DC Resistivity Survey Design Enhancement to Resolve Conductivity Structures Around Tunnels or Mine Workings

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Abstract

Keywords: DC resistivity (ERT/ERI), Survey Design, in-mine, tunnel

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1. Introduction

Underground environments, such as tunnels or mine workings, are challenging environments in which to collect DC resistivity data due to the limited electrode geometry afforded by the tunnels. Unlike surface applications where a dense grid of transmitters (TXs) and receivers (RXs) can be deployed to maximize model resolution within the region of interest (ROI), the subterranean environment often limits the location of TXs and RXs to existing tunnels, boreholes, or other workings. This can significantly reduce model resolution and create non-uniqueness issues in regions where we lack the geometry to properly sample the target region.

We came to appreciate these limitations while reading about previous studies and working on two underground DC resistivity field datasets, one from the Mosaic K2 potash mine near Esterhazy, Saskatchewan and the other from the Laboratory Souterrain in Bas Bruit (LSBB) in Rustrel, Vaucluse, France. Before being able to confidently interpret the inversion results we realized that there were a number questions that needed to be addressed regarding the resolution of the recovered conductivity models. To investigate these questions we created two synthetic tunnel models which mimicked the field examples. The first is a straight section of tunnel, akin to LSBB, while the second contains a tunnel laid out in an asymmetric horseshoe as in the Mosaic example. After some basic analysis we decided to focus on designing a survey to address the following pitfalls.

When collecting DC data along a straight section of tunnel, conventional surveys consist of a single linear array of electrodes placed along one face of the tunnel. While a 2D array of this type can often constrain the along tunnel location of a potential target it lacks the ability to resolve the targets around tunnel location or constrain how far the target is away from the tunnel. Similar challenges arise with more complex tunnel geometries if most of the transmitters and receivers fall on or near the same depth plane. In this situation it may be difficult or impossible to determine where the anomalous bodies are located relative to the measurement plane.

To address these model resolution and non-uniqueness issues we propose the use of ring shaped arrays of electrodes and in some cases electrodes in strategically placed off-tunnel boreholes. Using synthetic model analysis we assess the benefits of ring arrays and off-tunnel boreholes in order to design surveys which better constrain the location and shape of anomalous bodies around the tunnel. Since ring arrays utilize far more electrodes than conventional linear arrays, we developed a forward modelling based survey design methodology which aides in the selection of a subset of TXs and RXs. In the proposed survey design methodology TXs are selected based on charge accumulation on a target test volume which is moved through the ROI and RXs can be pseudo-randomly selected from a subset of measurements which have been found to be sufficiently sensitive to the test volume. We do not claim this to be a strictly optimal survey design, but we show it do be a practical and computationally efficient manner in which to balance improvements in model resolution with survey size.

1.1. Other Underground DC Resistivity Studies

Although DC resistivity surveys have been used extensively above ground since the 1950's, most studies involving subterranean use have occurred in the last 10-20 years. In one of the earliest applications, Scott et al. (1968) used 1D Wenner array soundings along the walls of a tunnel to characterize the competency of the rock and measure the thickness of fractured material from blasting. In-mine DC resistivity soundings and 2D arrays have been used in Germany to estimate the free water content and monitor wet regions within old salt mines which are being used for the storage of radioactive waste (Kessels et al., 1985; Yaramanci, 2000). For mineral exploration in Japan Sasaki and Matsuo (1990) used a 2D ERT inversion of surface-to-tunnel and tunnel-to-tunnel DC resistivity data to map disseminated copper ore at a mine site and Arai (1995) used a 2.5D ERT inversion to map the location of a resistive lead-zinc sulphide ore vein within a Japanese mine. Ramirez et al. (1996) showed that 3D ERT can be used to monitor underground storage tanks for leaks. In South Africa researchers have used tunnel to tunnel ERT surveys to identify potholes, dykes, and iron-rich ultramafic pegmatite (IRUP) bodies which disrupt ore zones in platinum mines (van Schoor, 2005; van Schoor and Binley, 2010). To characterize and monitor small scale rock fracturing due to excavation Kruschwitz and Yaramanci (2004); Gibert et al. (2006) used 2D DC modelling and inversion of a few rings of electrodes placed around the circumference of a tunnel. In Chinese coal mines a great deal of research has been undertaken to develop DC resistivity (Wang, 2011; Han et al., 2011) to detect water bearing structures ahead of the cutting machinery.

Much of our current research builds upon work done by Maxwell et al. (2005); Eso et al. (2006b,a) at the Mosaic potash mines near Esterhazy, Saskatchewan. Here they conducted a number of 2D and 3D DC resistivity studies to map regions of wet salt and brine. To improve resolution in their 3D surveys off-plane electrodes were placed in raises, subdrifts, and off-tunnel boreholes to better constrain the location of conductive targets. These studies along with nearly all of the others listed above discuss our inability to properly resolve 3D structures with 2D arrays or a limited number of off-plane electrodes in 3D surveys. This highlights the need for further research and refine survey design methodologies for in-mine or tunnel based environments.

