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Improved 2D and 3D resistivity surveys using buried electrodes and optimized arrays: The multi-electrode resistivity implant technique (MERIT)

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Improved 2D and 3D resistivity surveys using buried electrodes and optimized arrays: The multi-electrode resistivity implant technique (MERIT)

by

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DEDICATION

This dissertation is dedicated to my wonderful son Darius Henok. You are a blessing to our life and you have brought us great happiness. We are lucky to have you and we are confident that you are going to make us proud parents.
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ABSTRACT

This thesis presents a novel resistivity method called Multi-Electrode resistivity technique (MERIT) that is used for high resolution imaging of complex geologic features at depth and near the edges of survey lines. The MERIT electrodes are especially shaped and designed to be self-driven using a robust-direct push technique. Measurements are taken using optimized arrays that are generated using a modified version of the “Compare-R” optimization algorithm. This work focused on both two-dimensional (MERIT2D) and three-dimensional (MERIT3D) applications of the buried array and show the relevance of the additional information gained by the addition of deep electrodes especially in sites with limited survey area. Numerical and laboratory studies are used to test and develop the technique and are later applied to image complex subsurface geologic structures on the field.

The configuration of MERIT arrays brings some additional problems in terms of the sensitivity of the deep MERIT arrays to a problem of non-uniqueness, misinformation, geometric error and resolution break between the two layers of electrodes. Multiple vertical resolution characteristic curves (RC curves) are analyzed to study the effect of array type, resistivity contrast, target resistivity and implant depth on the above-mentioned problems. Results show that MERIT measurements taken using standard dipole -dipole and wenner arrays along the surface and deep electrodes will strongly suffer from the problem of non-uniqueness or ambiguity while measurements taken using optimized arrays are suitable for MERIT configuration and will not suffer from any problem of ambiguity or non-uniqueness. Based on our result, a procedural guideline is
developed to determine optimal MERIT implant depth and resolution cutoff that can be used for successful field implementation and for controlling misinformation during data interpretation.

Numerical studies involving simple shapes and complex geometries based on actual geological cross-sections from karst environments were used to compare the effectiveness of MERIT2D in terms its high depth resolution and results are compared in detail with traditional 2D surface resistivity methods of equal foot prints. Similar comparison was made between MERIT3D technique and 3D surface resistivity measurements. Results show that both methods achieve a high depth resolution compared to their equivalent traditional resistivity methods. Laboratory experiment conducted using a complex analogue model mimicking actual sinkhole structure is used to test MERIT2D. Also laboratory experiment involving a 3D printed plastic cave model mimicking an actual cave was conducted using MERIT3D approach. Both results show the promise of MERIT approach to better image complex geological structures or problems.

Finally, the method is applied to collect field data in three case study sites involving complex karst related sinkhole structures and an old landfill site. The results show the promising capability of the MERIT technique to study challenging geologic conditions with high depth resolution.
CHAPTER ONE:  
INTRODUCTION

This thesis describes a novel resistivity imaging technique called multi-electrode resistivity implant technique where multiple deep electrodes are buried at depth to increase resolution at depth and near the edges. The effectiveness of MERIT technique significantly increases when measurements are taken using optimized arrays. The present study is motivated by the need to image complex geological structures involving karst related sinkhole activities and geohazard problems. Hence, we will include a concise section discussing these problems and the subsurface structure of sinkholes in Florida.

Review of DC Resistivity Method

Geo-Electrical resistivity is a widely used geophysical method for investigating geological and hydrogeological (e.g. Kruse et al., 1998; Daniels et al., 2005; Nenna et al., 2011; Singha et al., 2014; Yeboah-Forson et al., 2014) engineering (Wilkinson et al., 2006a; Danielsen and Dahlin, 2010), mining (Legault et al., 2008) and environmental problems (Slater et al., 2000; Pidlisecky et al., 2006; Meju, 2006; Chambers et al., 2010; Power et al., 2015). The method can be applied to such a wide range of problems because measurements are sensitive to lithology, degree of saturation, and pore water composition (e.g. Lesmes and Friedman, 2005). Reviews of the recent developments in electrical resistivity tomography (ERT) are given by Dahlin, (2001), Auken et al. (2006) and more recently by Loke et al. (2013).

