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Reply to comment by D. Gibert and P. Sailhac on “Self-potential signals associated with preferential groundwater flow pathways in sinkholes”

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1. Introduction

[1] *Jardani et al.* [2006a] analyzed self-potential signals associated with the shallow groundwater flow in sinkholes. These signals were electrokinetic in nature resulting from the percolation of water in the ground and the drag of the excess of electrical charge that is present in the bulk pore water [e.g., *Leroy and Revil*, 2004]. Using the formulation of the electrokinetic coupling introduced by *Revil and Leroy* [2004] (and extended recently to unsaturated flow by *Revil et al.* [2007] and *Linde et al.* [2007] and to the inertial laminar flow regime by *Bolève et al.* [2007]), the electrical potential can be obtained from the solution of the Poisson equation. In this equation, the source term is equal to the divergence of the streaming current density, which in turn is equal to the excess of charge per unit pore volume time the seepage velocity. Generalizing the work by *Revil et al.* [2003b], *Jardani et al.* [2006a] used a cross-correlation method to reconstruct the possible shapes of the water table and to locate sinkholes at depth.

[2] Numerical simulations of self-potential signals associated with the flow of the groundwater shows the dipolar character of the source [e.g., *Revil et al.*, 1999; *Bolève et al.*, 2007]. In a multipole development of the self-potential field, the monopole contribution is equal to zero because of the global electroneutrality condition prevailing in porous materials. Therefore the leading term is the dipolar field.

[3] If the support volume of the source is small or if the sources are located along an interface (like the water table), it is possible to use the cross-correlation method to determine the position of the source or to image this interface by optimizing the semblance between the self-

potential anomaly, normalized by its power, and the signal modeled with the appropriate Green function [see *Birch*, 1993, 1998]. The Green’s function can be computed analytically for a homogeneous ground but it can be also computed numerically accounting for the real (or inverted) electrical resistivity distribution and appropriate boundary conditions for the self-potential field. The cross-correlation approach has been used as a source localization method in acoustic [e.g., *Omologo and Svaizer*, 1994; *Thomann*, 1996], in seismology [e.g., *Saccorotti and Del Pezzo*, 2000], in magnetoencephalography [e.g., *Cao et al.*, 2002], and in the localization of contaminant plumes in the atmosphere [e.g., *Roussel et al.*, 2002], just to cite few of them. This is therefore not a new approach. We discuss below the validity of this approach to self-potential data. Note that this approach was also used very successfully by *Revil et al.* [2001], *Iuliano et al.* [2002], and *Revil et al.* [2003a, 2003b] and recently by *Jardani et al.* [2006b] and *Bhattacharyal et al.* [2007] to localize the causative source of self-potential anomalies. Finally, we will discuss briefly future exciting trends in the inversion of self-potential signals.

2. Canonical Example

[4] We consider here the canonical problem of finding a dipole in the ground. We considered a Cartesian coordinate system (x, y, z) with the z axis positive downward. We assumed that the electrical field $\mathbf{E}(\mathbf{r})$ is due a single dipole with a moment \mathbf{d} ,

$$\mathbf{E}(\mathbf{r}) = \mathbf{d}\nabla\mathbf{G}, \quad (1)$$

where \mathbf{G} is the Green function of the source. The computation of the Green’s function can account for the dipolar nature of the source, boundary conditions (e.g., with the image method [e.g., *Linde and Revil*, 2007]), the resistivity distribution of the system, and topography. This can be accomplished with the use of finite difference or finite element schemes to solve the forward problem.

[5] We note E the modulus of the electrical field $\mathbf{E}(\mathbf{r})$. The power associated with the observed electrical field is

$$\wp(E) = \int_S E^2(\mathbf{r})dS \quad (2)$$

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$$\varphi(E) = \sum_v d_v \int_S \mathbf{E}(\mathbf{r}) \frac{\partial \mathbf{G}}{\partial v_p} dS, \quad (3)$$

where $v = x, y, z$, $v_p = x_p, y_p, z_p$. The projection of S onto the (x, y) horizontal plane is adapted to a rectangle with sides of total length $2X$ and $2Y$ along the x and y axis, respectively, and corresponding to the horizontal dimensions of the support volume V . We note $g(z)$ the topography regularization factor defined by [Iuliano *et al.*, 2002]

$$g(z) = \left[1 + \left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2 \right]^{1/2}. \quad (4)$$

The case $g(z) = 1$ corresponds to no topography. Iuliano *et al.* [2002] defined the semblance functions by the following integrals:

$$\eta_v(r_p) = C_v^p \int_{-X}^X \int_{-Y}^Y \mathbf{E}(\mathbf{r}) \frac{\partial \mathbf{G}(\mathbf{r}_p - \mathbf{r})}{\partial v_p} g(z) dx dy, \quad (5)$$

and where the normalization constant C_v^p is defined by

$$C_v^p = \left[\int_{-X}^X \int_{-Y}^Y E^2(\mathbf{r}) g(z) dx dy \int_{-X}^X \int_{-Y}^Y \left[\frac{\partial \mathbf{G}(\mathbf{r}_p - \mathbf{r})}{\partial v_p} \right]^2 g(z) dx dy \right]^{-1/2}. \quad (6)$$

