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SIMULATION OF ERT SURFACE-TO-TUNNEL MEASUREMENTS

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Abstract

The applicability of surface-to-tunnel electrical resistance tomography (ERT) measurements using a simulation tank for imaging subsurface targets is studied in this work. The tank was filled with water and inside of it was placed firmly a plastic construction where all targets were placed. Some of the targets that used were: a void plastic cylinder (resistive target) and metal plates (conductive target). Data were collected with a multichannel resistivity meter.

The initial scope for these tests was to verify the reliability of developed inversion software which was modified to cope with the specific measurements (surface-to-tunnel). Furthermore, during several experiments different electrode arrays (standard as well as new optimized) were validated. In our attempt to show the advantages of surface-to-tunnel measurements we analyzed the resolution for each configuration of traditional (surface) and surface-to-tunnel arrays. Studies also included testing the electrode displacement effect and also the effect of the tunnel size into the measurements.

Key words: *surface-to-tunnel, ERT, simulation-tank.*

Περίληψη

Στην παρούσα εργασία με τη χρήση μίας δεξαμενής προσομοίωσης πραγματικών συνθηκών πραγματοποιήθηκαν μία σειρά πειραμάτων ώστε να μελετηθεί η εφαρμογή της διάταξης επιφανειακών-τούνελ ηλεκτροδίων. Στη δεξαμενή τοποθετήθηκε ειδικά κατασκευασμένη διάταξη για την τέλεση των πειραμάτων. Χρησιμοποιήθηκαν μία σειρά από ετερογενείς στόχους (αντιστατικούς και αγώγιμους) και η δεξαμενή πληρώθηκε με ομογενές μέσο (νερό). Για τη λήψη των μετρήσεων χρησιμοποιήθηκε πολυκάναλο όργανο.

Ο αρχικός σκοπός των πειραμάτων ήταν να επιβεβαιωθεί η ορθότητα του κώδικα, ο οποίος προσμαρμόσθηκε ώστε να είναι εφικτές αυτού του είδους οι μετρήσεις. Επιπλέον εφαρμόσθηκαν καινούρια πρωτόκολλα, όπως επίσης και έγινε χρήση βέλτιστων μετρήσεων. Τέλος, μελετήθηκε η επίδραση των λανθασμένης θέσης των ηλεκτροδίων και η επίδραση του μεγέθους του τούνελ στα δεδομένα.

Λέξεις κλειδιά: *Τούνελ, δεξαμενή προσομοίωσης.*

1. Introduction

ERT measurements are routinely being used in order to map the subsurface. Initial limitations of surface electrode arrays regarding the resolution with depth were overcome by introducing electrodes in boreholes. Among existing electrode arrangements one special case is when electrodes are used in tunnels. Actually, installing electrodes in tunnels is an easy way to obtain information of increased sensitivity by taking advantage of the proximity of the tunnel to the prospected targets. Application of electrodes in tunnels has been proposed in geotechnical investigation (Danielsen et al., 2010), as well as in the case of in-tunnel mining prospection (van Schoor et al., 2010). The present study deals with the case of ERT measurements obtained in a combined mode using electrodes both on surface and in tunnel. Such an arrangement is expected to provide an increased imaging resolution for the area in-between the tunnel and surface and can be used for geological, geotechnical and mining applications. Only limited application of such a measuring mode has been reported in literature describing surface-to-tunnel application for very deep mining (Sasaki et al., 1993).

Although this arrangement shares many similarities with the cross-hole ERT mode the major difference has to do with the fact that measurements associated with surface electrodes exhibit different sensitivities compared to measurements involving tunnel electrodes. Further, the tunnel itself may be a source of significant noise for the measurements. Other issues that need to be investigated have to do with the sensitivity of the results in relation to the accuracy of the electrode positioning which may be problematic for the case of surface-to-tunnel measurements.

Simulation tank simulations are being used as a bridge between synthetic and real data. Simulation tank data verify computer simulations and at the same time provide more realistic measurements which reassemble more closely the actual field data. At the same time simulation tank data allow to use not only simple but also complicated models. Several such models were tested using different array protocols in order to evaluate the tunnel-to-surface measuring mode.