During a resistivity survey DC (direct current) is driven through the earth between pairs of electrodes installed at the surface or buried at depth. While current flows, electric potential differences are measured between other pairs
of electrodes. The measured potential differences are related to the resistivity structure of the ground through which the current flows. There is great flexibility in how the electrodes used to drive current and those used to measure potential can be spatially configured. Use of traditional electrode arrangements with simple rules for displaying apparent resistivities as pseudo-sections, such as Wenner (e.g. Loke, 2010) and dipole-dipole arrays (e.g. Telford and Sheriff, 1990), persists even after the development of commercial systems that can automate acquisition of more flexible array geometries.

Current commercial resistivity systems offer automated switching capabilities for driving current and measuring potentials, so users install an array of electrodes, often ~30-100. Then a sequence of readings is taken by addressing pairs of current and potential electrodes within the array. Most surveys conducted today are two-dimensional (2D); a series of electrodes are laid out in a straight line. Typically, electrodes are evenly spaced along the line. Such conventional 2D surveys are logistically efficient to deploy, but there are well-recognized limitations to conventional 2D surveys, which are discussed further below.

Other arrangements of electrodes have been tested and described, including 3D surveys in which electrodes are arranged in grids on the surface (Loke and Barker, 1996; Tsourlos and Ogilvy, 1999). More labor-intensive methods involve installing electrodes in vertical downhole arrays, for cross-borehole surveys (e.g Daily & Owen, 1991; Slater et al., 2000; Perri et al., 2012). Pidlisecky et al. (2006) used deep electrodes as current source in resistivity measurements done using a cone penetration testing (CPT) rig. Danielson and Dahlin (2010) used horizontal boreholes drilled on the working face of a tunnel boring machine (TBM) to gain information about the rock conditions before the next heading. Power et al. (2015) demonstrated improved time-lapse monitoring of contaminant
remediation using surface-to-horizontal borehole ERT relative to surface ERT. Simyrdanis et al. (2015) used surface-to-tunnel electrical resistivity tomography to study the subsurface between the ground and a tunnel. Clearly, the current state of the practice in resistivity surveys offers unprecedented flexibility in the spatial positioning of a set of electrodes.

**MERIT Array Installation**

In the MERIT approach, the subsurface electrodes are implanted using a Geoprobe® (Direct-Push) system (e.g. United States Environmental Protection Agency, 2005). The implanted electrode is an expendable drive point with an attached wire (Harro and Kruse, 2013). The drive point is placed in the lower end of a groundwater sampling sheath that is pushed downwards by percussion (Fig 1c). When it reaches the desired depth, the sheath is withdrawn leaving the implanted electrode joined to the surface by the attached wire. This installation is more rapid and less costly compared to vertical boreholes with an average rate of installation of 20 m/hr. Cost wise, a MERIT array with 14 buried electrodes at 7.6 m depth is typically less costly than two cross-boreholes with 15-electrode string (United States Environmental Protection Agency, 1998) making it an attractive choice for deeper targets with large horizontal extent. In addition, compared to most drilling techniques, the MERIT approach minimizes the disturbance to the target itself by avoiding the use of circulation fluid and by utilizing a small borehole radius (~2.5cm). The borehole radius is much smaller than the targets of the studies described here.

