four-channel JFET-input operational amplifier (Texas Instruments TL064) is used for this purpose, configured as a buffer amplifier (Jung, 2004). The JFET-input stage has an extremely high input impedance (1TΩ), much higher than the maximum expected contact resistance (in the MΩ range) typically measured in the field (Corry *et al.*, 1983). Moreover the low output impedance of the operational amplifier significantly reduces the error relative to the input offset current of the acquisition device. The TL064 features low input offset and input bias current thus further reducing the measurement errors. Furthermore, the TL064 is a low-power consumption device with a typical supply current of 200 μA per channel which makes it particularly suitable for a battery-powered system.

Printed circuit boards, amplifier boxes, cables and data logger chassis were self-made and all parts were assembled in laboratory. The connections between devices were made by means of shielded multicore cables with multipole connectors. Two 6LR61 9 V batteries (550 mAh capacity) were used to power each TL064 with a current drawing of 0.8 mA and a runtime of about 28 days. One 12 V, 90 Ah battery was used to power the data logger. The current drawing of the data logger was about 200 mA and the battery life of about 18 days.

The devices were tested in laboratory feeding a signal through each channel with a HP 33120A signal generator and verifying their performance (gain, distortion, frequency response and noise) with test equipment.

The key benefits of the proposed system design are: i) the low bias currents at input stage which prevent the polarization of the electrodes, ii) the low-impedance output of the operational amplifier which decreases the time required for settling of the multiplexed acquisition device, reducing ghosting and crosstalk between channels, iii) the high-impedance input of the amplifier which prevents the source impedance act as a voltage divider across the input of the acquisition device (loading error).

Electrodes. The measurements were performed with non-commercial electrodes (Fig. 1d): they were designed and realized in order to be cheap, resistant, high conductivity and easily portable. The basic requirements for the electrodes were durability, long-term stability, and low noise level. Usually non-polarizing porous-pot electrodes (typically Ag-AgCl, Cu-$CuSO_4$, or Pb-$PbCl_2$) are used to perform self-potential measurements. Numerous authors have investigated electrode designs that reduce measurement errors and are stable over long periods of time (Perrier *et al.*, 1997; Clerc *et al.*, 1998; Petiau, 2000). Measurement errors on the order of several (~5) millivolts should be expected with modern surveying equipment, and this can be significantly reduced by installing the electrodes (semi) permanently (Perrier *et al.*, 1997; Perrier and Pant, 2005).

Since graphite is an excellent electrical conductor and it is not affected by corrosion or electro-chemical effects, graphite electrodes are commonly employed for the application of electric fields such in electrokinetic remediation (Pazzi *et al.*, 2012). Electrodes made of graphite are also found commercially and used for geophysical monitoring purposes, to eliminate the damaging effects of corrosion and electrochemical degradation with time (Patent US 6,674,286).

The electrodes were made of carbon rod 100 mm long with a diameter of 6 mm; at the top a 5 cm carbon rope (®Sigrafil D2-3K Cord, Ø = 19 mm) was fixed with a self-fusing silicon rubber tape and a stainless steel male-connection was protected with heat shrinks. The connection with the amplifier boxes were carried out by means of wires with a stainless steel female-connection on one end. Furthermore, to avoid chemical oxidation all the connections were isolated by means of heat shrinks.

Graphite electrodes have been tested in laboratory in a 7-days experiment. The electrodes were placed in an experimental cell (Masi *et al.*, 2013) filled with quartz sand. The sand was saturated with tap water and the saturation was ensured by recirculating water inside

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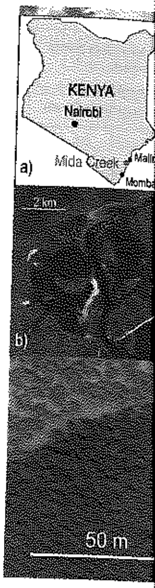

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Field tests. The instrumental apparatus has been tested during a scientific expedition in the north-western margin of Mida Creek (03°20'S, 40°5'E), a wide swamp about 25 km south of Malindi (Kenya) (Fig. 2a, b). Mida Creek is bordered by a mangrove belt consisting of three different species: *Avicennia marina* at the landward level and *Rhizophora mucronata* and *Ceriops tagal* at the seaward level. In the test area the whole belt is about 300 m wide: the area dominated by *Avicennia marina* is nearly the half and it is comprised between the average high water spring tide and the average high water neap tide. Within the creek the tidal range is at least 2 m, while on the surrounding coast is about 4.2 m (Vannini *et al.*, 2008).

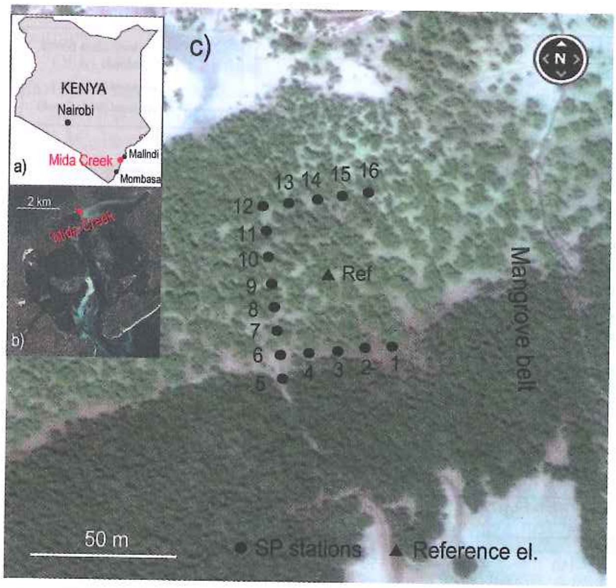

Fig. 2 – The test area in Kenya, about 25 km south of Malindi (a) in the north-western margin of Mida Creek (b); c) the C-shaped self-potential array.