2. Methodology

2.1. Electrode Arrays - Protocols

An existing Matlab based 2.5D modelling /inversion algorithm (Karaoulis 2009; Tsourlos , 1995) has been modified in order to accommodate the tunnel-to-surface measuring mode. The scheme is being based on a finite element forward solver (Figure 1) while inversion is performed via an iterative smoothness constrained scheme. The forward solver, given the coordinates of the electrodes, generates an appropriate mesh so that the forward and inverse calculations can take place.

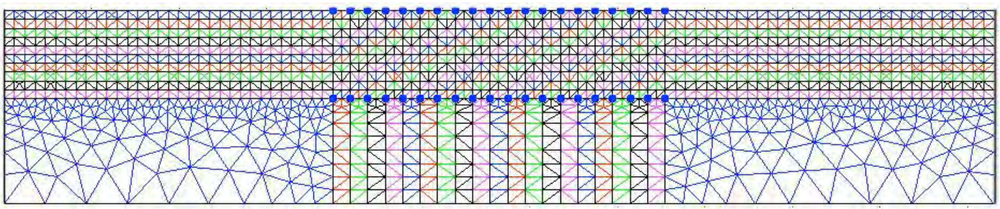

Figure 1 – Mesh (created by FEM) used using surface to tunnel measurements.

Tunnel-to-surface measuring mode can be applied in order to increase the investigation depth of the geoelectrical measurements when there is the possibility of installing electrodes within an existing tunnel (see Figure 2).

It is noted that for the tunnel-to-surface there are no standard array configuration that can be used. However due to the analogy with the cross-hole ERT arrangement arrays proposed and used in this mode can be transferred and used in the tunnel-to-surface case. The electrode arrays that have been used are: bipole-bipole (bb), pole-dipole (pd) and pole-tripole (pt), where A, B are the current electrodes and M, N are the potential electrodes (Figure 3).

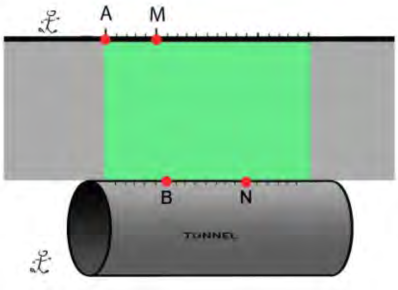

Figure 2 – Application of surface-to-tunnel arrays (A, B current electrodes, M, N potential electrodes).

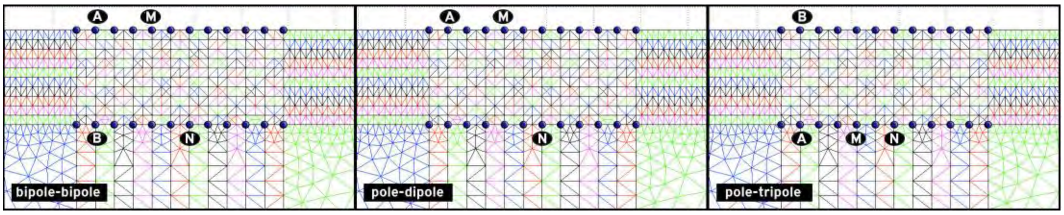

Figure 3 – Protocols that were used for this work: Bipole-bipole, Pole-dipole and Pole-Tripole.

3. Simulation Tank – Experiment Setup

The simulation tank experiments took place at the Laboratory of Geophysics & Seismology, Department of Natural Resources & Environment (Technological Educational Institute of Crete) (Figure 4). The simulation tank is made by Plexiglas and is placed within a metal framework to increase its stability. The capacity is $1m^3$ and can hold weight more than 10^3 liters of water. During the experiment the tank was filled with drinking and deionized water, so conductivity could be altered at will.

Figure 4 – Simulation tank used for the experiments in Laboratory of Geophysics & Seismology (Department of Natural Resources & Environment).

On top of the tank a special construction to simulate tunnel-to-surface measurements was placed. The construction consists of three parallel plastic pipes: green, blue and black (each has a different purpose) (Figure 5). The green pipe contains a series of electrodes that are situated on surface of water. Blue coloured part contains electrodes that will be induced inside medium and black pipe contains electrodes that simulate a “tunnel” condition since is fully sealed and air filled. The whole construction was built with plastic parts (for conductivity reasons) and additionally has the ability to adjust the distance between the series of “surface” and “tunnel” electrodes (form 5 to 25cm). The probe spacing between electrodes is fixed to 2 cm while 20 electrodes have been placed in each of the pipe. (60 electrodes total). The blue pipe has the extra ability to slightly shift its position horizontally so that the effect of electrode displacement can be studied. The black pipe has a diameter of 7 cm. The whole construction can be firmly placed on tank so that can be stable as experiment takes place.