1.2. Inversion Background

- Overview of our formulation of the forward and inverse problems.

- Qualitative assessment of model resolution and non-uniqueness based on structures present in the recovered models. More quantitative measures are difficult since the amplitude of recovered anomalies can vary significantly based on the # of data and your chosen uncertainties. For example, adding many additional measurements which are primarily sensitive to the background down-weights the importance of data which are more difficult for the inversion algorithm to fit but contain important information about the potential target. This leads to a decrease in amplitude of the recovered anomaly since the global target misfit is easier to reach with addition of the easy to fit data.

2. Motivating Case Studies

2.1. LSBB

- Description of the survey area, geology, and geophysical problem.
- Description of instrumentation and collected data.

2.1.1. LSBB: Field Survey Results

- Build up from linear arrays of electrodes along tunnel walls to the ring array.
- Show how this seems to improve our ability to resolve the shape/location of structures around the tunnel.
- Difficult to really assess the benefits of ring arrays with field data so we switch to synthetic models to further investigate the benefits/limitations of the ring arrays.

2.2. K2 Potash Mine

- Description of the survey area, geology, and geophysical problem.
- Description of instrumentation and collected data.
- Keep things brief and reference our paper.

2.2.1. K2 Potash Mine: Field Survey Results

- Show final inversion result.
- Discuss possible limitations which occur from having all electrodes close to a single plane with the single linear array.
- Further analyze these limitations using the synthetic horseshoe tunnel models.

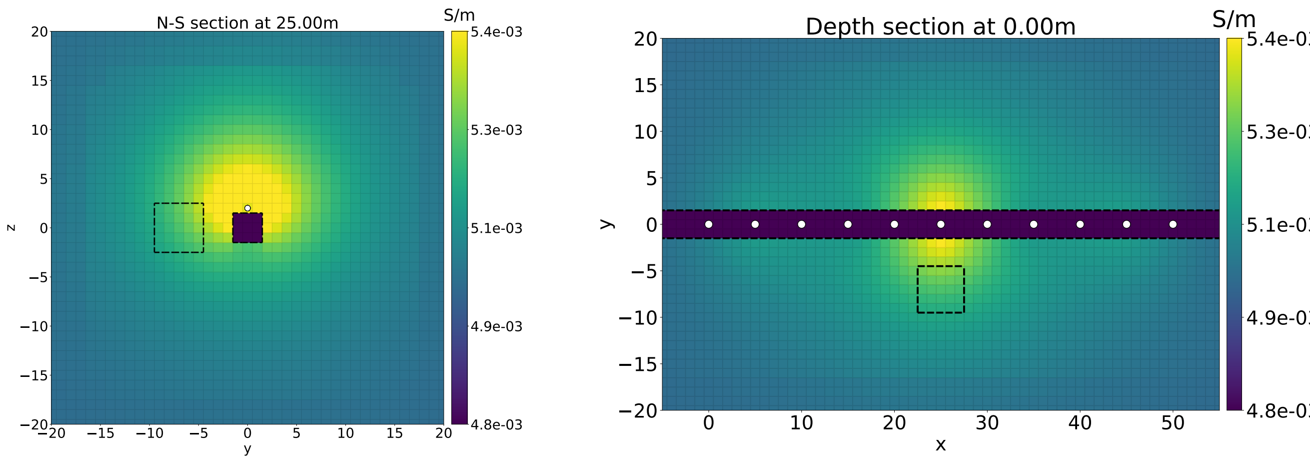
3. Straight Tunnel Synthetics

- Overview the the model, survey setup, and selected region of interest (ROI)
- Build up complexity of survey (single linear array, 4 linear arrays, ring array, and ring array + boreholes) to characterize benefits/limitations of each.
- Practical considerations:
  - Ring separation considerations:
    - Ring separation $\approx$ the size of target if the expected distance of the target from the tunnel $\leq$ the size of the target.

      Otherwise:
    - Ring separation $\approx$ the expected distance of the target from the tunnel.
  - For these synthetic examples with a 5m block which varies from 3-7m from the tunnel we found that a ring separation of 10m outside the ROI and 5m inside the ROI performed well. If rings are too sparsely spaced we begin to lose the relative benefits of the ring array. Have figures which support this...
  - Where to place boreholes? Boreholes are expensive so you want to minimize the number of them required. Do as much reconnaissance surveying as possible before deciding on locations. Here we place them on the boundary of the ROI to avoid drilling into water bearing regions.