The semblance function is therefore the normalized scalar product between the form anomaly factor indicated by the self-potential measurements at the ground surface and the form factor associated with a hypothetical dipolar source located in the source volume. The components of the semblance function have the following property $-1 \leq \eta_v(r_p) \leq 1$. The scalar semblance function corresponds to the norm of the vector $\boldsymbol{\eta}(\eta_x, \eta_y, \eta_z)$,

$$\eta(r_p) = \sqrt{\eta_x(r_p)^2 + \eta_y(r_p)^2 + \eta_z(r_p)^2}. \quad (7)$$

[6] For the canonical problem of finding a dipole in a homogeneous ground, the position of the source is given by $\text{Max}[\eta(r_p)]_V$ (where $\text{Max}[f(x)]_{x_1}^{x_2}$ is the maximum of the function $f(x)$ over the support (x_1, x_2)). In other words, the position of the source is obtained by maximizing the semblance between the form anomaly factor and the form factor associated with the dipolar source distribution. The coordinates of the vector $\boldsymbol{\eta}(\eta_x, \eta_y, \eta_z)$ at this point provides the directivity of the dipole moment \mathbf{d} at the source. The advantage of this method by comparison with the wavelet approach is to be able to account for topography, boundary conditions, and the resistivity distribution of the medium. The influence of the position of the electrodes in the source localization problem has been studied in details by Alecu *et al.* [2004] for applications in electroencephalography.

[7] Recently, Crespy *et al.* [2008] performed a controlled sandbox experiment to test the validity of the

cross-correlation approach with real self-potential data. In this experiment, ~ 0.5 mL of water was abruptly injected through a small vertical capillary with its outlet located at a depth of 15 cm in the middle of the sandbox. The self-potential signals resulting from the pulse injection of water were measured using 32 sintered Ag/AgCl electrodes located at the surface of the tank. These electrodes were connected to a voltmeter with a sensitivity of $0.1 \mu\text{V}$ and an acquisition frequency of 1.024 kHz.

[8] We applied the cross-correlation method to the self-potential anomaly observed at the top surface of the tank when it reached its maximum amplitude. The maximum of the scalar semblance function was obtained for a vertical dipolar source located at position $S_p(0 \pm 2 \text{ cm}, 0 \pm 2 \text{ cm}, 14 \pm 2 \text{ cm})$. This was consistent with the actual position of the outlet of the capillary in the tank $S_{true}(0 \text{ cm}, 0 \text{ cm}, 15 \text{ cm})$ and the physics of the primary flow problem. This illustrates the usefulness of the cross-correlation approach in locating precisely the causative source of self-potential signals at depth when the support volume of the source is small with respect to the distance between the barycenter of the source and the observation stations usually located at the ground surface.

[9] We point out that we believe in the usefulness of the cross-correlation approach as being a preliminary step toward more sophisticated inversion approaches. Such approaches are briefly outlined in section 3.

3. Future Trends

[10] Several algorithms have been developed recently to interpret self-potential data using deterministic approaches based on regularized least squares techniques (Jardani *et al.* [2006c], Minsley *et al.* [2007], Linde and Revil [2007], and Jardani *et al.* [2007a] just to cite few of them). We believe that these approaches are much more fruitful than the cross-correlation method or the wavelet analysis of potential fields because they account, in the regularization of the inverse problem, about the physical nature of the primary flow problem giving rise to the self-potential anomalies. For example, Jardani *et al.* [2006c] inverted self-potential data using the formulation introduced by Fournier [1989] that relates the self-potential signals to the shape of the water table. Linde and Revil [2007] inverted self-potential over a contaminated plume to obtain the distribution of the redox potential in the aquifer. In both cases, the inversion was accounting explicitly about the physical nature of the primary flow problem (electrokinetic conversion of the groundwater flow in the first case, the biogeobattery model in the second case). We strongly believe that the future of the inversion of self-potential data is there. In addition, the joint inversion of self-potential data with other geophysical data sets (see, e.g., Jardani *et al.* [2007a], who developed a joint inversion of self-potential and EM-34 resistivity data) seems already a very promising approach in hydrogeophysics.

4. Conclusions

[11] 1. While the wavelet analysis is a useful tool to locate the causative source of magnetic anomalies, it is a useless

method for the interpretation of self-potential data. This is because of its inherent inability to account for the resistivity distribution of the medium, appropriate boundary conditions, topography, and the physical nature of the primary flow problem.

[12] 2. All the conclusions reached by *Jardani et al.* [2006a] are perfectly valid. The detection of crypto-sinkholes with the self-potential method is very promising approach to this crucial geohazard problem in Normandy (France) and elsewhere in the world.

[13] 3. Recent developments to solve the inverse problem of self-potential signals are based on the use of deterministic approaches based on regularized least squares techniques and making use the differentiability of the objective function. An example of these methods is the MAP method (maximum a posteriori estimate [see *Tarantola and Valette*, 1982]). The use of automatic differentiation [see *Rath et al.*, 2006; *Sambridge et al.*, 2007] could be a very efficient approach to determine the Jacobian of the forward model used in these optimization algorithms. The use of these approaches is the topic of future works where, in particular, we wish to perform a joint inversion of self-potential and thermal data to obtain the three-dimensional distribution of the seepage velocity in the ground. This would represent a breakthrough in hydrogeology.

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