Figure 5 – Construction used for the experiments. It consists of three parts (green, blue and black) which distance can be chosen by will. Whole construction is made by plastic parts for conductivity reasons.

The equipment that was used for obtaining the measurement is the single channel resistivity meter Syscal R1 Plus (Iris Instruments) (Figure 6, left) while a pocket conductivity meter was used to measure in situ the conductivity of the water that filled the tank (Figure 6, right).

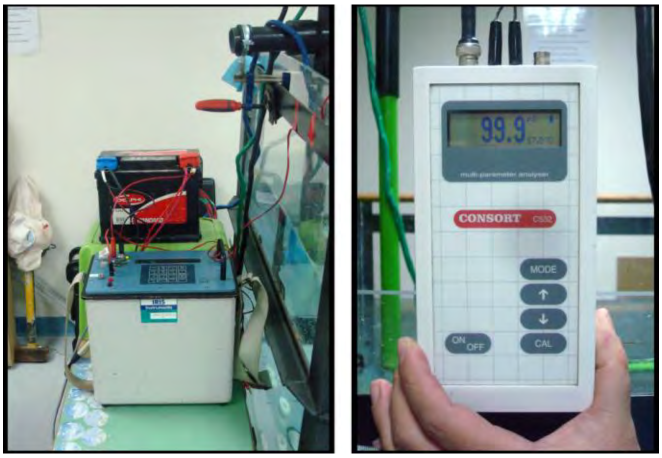

Figure 6 – (left) “Iris” instrument for acquiring electrical data, (right) “Consort” a conductivity meter for measuring medium inside tank.

Some typical targets that were used include: void plastic cylinder filled with air or polystyrene pieces (resistive objects) and metal plates (as conductive objects) (Figure 7). The distance between the surface and "tunnel" arrays that was tested was 10, 15 and 20 cm. The conductivity of drinking water was measured to 34 ohm and for deionized water to 100 ohm.

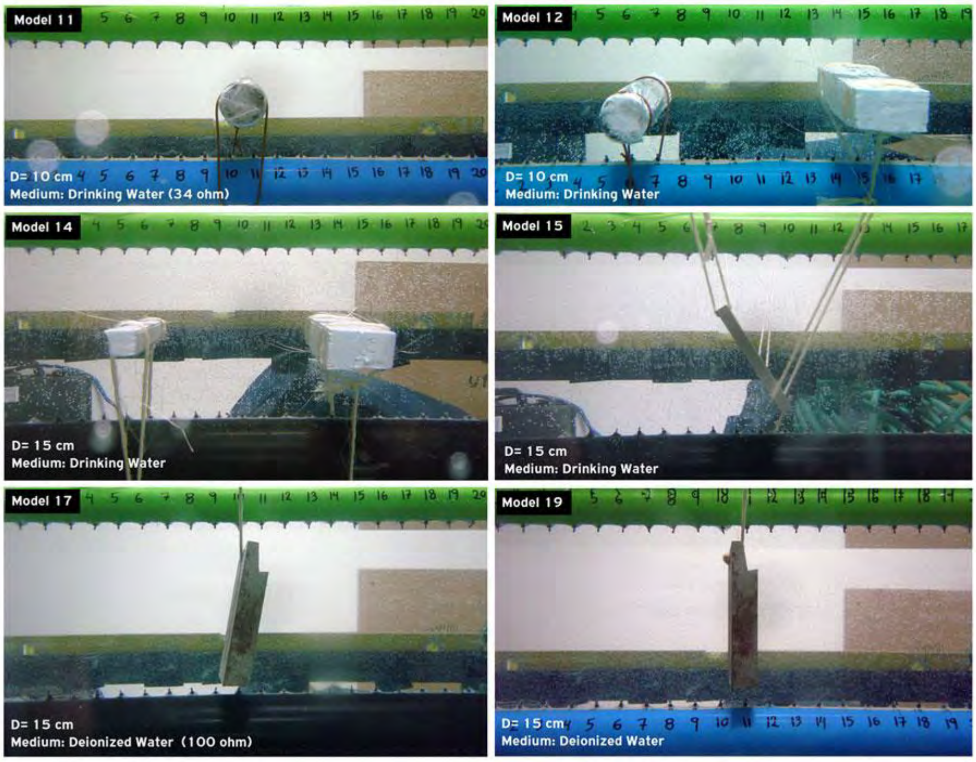

Figure 7 - Targets for detection embedded inside water (void cylinder, polystyrene, metal plates).