3.1. Around Tunnel Location of the Target

- Model: 5m conductive block located 3m away from the side of the tunnel
- Ability to constrain the around tunnel location improves substantially as we build up from a single linear array to the ring array.
- Off-tunnel boreholes do not offer much improvement in the case. (The ring array already recovers the block quite well since the block is fairly close to the tunnel.)



(a) (b)

Figure 1: Single linear array helps determine the along tunnel location shown in 1b but does not do a good job of constraining the around tunnel location. Panel 1a recovered anomaly lies above the tunnel, where the electrodes are located and the sensitivity is the highest, instead of its true location off the western side of the tunnel.

3.2. Distance of the Target Away From the Tunnel

- Model: 5m conductive block gradually moved further away from the tunnel ceiling (3m, 5m, 7m)

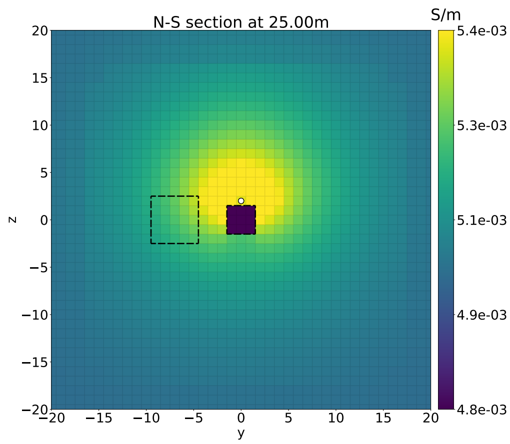
- The use of 4 linear arrays proves little improvement over the use of a single linear array along the ceiling. As shown in the previous section this is not the case if the conductive target is located off to the side of the tunnel.

- Ability to constrain the distance of the target from the tunnel improves greatly from the single linear array to the ring array.

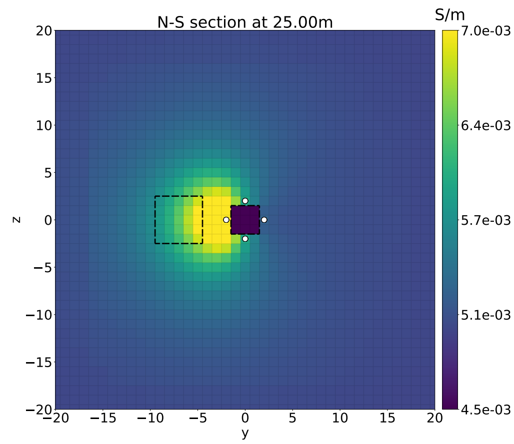
- Some improvement in the recovery of blocks which are furthest from the tunnel with the use of off-tunnel boreholes.

3.3. Resolving More Complex "Geological" Structures

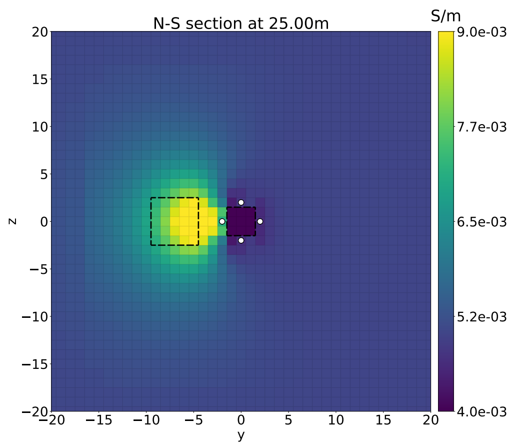
- Mosaic synthetic model or similarly complex model



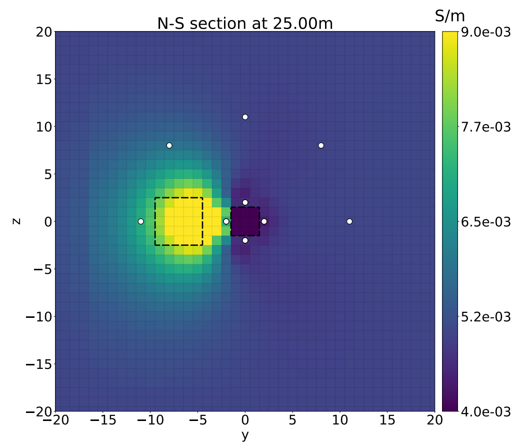
(a) Single Linear Array



(b) 4 Linear Arrays



(c) Ring Array (Full)



(d) Ring Array (Full) + Boreholes

Figure 2: N-S cross sections show how our ability to constrain the location of a conductive block off to the side of the tunnel incrementally improves with the different survey designs. The white dots are projections of the electrode locations onto the section that the black dashed outlines show the edges of structures in the true model.

