Variogram-based inversion of time-lapse electrical resistivity data: development and application to a thermal tracing experiment

Hermans T.*(1, 2) and Nguyen F. (1)

(1) Liege University, Belgium – (2) F.R.S. - FNRS, Belgium *thomas.hermans@ulg.ac.be

1. Introduction

Electrical resistivity tomography (ERT) has become a popular imaging methodology in many applications given its large sensitivity to subsurface parameters and its relative simplicity to implement. More particularly, time-lapse ERT is now increasingly used for monitoring purposes in many contexts such as water content, permafrost, landslide, seawater intrusion, solute transport or heat transport experiments [1 and references therein].

Specific inversion schemes have been developed for time-lapse data sets. However, in contrast with static inversions for which many techniques including geostatistical, minimum support or structural inversion are commonly applied [1], most methodologies for time-lapse inversion still rely on non-physically based spatial and/or temporal smoothing of the parameters or parameter changes.

2. Formulation of the problem

We have implemented a time-lapse inversion scheme using the parameter change covariance matrix as regularization operator in a difference inversion scheme [2]. The objective function is expressed as

$$\psi_{\mathrm{diff}}(\Delta\mathbf{m}) = \left\| W_d[\mathbf{d}-\mathbf{d}_0+f(\mathbf{m}_0)-f(\mathbf{m})] \right\|^2 + \lambda \left\| C_{\Delta m}^{-0.5}\Delta\mathbf{m} \right\|^2$$

- W_d is the data weighting matrix
- **d** and $\mathbf{d_0}$ are the data sets corresponding to the considered time-step and to the background
- **m** and $\mathbf{m_0}$ are the corresponding models
- f() is the forward operator
- **Δm** is the parameter change (resistivity)
- $\mathbf{C_{\Delta m}}$ is the parameter change covariance matrix (computed using a variogram or logging data)
- λ the regularization parameter.

3. Synthetic model

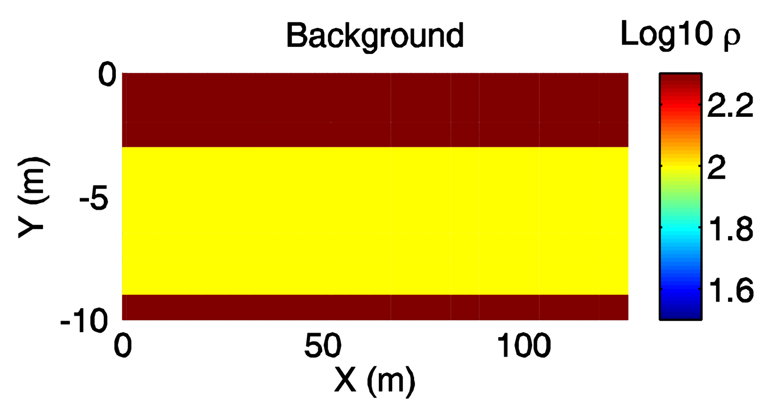

Fig 1. Background model

The background model (Fig. 1) is a three-layer model with resistivity 200 Ohm.m (top and bottom) and 100 Ohm.m (middle). The simulated changes take place in the middle layer with a minimum resistivity of 20 Ohm.m (Fig. 2, top-left).