4. Results

4.1. Resolving ability of tunnel-to-surface measuring mode

Initial tests are related to establishing the increased resolving ability of surface-to-tunnel array over standard measuring modes (i.e. surface measurements). For the particular example the tank was filled with deionized water (100 ohm resistivity) and a metal plate (see Figure 8) was used as a target. Protocols tested involved bipole-bipole, pole-dipole and pole-tripole arrays.

For all cases individual surface and tunnel data sets were inverted and results are compared with the inversions of the surface-to-tunnel arrays. The results are presented in Figure 9 and it is clear that surface measurements sensitivity is limited only to the top part of the model: the metal target is identified only close to electrodes for all tested arrays. Same happens when electrodes inside earth since only the part of the target which is close to interior electrodes is reconstructed. On the other hand when surface-to-tunnel array is used resolution is increased and the modeling body is clearly depicted throughout its length suggesting that this type of measuring mode is optimum. Comparing the protocols it can be observed that pole-tripole describes better the limits of the target. Bipole-bipole depicts the conductive body is less accurate and pole-dipole is more accurate at bottom area.

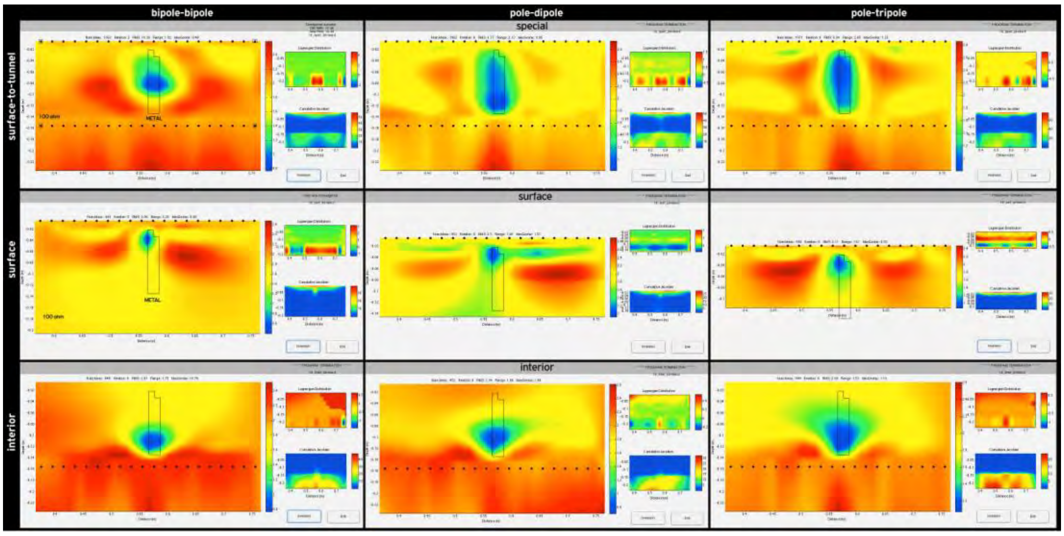

Figure 8 - Inversion results using conductive target inside water.

4.2. Comparing Array Protocols

Furthermore optimum measurements were created in order to reduce acquisition time and inversion procedure time. Starting from a complete large data set a limited initial set is generated using a criterion based on Jacobian matrix (Athanasiou et al., 2007). Subsequently, this initial set is enriched with additional optimum measurements which are selected on the basis of a resolution matrix analysis following the procedure proposed by Wilkinson et al (2006).

As it can be seen in Figure 10 inverted results of the optimized data sets for the model 12 (see Figure 8) produce at least equally good results and in many cases their inverted images are superior to the standard arrays' results. Bipole-Bipole optimum sets have resistivity values closer to the target resistivity than the standard data set. Pole-Dipole optimum protocols define better the target limits than the standard data set. Pole-Tripole optimum protocol has better results (taking into account % RMS error) than the standard set of measurements.