The direct push rig has a controlled hydraulic system that permits vertical advancements in increments as small as 0.125cm. When the lengths of the push rods for installation are accurately measured, the vertical accuracy of the implanted electrodes is expected to be similar to that of an electrode mounted
Figure 1. Field installation and arrangement of electrodes. (a) Conventional surface array. (b) Field arrangement of MERIT array. (c) Schematic diagram showing the installation of MERIT arrays on a rigid support in vertical boreholes (e.g. Wilkinson et al., 2008).
Following Paasche et al. (2009), the maximum horizontal deviation of the direct push rod from vertical is expected to be less than 5 degrees.

Figure 2. Arrangement of MERIT3D with offset measurements. MERIT3D measurement requires a minimum of one MERIT line with deep electrodes (green) and few offset lines with surface electrodes (red). Top shows a possible expansion of MERIT3D approach. Depending on site specific requirement, intermediate MERIT arrays (blue) or parallel MERIT line can be added. Bottom shows planes connecting offset measurements taken between the multiple layers of electrodes. Gray vertical cylinders represent jet grout columns that are usually constructed for foundation support.

Because MERIT2D is similar to a cross-borehole array rotated to horizontal, we can take advantage of lessons learned from cross-borehole surveys. For example, a large separation between the deep and the surface electrodes can result in
decreased sensitivities at the center and problems of non-uniqueness and spurious inversion results around the lower array. For cross-boreholes, LaBrecque et al (1996) suggest a maximum borehole separation of 0.75 of the borehole array length. In this paper, we derive analogous guidelines for MERIT arrays. The optimal depth of implants balances tradeoffs between data quality, cost, effective depth of investigation and target depth. Choice of implant depth can further be improved by carrying out pre-survey forward modelling. After deployment of the array, the user must select the optimal combinations of electrodes as current and potential pairs to maximize information extracted per reading.

As discussed above, in MERIT2D, electrodes are installed using a rapid robust direct-push technology that is much faster and cheaper than the conventional drilling required for cross-boreholes. Nevertheless, a MERIT array installation still requires additional cost and field time over that needed for a conventional surface array. In order to add more relevance to the increased cost and effort in a MERIT installation, we examine here the additional benefit that can be gained by the less incrementally expensive addition of parallel surface electrode arrays. Such arrays sequentially laterally offset to make both inline and offset measurements involving the surface and deep electrodes. We refer to this technique as MERIT3D (figure 2). MERIT3D technique can be further advanced by making full 3D measurements involving surface electrodes across multiple offset lines and the deep MERIT electrodes. Furthermore, additional parallel MERIT lines or intermediate MERIT electrodes can be added (figure 2) to further enhance resolving capabilities geared toward specific targets or problems.

**Array Optimization**

Deployment of MERIT arrays offers complex spatial geometries with opportunities to select optimal combinations of electrodes as current and potential pairs
that would maximize information extracted per reading. Optimization of reading selection is also very important, as many possible combinations of readings have high geometric factors and tend to introduce significant noise into the data set. Wilkinson et al (2008) showed that some cross-boreholes arrays are highly sensitive to slight positioning errors. Hence, the optimized arrays will exclude unstable arrays that are highly sensitive to geometric errors and those that have high geometric factors.

The selection of optimal sets of readings for MERIT arrays is created using the modified version of the “Compare R” method of Loke et al (2014b) with algorithms suitable to these new electrode arrangements and is described in Loke et al. (2015). The optimization algorithm works by efficiently selecting a predetermined number of stable arrays that will maximize the model resolution from a myriad of possible array combinations of which there are N(N-1)(N-2)(N-3)/8 non-equivalent four electrode configurations for N electrodes when reciprocity is taken into account (Noel and Xu, 1991; Wilkinson et al, 2006b).

The model resolution matrix \( R \) measures how well the resistivity of each model cell can be estimated from the observed data (Menke, 1984).