- Ring array is better at resolving these structures than the linear arrays.
- Off-tunnel boreholes are key to our ability to correctly define the geometry and recover the conductive structure which passes diagonally

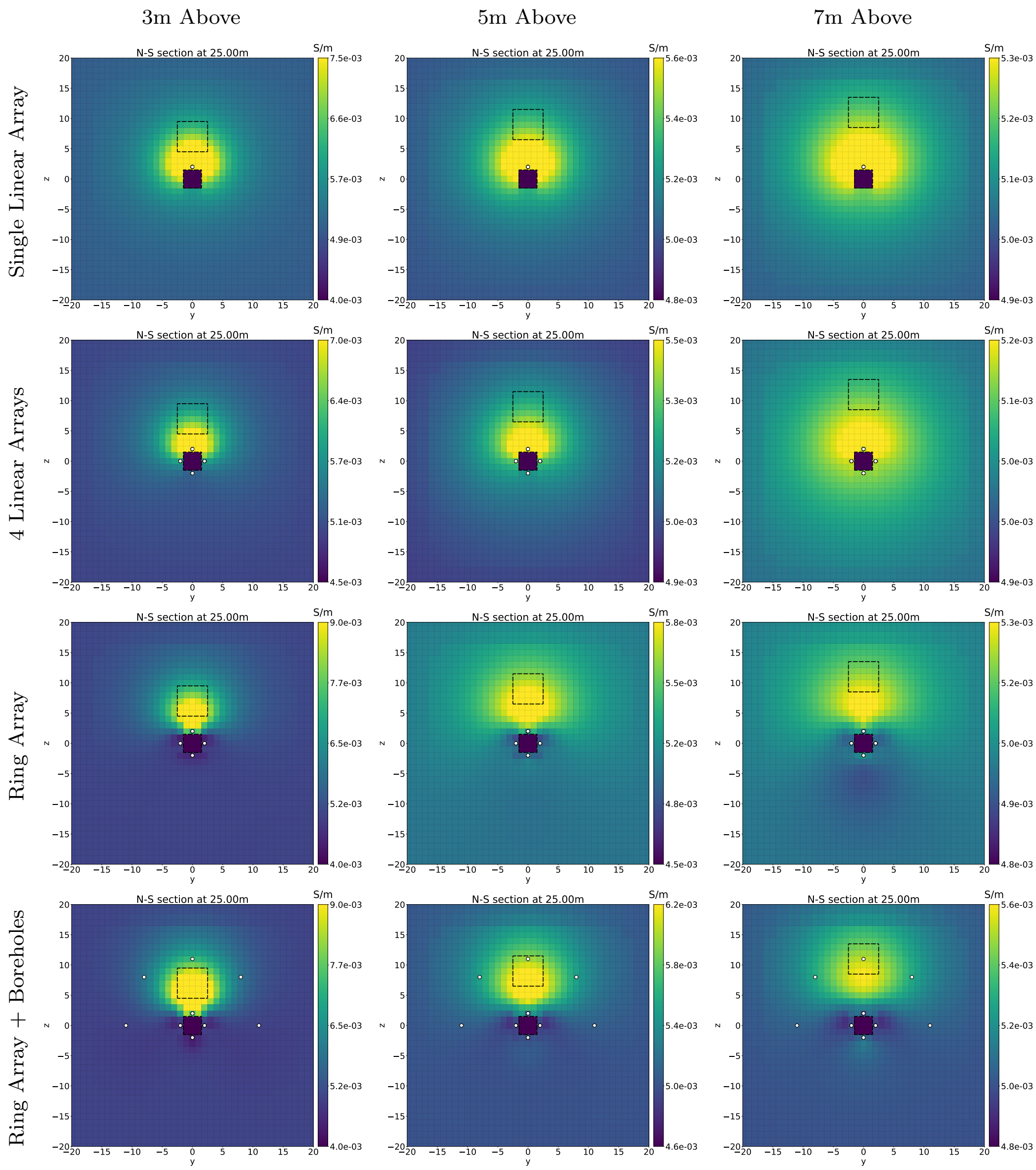


Figure 3: N-S cross sections through the recovered models for each survey design as the conductive block is moved progressively further away from the top of the tunnel.

above the tunnel.