Sixteen electrodes have been placed to obtain a C-shaped array (Fig. 2c): this configuration was selected in order to measure the self-potential variation along the sea-land direction (NS direction, electrodes 5-12) and along two profiles perpendicular to this direction (EW direction, electrodes 1-6 the southern and electrodes 12-16 the northern). The distance between two adjacent electrodes was 10 m. The reference electrode was located at the centre of the array as shown in Fig. 2c. The acquisition run for about 10 days (245 hours). The sampling interval was 1 s.

As an example, sample data corresponding to a semidiurnal cycle of the tide (12 hours duration) were selected from the whole time-series. The data have been pre-processed with a low-pass filter in order to remove the high-frequency content from the signals. Time-lapse mapping of the SP anomalies was obtained from the data at five different time instants (Fig. 3). The tide data were obtained by reconstruction from the tide heights recorded in Mombasa harbour. The data then were shifted in time to match the delayed arrival of the tide in Mida Creek, calibrated with on-site sea level measurements. The results are shown in Fig. 3. Negative SP anomalies are observed throughout the selected period and they were of the order of magnitude of hundreds millivolts with respect to the voltage at the reference electrode. The changes in the sea level clearly affect the SP response. This effect is most likely due to both the electrokinetic effect of the tidal volume flowing through the subsurface and the change in the ionic concentration and species of the pore water (Martínez-Pagán, 2010).

Conclusions. The design and implementation of a low-cost setup for SP monitoring in the field was discussed. The main advantages of such setup are the portability, the ruggedness and the low power consumption while ensuring a good measurement reliability. The system is capable of measuring the electric potential from up to 16 electrodes referenced to a common ground (reference electrode). The maximum acquisition rate in 200 kS/s per channel and the analog-to-digital converters resolution in 16 bits, allowing for a sensitivity of 32 μV. The recorded data is stored in an internal non-volatile memory for standalone operation. The measurement errors due to source loading and offset currents are minimized through the use of

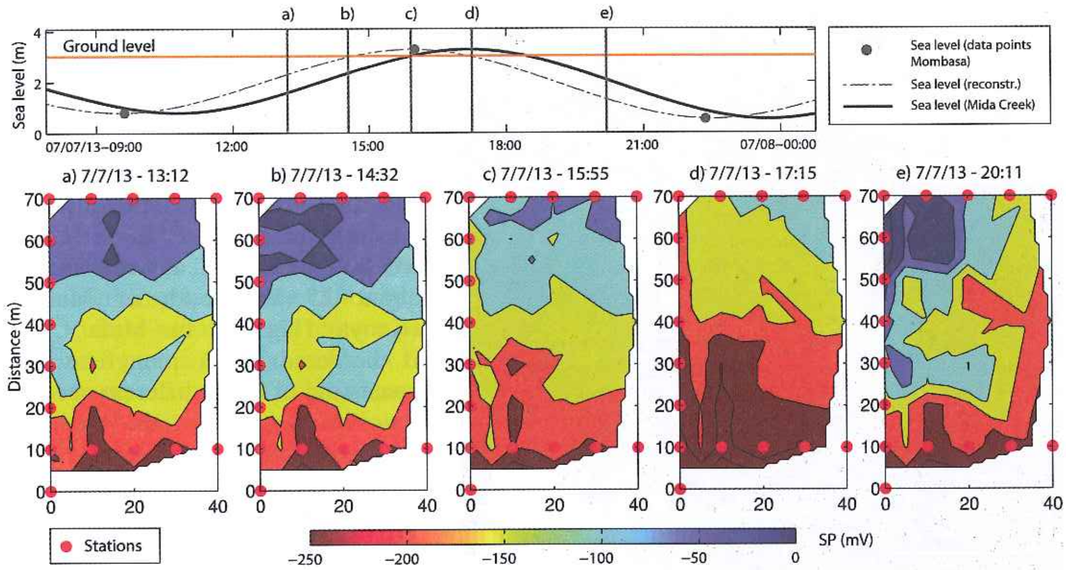

Fig. 3 – On the top the tide data (black dots) obtained from the Tide Table of Mombasa harbour, the reconstructed sea level (dashed black line) and the sea level in Mida Creek (solid black line) obtained shifting in time the reconstructed sea level to match the delayed arrival of the tide in Mida Creek recorded by on-site sea level measurements. On the bottom the time-lapse mapping of the SP anomalies obtained from the data at five different time instants (a-e).

high input impedance (1TΩ) buffer amplifiers. The system was tested in the field to monitor the SP anomalies due to the fluctuations of the sea level during tides. It is seen that the combination of various sources of SP due to the tides can affect the SP response with time. These effects are most likely due to the electrokinetic effect and diffusion potentials induced by the tidal fluctuations. The graphite electrodes used in this work for SP acquisition are proven to be stable in laboratory. In the field they were not subjected to relevant drifts over the entire duration of acquisition (10 days), as well.

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