The model resolution matrix \( R \) is calculated from Jacobian (sensitivity) matrix \( G \). \( G \) describes the sensitivity of the observations to the resistivities of each model cell. \( G_{ij} = \frac{\partial f_i}{\partial \theta_j} \), where \( f_i \) = the ith model response and \( \theta_j \) = the jth model parameter. In common 2D resistivity inversions, \( G \) is used in the linearized least-squares equation as

\[
(G^T G + \lambda C) \Delta r_i = G^T d - \lambda C r_{i-1}
\] (1)
where $\Delta\mathbf{r}_i = \mathbf{r}_i - \mathbf{r}_{i-1}$ with $\Delta\mathbf{r}_i$ represents the model parameter change vector between consecutive iterations. $\mathbf{C}$ is the roughness filter constraint, $\lambda$ is the damping factor and $\mathbf{d}$ is the data misfit vector.

The model resolution matrix is then given by

$$\mathbf{R} = \mathbf{B}\mathbf{A}$$

(2)

where $\mathbf{A} = \mathbf{G}^T\mathbf{G}$ and $\mathbf{B} = (\mathbf{G}^T\mathbf{G} + \lambda \mathbf{C})^{-1}$ and the main diagonal elements of $\mathbf{R}$ are used to estimate the model cell’s resolution.

In the ‘Compare R’ method, the number of possible configurations are reduced initially by ‘gamma’ type arrays (carpenter and Habberjam 1956) and arrays with large geometric factors (Strummer et al. 2004) are excluded from the set of possible arrays. The remaining arrays will make the comprehensive dataset.

The optimization process will start by using a preselected base dataset that consists small number of dipole-dipole arrays with ‘a’ spacing of 1. This is followed by calculating the change in the model resolution matrix $\mathbf{R}$ for each new array. Accordingly, a selected number of configurations that gives the largest model resolution increase with a suitable degree of orthogonality to the existing arrays (Wilkinson et al. 2010) are added to the existing dataset. Until the designed number of arrays is reached, this process is repeated several times.

The change in $\mathbf{R}$ when a new set of array is added to the base set is calculated using the Sherman-Morrison Rank-1 update (Golub and Van Loan 1989). The new resolution matrix $\mathbf{R}_{n+1}$ after a new set of arrays are added is calculated using a computationally efficient method (Loke et al., 2015) by using the sets of updating formulae (Loke et al. 2010b) give as
\[ R_{b+1} = R_b + \Delta R_b, \]

where
\[ \Delta R_b = \frac{z}{1 + \mu} (g^T - y^T), \]

and \[ z = B_b g, \quad y = A_b z \quad \text{and} \quad \mu = g_z z \]

where the vector \( g \) contains the sensitivity of the new sets of arrays. The subsequent increase in model resolution due to the new added sets is ranked by using the function, FCR (Wilkinson et al., 2012). The FCR function is the ratio of the change in the model resolution to the comprehensive dataset resolution

\[ F_{CR} = \frac{1}{m} \sum_{j=1}^{i=m} \frac{\Delta R_b(j,j)}{R_c(j,j)}. \]  

where \( m \) represents cells of the model resolution, \( R_b \) and \( R_c \) are the base and comprehensive data set model resolutions. Arrays that have the largest \( F_{CR} \) values are selected by the 'Compare R' algorithm. The performance of the optimization process is measured using an average relative model resolution, \( S_r \) given as

\[ S_r = \frac{1}{m} \sum_{j=1}^{i=m} \frac{R_b(j,j)}{R_c(j,j)}. \]  

Arrays with very high geometric factors are unstable and can result in negative apparent resistivity values. Also, Wilkinson et al., 2008 observed that some cross-borehole array configurations are extremely unstable and sensitive to position errors. In the optimization process, we have used a method to filter these unstable arrays. For the arrays involving the surface electrodes, we used a geometric cut-off factor to remove the ones which more likely unstable. We used the method suggested by Wilkinson et al., 2008 to filter out the unstable arrays involving the deep electrodes. The method uses the ratio of the sensitivity of the geometric factor to position errors to the geometric factor value. In the MERIT arrangement, the geometric factor for any four electrodes involving subsurface electrodes is given by
\[ K = 4\pi / \left( \frac{1}{r_{AM}} - \frac{1}{r_{AN}} - \frac{1}{r_{BN}} + \frac{1}{r_{AM}} - \frac{1}{r_{AN}} - \frac{1}{r_{BN}} \right) . \] (6)