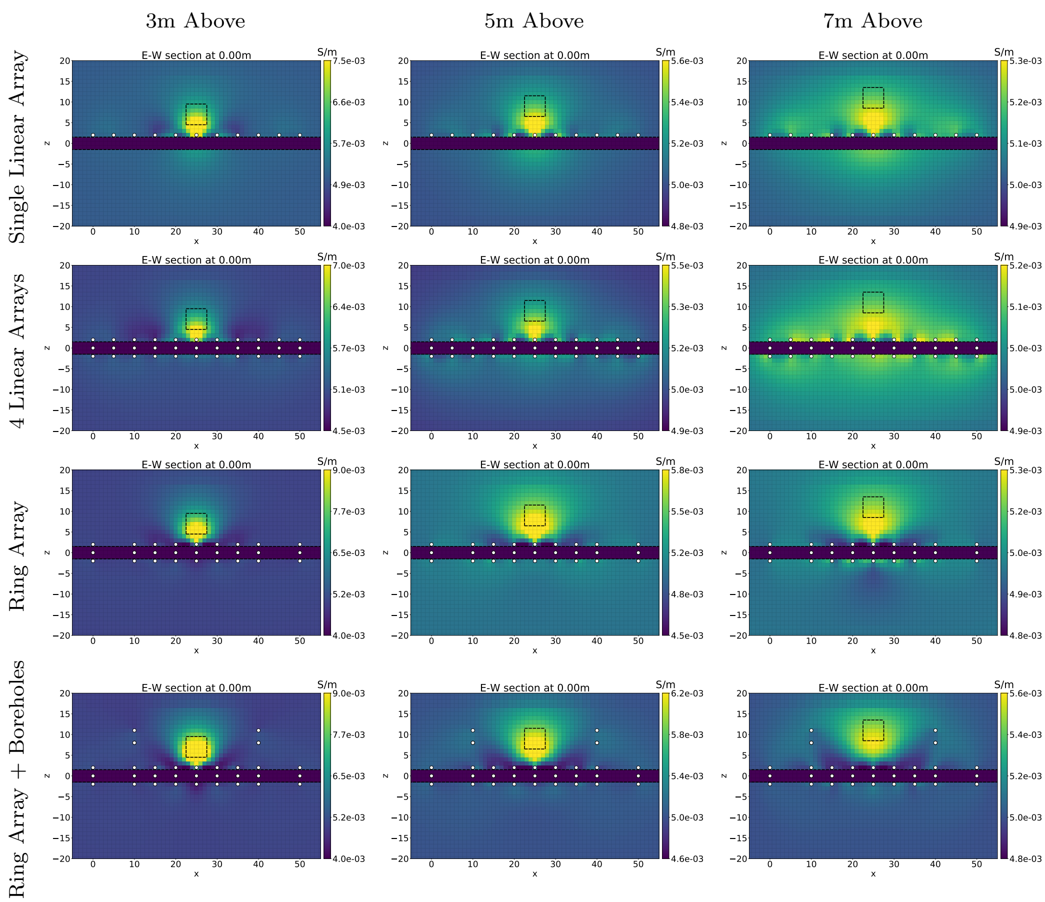
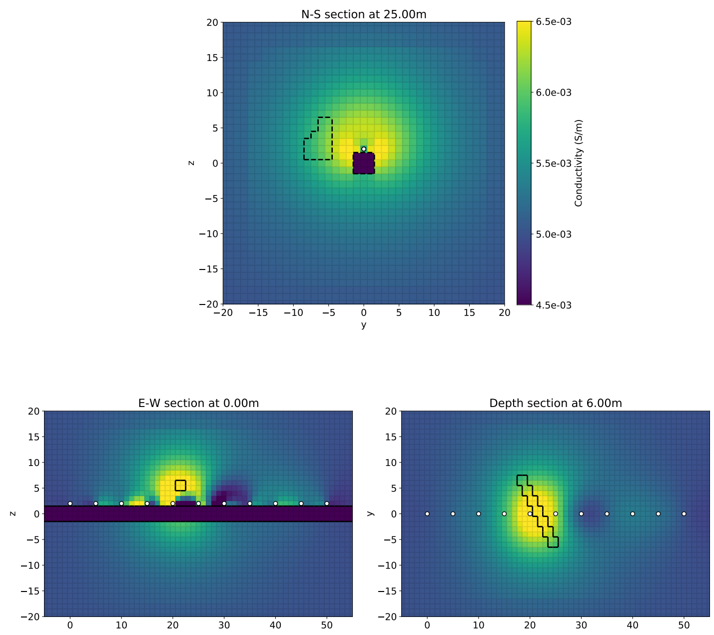
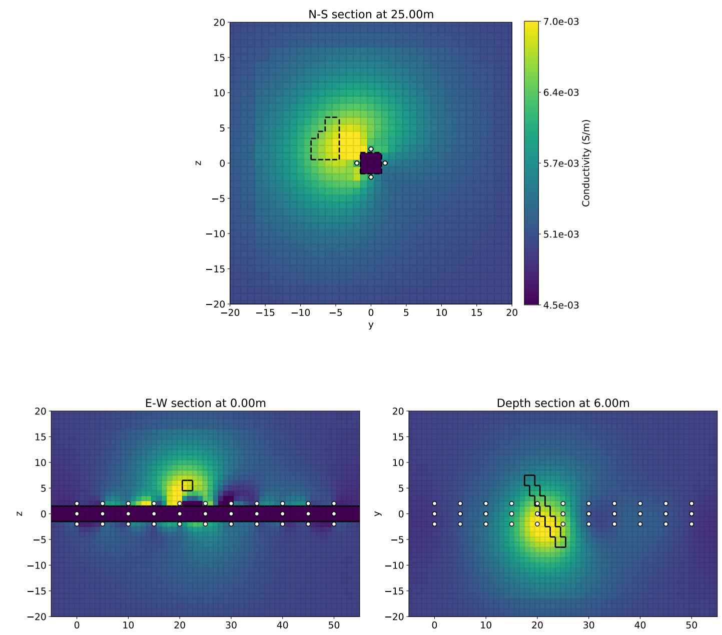