The obvious benefit of choosing optimum arrays instead of standard protocols is that they can produce these results by just using only a small portion of the complete set of measurements. In the presented model (Figure 10) and for all tested arrays all standard sets of measurements include more than 1900 measurements while all optimum sets involve less than 500 measurements. Apparently both measuring and inversion time is reduced in the case of optimum arrays.

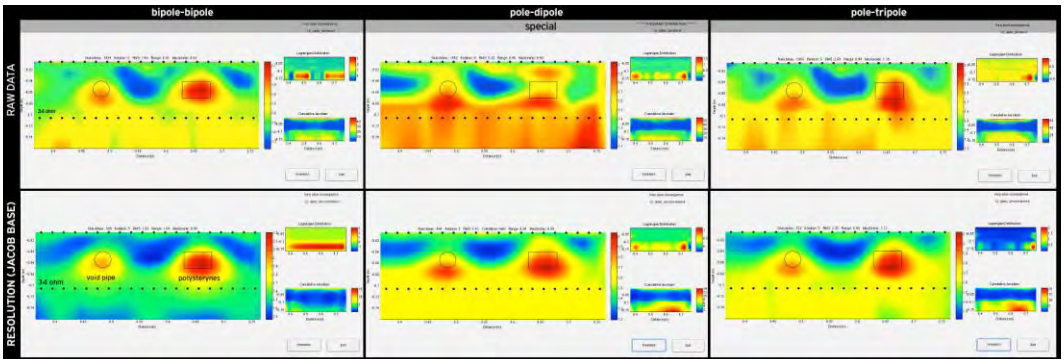

Figure 9 – Inversion results using optimum measurements: Jacobian matrix (second row), Resolution matrix (third row).

4.3. Tunnel Effect

A particular problem of the tunnel-to-surface measuring mode has to do with the effect that an air-filled tunnel has to our measurements and subsequent inversions. Several model and array configurations were tested to study this effect by using an air filled pipe (black pipe in Fig. 11) to simulate the effect of a tunnel to our measurements.

Figure 10, depicts the raw data inversions (top row) for several arrays when an air filled “tunnel” is considered. It is clear that the existence of the tunnel affects inversions severely generating major artifacts. Actually it can be easily seen that the amount of induced noise has to do with the size of the tunnel (tunnel diameter) in relation to the inter-electrode spacing. There are many possible procedures to alleviate this affect but the simplest (and crudest one) is to ignore measurements which have spacing comparable (i.e equal or smaller) to the diameter for the tunnel (figure 11, bottom row).

As it can be seen in Figure 11 for all protocols after applying this type of correction target appears more clearly this procedure may affect the resolving ability of the measuring mode near the tunnel area.

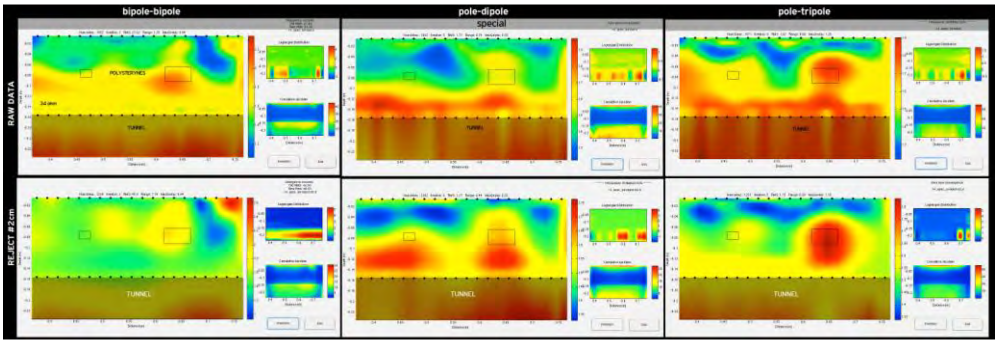

Figure 10 – Inversion results depicting target above a tunnel raw data (top row) and corrected data (bottom row).

4.4. Electrode Displacement

In real case situations many times electrode displacement can occur and this can lead to erroneous results. We used the simulating tank to test this effect using all different protocols (bb, pd, pt). The “tunnel” electrodes were slightly displaced (1 inter-electrode spacing step) and measurements were obtained for different modes. Data were then inverted as if top and “tunnel” electrodes were aligned.