The current electrodes are denoted by A and B, while the potential electrodes are M and N. \( r_{AM} \) is the distance between A and M. A' and B' represent the location of the images above the ground surface of the current electrodes if they are below the surface. Assuming all the electrodes are located along the \( y=0 \) plane for a 2-D survey, the location of the A electrode is given by \((xA, zA)\). The sensitivity of the geometric factor to errors in the position of the A electrode can be calculated using the following equation.

\[ \left( \frac{\partial K}{\partial A} \right)^2 = \left( \frac{\partial K}{\partial x_A} \right)^2 + \left( \frac{\partial K}{\partial z_A} \right)^2 \] (7)

The overall sensitivity \( s \) of \( K \) to errors in the positions of all the four electrodes is then obtained by summing up the individual contributions.

\[ s^2 = \left( \frac{\partial K}{\partial A} \right)^2 + \left( \frac{\partial K}{\partial B} \right)^2 + \left( \frac{\partial K}{\partial M} \right)^2 + \left( \frac{\partial K}{\partial N} \right)^2 \] (8)

The relative error in \( K \) (Wilkinson et al., 2008) is then defined to be

\[ R_E = s / K . \] (9)

We note that \( s \) is a dimensionless quantity that depends only on the relative positions of the electrodes. It does not change with the electrode spacing. For example, the Wenner array will always have a value of 1.295 regardless of the 'a' spacing between the electrodes. However, the geometric factor \( K \) depends on the electrode spacing. Thus, the value of \( R_E \) that is used to filter the potentially unstable arrays should be adjusted accordingly.

**Sinkhole Structure**

This thesis examines the efficacy of MERIT surveys in studying covered karst terrain. Karst processes commonly result in complex subsurface geologic
features, including sinkholes, irregular dissolution cavities, randomly spaced fractures and complex interfaces between units. Imaging karst features can be critical to avoiding infrastructure damage. Sinkholes are extremely common, with nearly 6,694 reported sinkholes in 2010 in Florida, USA (Figure 3a), and subsidence associated with these sinkholes costs $200 million/year in infrastructure damage (Florida Senate Interim report, 2010). Tihansky, (1999) gives a detailed description of the distribution and characteristics of sinkholes in West-Central Florida. Furthermore, sinkholes serve as a critical hydrological connection between the surface and underlying aquifers, functioning as zones of concentrated recharge (e.g. Stewart, 1998). Resistivity surveys are used globally to image geologic features associated with sinkhole formation and karst evolution (Gibson et al, 2004; El-Qady et al, 2005; Ahmed et al, 2012). Nevertheless, in many settings these features remain challenging targets for traditional resistivity arrays, and we focus our assessment of the MERIT method on these societally important structures. The fundamental results, however, are applicable to any geologic setting.

In west-central Florida, sinkhole structures typically involve, from the bottom upwards, dissolution cavities\conduits\fractures in the limestone; undulations of bedrock contact; weathered limestone; sediment raveling zones connecting surface features with deeper voids in the bedrock; localized dissolution cavities or voids in the overburden sands and clays; and surface and subsurface depressions (Figure 3b).