Figure 4: E-W cross sections through the recovered models for each survey design as the conductive block is moved progressively further away from the top of the tunnel.

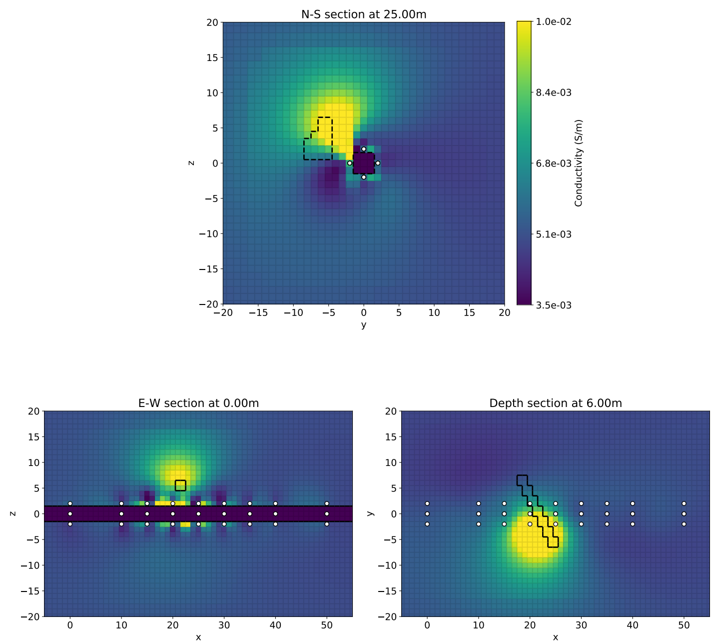


(a) Single Linear Array

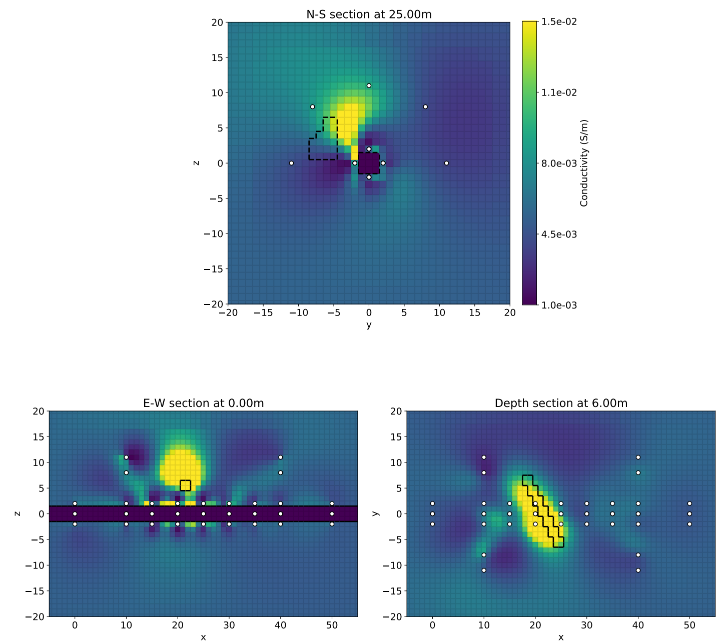


(b) 4 Linear Arrays

Figure 5: SynthMosaic1



(a) Ring Array (Full)



(b) Ring Array (Full, Bore1)

Figure 6: SynthMosaic1

4. Horseshoe Tunnel Synthetics

- Overview the the model, survey setup, and selected region of interest (ROI)
- Build up complexity of survey (single linear array, 4 linear arrays, ring array, and ring array + boreholes) to characterize benefits/limitations of each.

4.1. Vertical Location of a Target Between the Tunnels

- 7m conductive block gradually moved away from the plane of electrodes (centred, 3m above, and 5m above)
- Ring arrays allow you to determine if the target is above or below the electrode plane.
- Borehole benefits?