The derived results suggest that protocols have varying sensitivity to this source of noise. Figure 11 shows the misfit that occurs when there is offset between the two arrays, using all protocols.

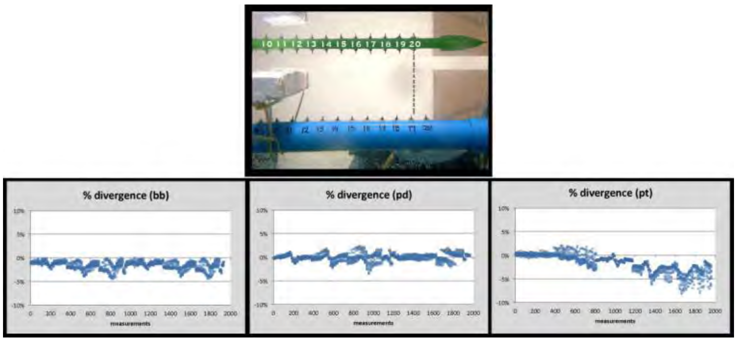

Figure 11 – Offset calculated with electrode displacement (top), % divergence occurred (bottom).

Results show that bb and pd are the two less sensitive protocols. In Figure 12 we can see inversion results for 0% and 100% offset for protocol bb and pt. The distortion of the target shows clearly how electrode displacement effects data in pt protocol.

All tests suggest that bb is the least sensitive protocol to the electrode displacement, which means the most appropriate to use, when the electrode position is not accurate.

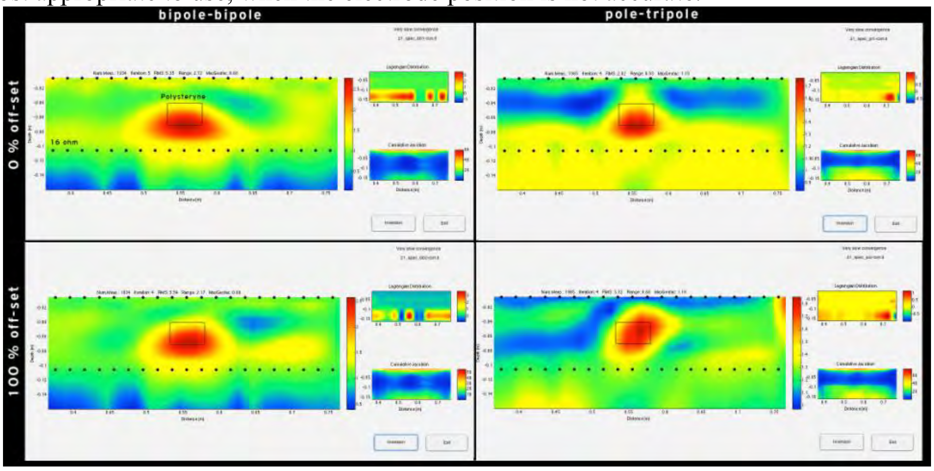

Figure 12 – Inversion results with 0% (top row) and 100% (bottom row) electrode displacement for protocol bb (left column) and pt (right column).

5. Conclusions

The simulation tank experiments proved a valuable tool that can act as a bridge between computer simulated data and reality since many scenarios can be studied in a fully controlled environment. Experiments have clearly demonstrated that the surface-to-tunnel array has increased resolution over the standard surface array therefore this type of measuring mode, when feasible, is preferable.

Optimum measurements were generated in order to reduce acquisition and inversion procedure time. Bipole-bipole optimum sets have resistivity values closer to the target resistivity than the standard data set. Pole-dipole optimum protocols define better the target limits than the standard data set and pole-tripole optimum protocol has better results than the standard set of measurements.

A particular problem of the tunnel-to-surface measuring mode has to do with the effect that an air-filled tunnel has to our measurements and subsequent inversions. It is shown that this effect can be very important and that it need to be taken in to account. There are many possible procedures to alleviate this affect and in this work we have chosen to ignore measurements which have spacing comparable (i.e. equal or smaller) to the diameter for the tunnel. Results suggest that inversion quality is significantly improved when this correction is applied.

Finally the electrode displacement effect was studied and results suggest that that bipole-bipole is the least sensitive protocol to this source of noise. Therefore it is suggested that this array is used when a limited positioning accuracy can be achieved.

6. Acknowledgements

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