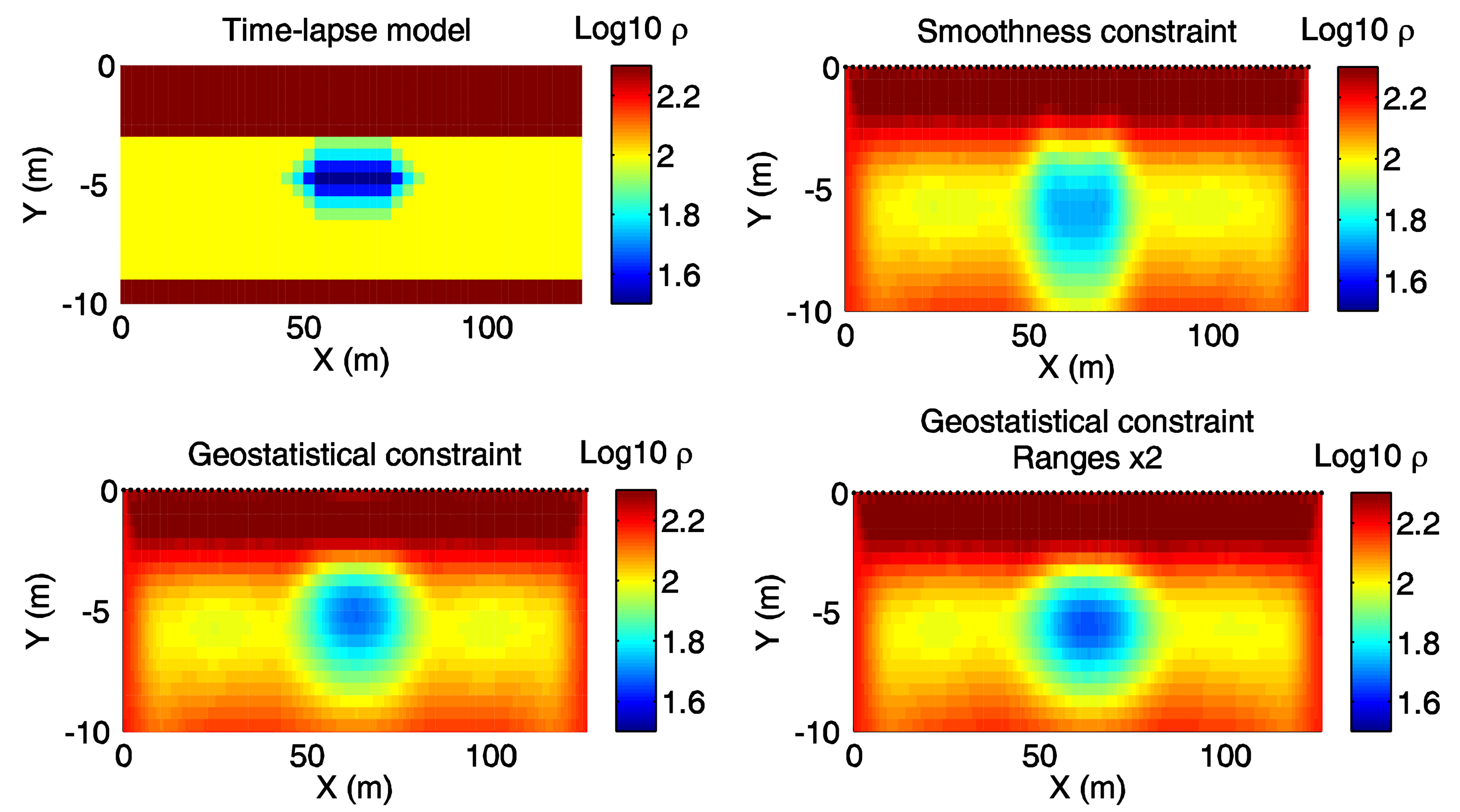

Fig 2. True changes and inverted solutions with various constraints

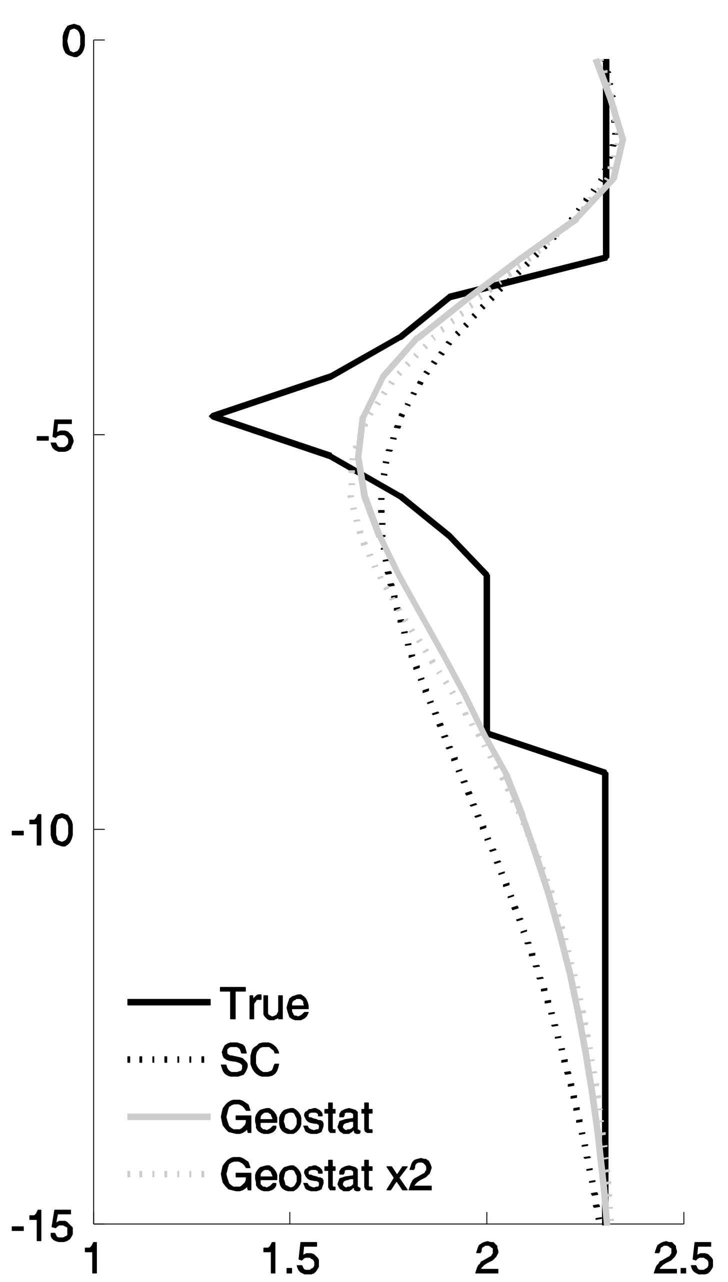

Fig 3. Comparison at X = 63 m

The vertical and horizontal ranges of the change in resistivity were computed based on the true model (2.2 and 20 m); The geostatistical constraint solution (Fig. 2, bottom-left) is less smooth and recovers better the amplitude and location of the maximum change (Fig. 3) than the smoothness constraint solution (Fig. 2, top-right). An error on the ranges (Fig. 2, bottom-right), does not degrade too much the solution, even if it is slightly smoother (Fig. 3)

4. Field experiment

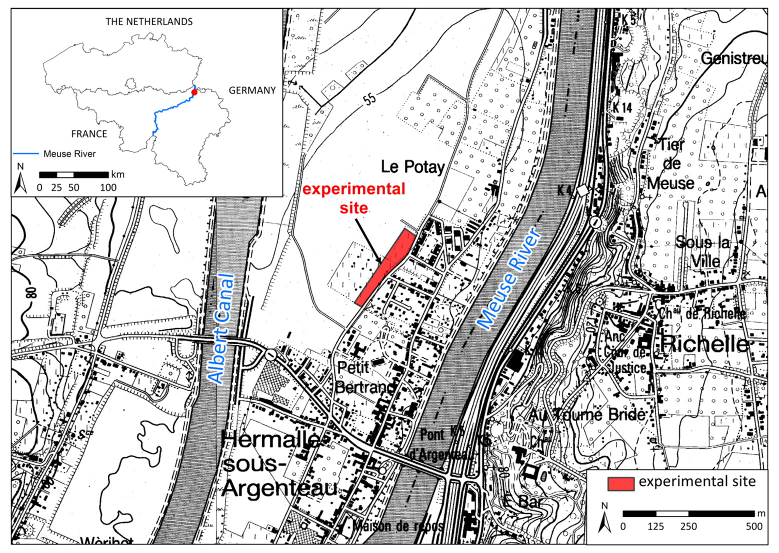

Fig 4. Field site

The study site is located in the alluvial plain of the Meuse River in Belgium (Fig. 4). A thermal injection and pumping experiment was carried out. Heated water was injected at 3 m³/h with an increase in temperature of 25°C during 24h. The temperature was monitored using cross-borehole ERT (Pz13 and Pz17 in Fig. 5) and direct measurements (Fig. 5).