4.2. Resolving Multiple Bodies or More Complex "Geological" Structures

- Mosaic synthetic
  - See improvements with the ring arrays but not super pronounced. Single linear array does a fair job already. This is likely since the structure is concentrated close to the plane of electrodes.
  - Might be good to alter example so that structure is further offset from the electrode plane to highlight benefits of the ring arrays or boreholes.
- 2 block model
  - More pronounced improvement with the ring array than the Mosaic synthetic.
  - Boreholes further tighten up recovered anomalies
  - Draw backs: Still a fairly simple model, difficult to nicely show results using sections since the 2 blocks cannot be intersected using a single plane orthogonal to coordinate axes. Consider reworking model or using iso-surfaces to show recovered models...

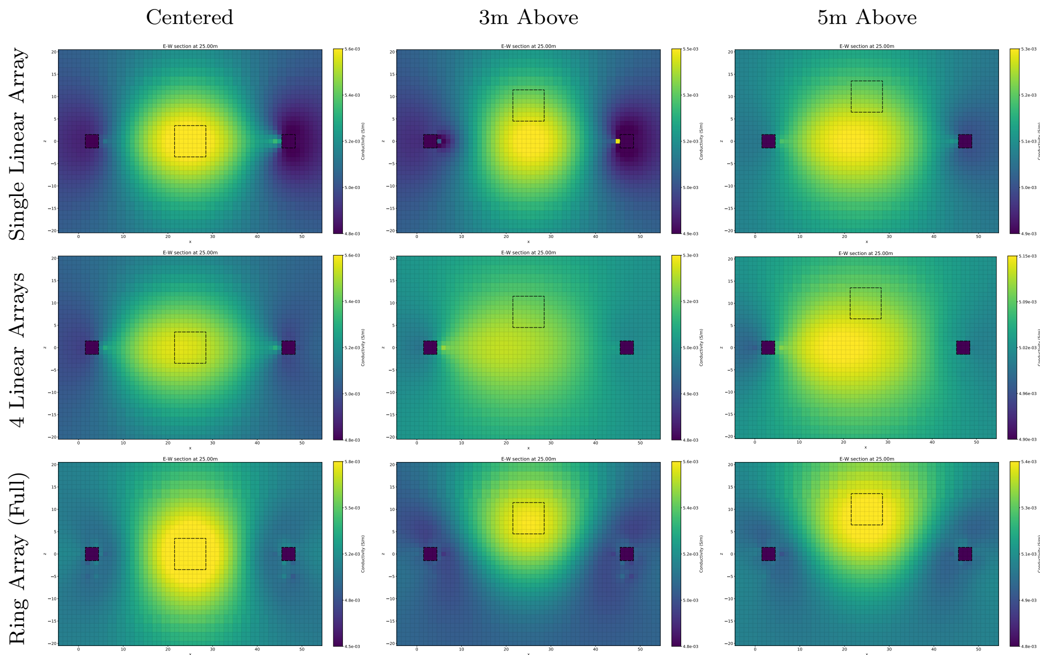


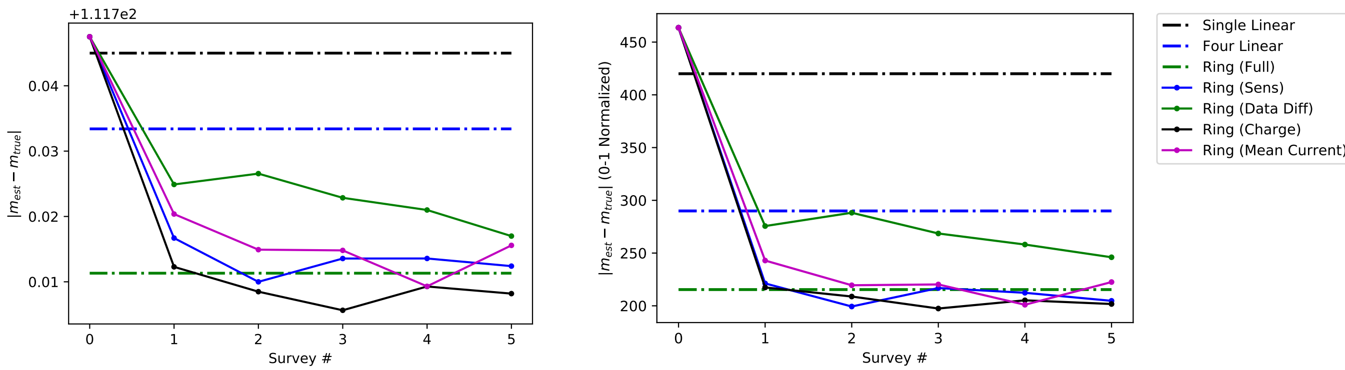
Figure 7: E-W cross sections through the recovered model from the synthetic horseshoe shaped tunnel with a conductive block in the central region between the two arms of the tunnel. These are the results from the UBC code so I should re-run them to insure they are valid.