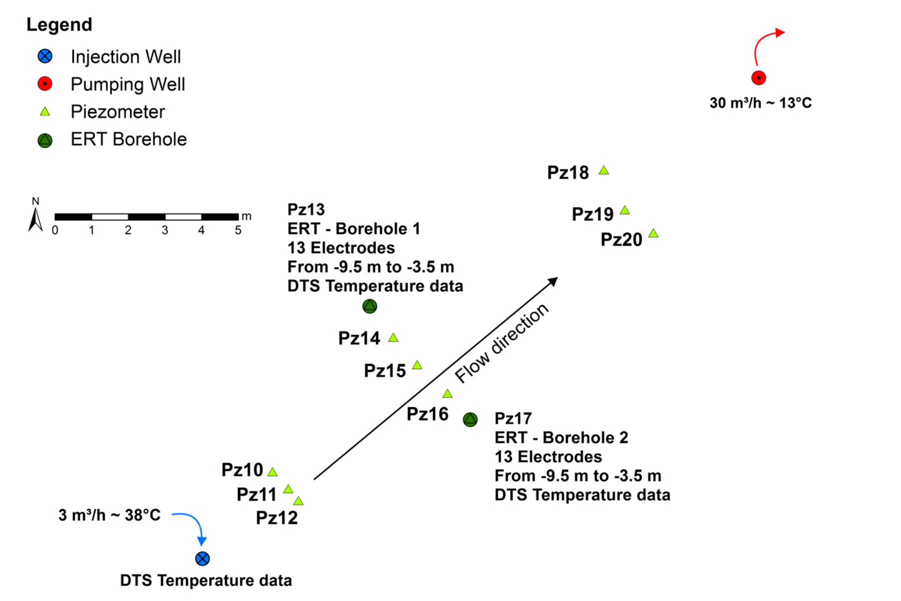

Fig 5. Experimental layout

5. Results

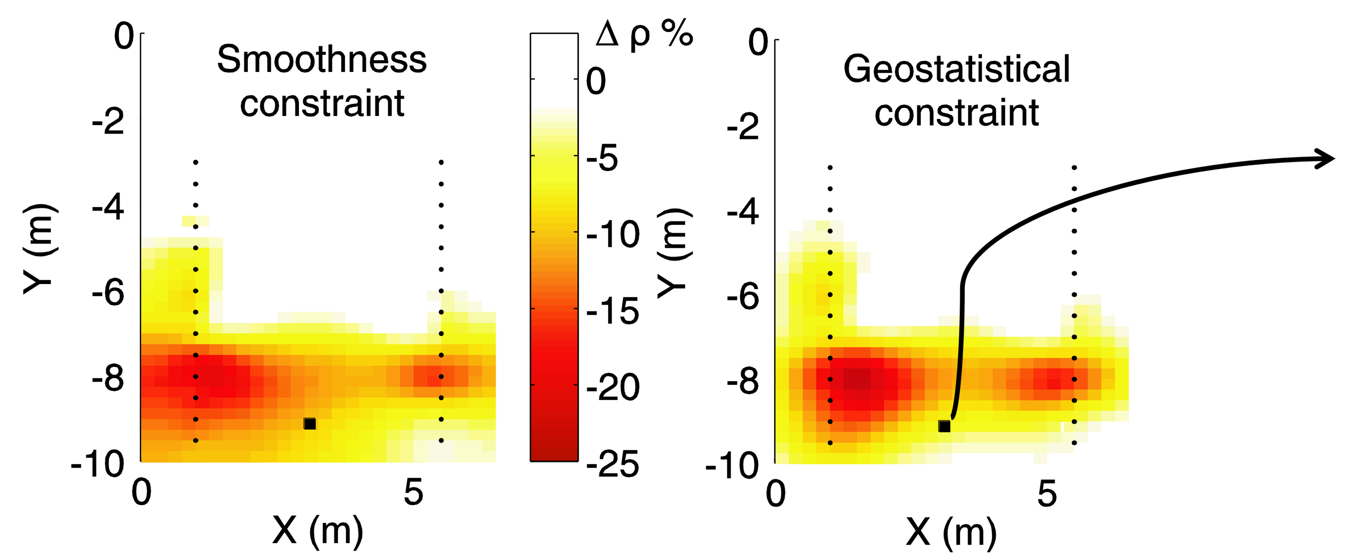

Fig 6. Time-lapse changes 30h after injection

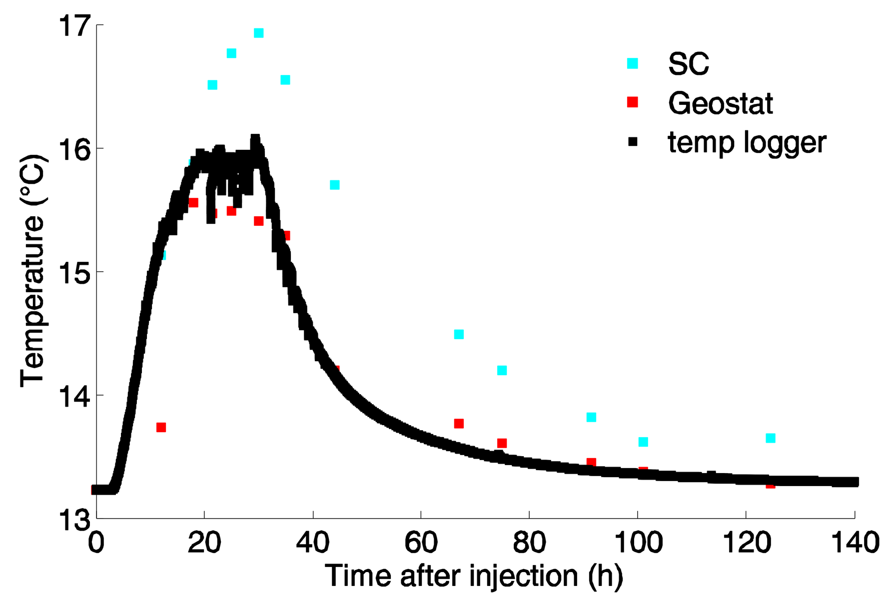

Fig 7. Comparison in Pz 15

We used DTS measurements to compute the variogram of temperature changes at each time step (between 0.9 and 1.9 m) and used it to calculate the geostatistical constraint (Fig. 6, right). Resistivity were transformed into temperatures considering the increase of water electrical resistivity with temperature (about 2%/°C at 25°C)[3].

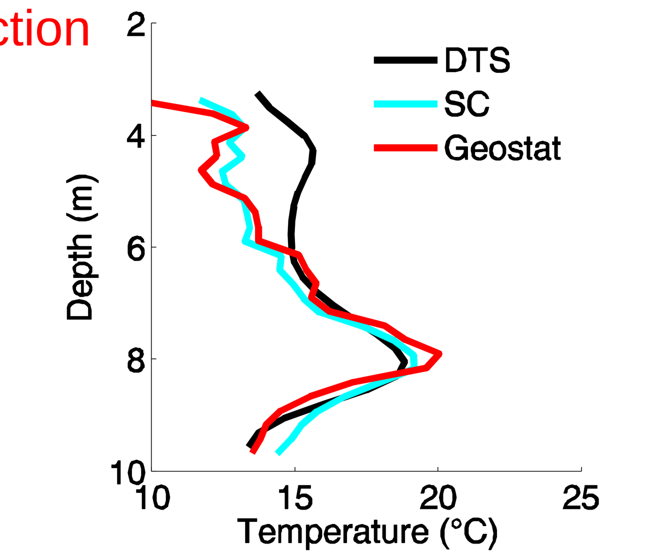

Fig 8. Comparison with DTS

Compared to a true breakthrough curve (Fig. 7), the temperatures are better estimated when variograms are used as constraint for ERT inversion. The maximum and tailing part of the curve are better recovered. The effect is mainly visible in low sensitivity zone (middle of the panel), near boreholes solution are more similar (Fig. 8).

6. Conclusion and perspectives

- The proposed methodology replaces the smoothness constraint commonly used in time-lapse ERT inversion by a physically based constraint related to the model parameter covariance matrix (or variogram).
- The method allows to reduce the smoothing of resistivity changes in time-lapse images. In the field case, an improvement is clearly visible by comparison with direct temperature measurements.
- The integration of spatio-temporal variogram constraints will enable to extend the method to 4D inversion scheme [4].

References

[1] Hermans et al. 2014. Geophysical methods for monitoring temperature changes in shallow low enthalpy geothermal systems. Energies, 7, 5083-5118.

[2] Kemna et al. 2002. Imaging and characterization of subsurface solute transport using electrical resistivity tomography (ERT) and equivalent transport models, Journal of hydrology,267, 125-146.

[3] Hermans et al. 2015. Quantitative temperature monitoring of a heat tracing experiment using cross-borehole ERT, Geothermics, 53, 14-26.

[4] Karaoulis et al. 2014. 4D Time-lapse ERT inversion: Introducing combined time and space constraint. Near Surface Geophysics, 12, 25-34.