5. Survey Design: Balance Resolution Improvement and Survey Size

- Primary draw back of ring arrays and the addition of off-tunnel boreholes is the increase in the potential number of Tx/Rx pairs.
- Which of these measurements are really required to glean most of the resolution improvements? How do we strike a balance between resolution improvement and survey size?
- The presented methodologies are only one possible way of selecting a subset of Txs and Rxs. While the resulting survey may not be strictly optimal the design process is physics based, computationally inexpensive, and has been proven effective by all of the tests we conducted.

5.1. Tx Selection

- Define the region of interest (ROI)
- Break ROI up into blocks of reasonable size (1 to 2 times the ring separation distance? What is feasible given the size of your ROI?)
- Move block of target conductivity through ROI and forward model responses.
- Analyze the response of each Tx to a give block and select the best Tx or group of Txs for each block location.
  - Looked at many different metrics for choosing the "best" Txs (For each Tx and each block locations we calculated: secondary charge, secondary currents, cumulative sensitivity, and measured data differences.)
  - All metrics produced slightly different surveys but recovered models were similar and reasonable. Settled on secondary charges since this metric produced slightly better results and is less expensive to compute than sensitivity. (See Fig. 8)
- Incrementally build up survey using the best Tx for each block, then the best 2 Txs, then the best 3 Txs, and so on until you have struck an acceptable balance between resolution improvements and survey size. (Depending on the geometry of your tunnel and electrode array you may want to enforce a symmetric distribution of Txs so that the ROI is uniformly excited.)
- Results show that you can reap most of the benefits with only a small subset (approximately 5-10%) of the full Tx combinations. (See Fig.8)
- From a synthetic viewpoint minimizing the number of Tx and using all of the Rx associated with these Tx makes since adding additional sources is computationally more costly than adding data to the forward modelling and inversion.



(a) (b)

Figure 8: 2 plots which show the L_2 norm of model differences between the recovered model and true model. In panel 6b the models have been normalized so that all values fall between 0 and 1. These plots show the resolution of different data subsets compared with the single linear array, 4 linear arrays and full ring array surveys for the straight tunnel with a conductive block located 3m off to the side of the tunnel.

5.2. Rx Selection for each Tx

- If the # of measurements is still too large a subset of Rx can be selected for each Tx. This might be necessary when designing a field survey since addational data increase data collection costs.

- Possible methodology:

  - Go back to forward modelled data. For each selected Tx identify Rxs with a % difference greater than some tolerance (maybe 5-10%) for each block location within the ROI.
  - Bin the sufficiently sensitive Rxs based on their MN separations and randomly select a set # of Rxs from each bin.
  - This provides a subset of Rxs for each Tx which are sensitive to all block locations within the ROI and evenly cover the full range of MN separation distances.

Survey ID	# Tx
1	30-40
2	60-70
3	90-100
4	120-130
5	150-160

Table 1: This table specifies the number of transmitters in each of the selected subsets.

6. Discussion

- When working in tunnels other subterranean environments ring arrays of electrodes can be effectively used to greatly improve resolution of and reduce non-uniqueness in recovered conductivity models when compared to the more conventional single linear arrays.
  - Straight tunnel
    - Constrain the around tunnel location of targets.
    - Improve our ability to constrain the distance of the target away from the tunnel.
    - Improve our ability to accurately resolve complex structures.
  - Complex tunnel geometries (Horseshoe)
    - Helps constrain the vertical location of targets relative to the electrode or tunnel plane.
  - Primary drawback of ring arrays is the dramatic increase in the number of potential measurements.
    - Simple survey design methodologies can be utilized to try and balance resolution improvements and survey size.
    - Trials show that most of the resolution improvements can be gleaned with only a small subset (approximately 10%) of the possible Txs and Rxs.
- Off-tunnel boreholes can provide additional information regarding conductivity structures around tunnels but careful modelling should be done ahead of time to see if benefits offset additional costs.

  - Add more value when the targets are further away from the tunnel or when trying to resolve complex structures.

- If a large section of tunnel needs to be surveyed and it is not possible to identify a reasonably sized ROI beforehand and linear array survey might be a useful reconnaissance tool to better focus the larger ring array survey or identify locations where off tunnel boreholes could be useful.

- Future work:

  - Although the use of ring arrays substantially improves our ability to resolve conductivity structures around tunnels and mine workings when compared with the more conventional linear electrode arrays, we believe that the use of electromagnetic (EM) methods hold the potential for even further improvements and advancement. Our future research will focus on the extension of this study to assess the feasibility and possible benefits of using grounded source frequency domain EM data instead of DC resistivity data.

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