Ground penetrating radar (GPR) is the most commonly used geophysical method in sinkhole investigations due to its capability to detect shallow soil and stratigraphic anomalies (e.g. sub-surface depressions) related to sinkhole processes (Benson and La Fountain, 1984; Beck and Sayed, 1991; Stewart and Parker, 1992; Carpenter et al., 1998; Batayneh et al., 2002; Dobecki and
Upchurch, 2006; Kruse et al, 2006). However, GPR depth of investigation is typically limited to the uppermost few meters. These shallowest features are commonly only indirectly related to the actual deep dissolution cavities in the bedrock, which are the primal causes of the sinkhole hazards. Further complicating the picture, the surface features are frequently laterally offset
from the deep cavities, as illustrated in Figure 3b (Kiflu et al., 2013). There is clearly a need for methods, such as resistivity, that could image both within and below the sediment cover. Here we examine the resolution of this range of targets expected from sinkhole activity using numerical, laboratory and field studies.

**Guideline of the Thesis**

The thesis is composed of three main chapters:

**Chapter Two: Improving resistivity survey resolution at sites with limited spatial extent using buried electrode arrays**

The second chapter of this paper focuses on discussing the fundamental limitations of traditional surface resistivity methods and explains the development and fundamental concepts of MERIT and establishes the discussion for the next chapters. Numerical, laboratory, and field case studies are applied to examine the effectiveness of the MERIT method, particularly for use in covered karst terrain. In the field case studies, resistivity images are compared against subsurface structure defined from borings, GPR surveys, and knowledge of prior land use. In karst terrain where limestone has a clay overburden, traditional surface resistivity methods suffer from lack of current penetration through the shallow clay layer. In these settings, the MERIT method is found to improve resolution of features between the surface and buried array, as well as increasing depth of penetration and enhancing imaging capabilities at the array ends. The method functions similar to a cross-borehole array between horizontal boreholes, and suffers from limitations common to borehole arrays. Inversion artifacts are common at depths close to the buried array. Because some readings involve high geometric factors, inversions are more susceptible to noise than traditional surface arrays. Results are improved by using errors from reciprocal measurements to weight the data during the inversion.
This chapter is a modified version of a paper that is published in Journal of applied geophysics.


Chapter Three: 3D resistivity surveying with multiple deep implanted (MERIT) electrodes and sequentially offset surface arrays

This chapter introduces a 3D application of MERIT for the first time. This new application of multi-electrode resistivity implant technique is called MERIT3D. The method works by sequentially offsetting the multiple offset lines with surface electrodes and readings are taken combining electrodes along the offset lines and the deep MERIT electrodes. 3D electrical resistivity surveys are used where the need for better resolution of the subsurface outweighs the extra cost and time compared to 2D surveys. A well-planned 3D electrical resistivity will usually give a result that is superior to conventional 2D surveys by avoiding: 1) artifacts from offline objects and 2) misinterpretation of 3D features with low continuity perpendicular to the survey line. These 3D surface arrays suffer, however, from some of the same fundamental limitations of 2D resistivity surveys, namely a decrease in resolution and sensitivity with depth and near the edges. In this paper, we introduce a 3D resistivity method, called MERIT3D in which a 3D surface array is combined with a 2D rapidly-implanted buried electrode array. This method is an expansion of a previously described geometry in which a 2D buried array is installed directly beneath a 2D surface array (MERIT or MERIT2D). Once a deep array is installed, parallel surface arrays are set up laterally offset from the buried array. Results from numerical, laboratory and field studies are used to assess the technique with simple
geometries and complex features of interest in covered karst, including caves and covered sinkholes. The MERIT3D approach is found to have significant advantages in resolution near the ends of the survey and at depth compared to both 2D MERIT and 3D surface resistivity arrays.

This chapter is a modified version of a paper that is prepared to be submitted to the journal Near surface geophysics.


Chapter four: Practical aspects of Mutli-Electrode resistivity implant technique (MERIT)

In this chapter, we use numerical studies to investigate the resolution of the MERIT technique as a function of the depth of the buried array using vertical resolution characteristics curves (RC curves). We describe the depth of low-resolution as depth of resolution break. We will examine the effect of resolution contrast on resolution cut-off values and depth of resolution break in order to determine the most appropriate MERIT implant depth for different target sizes.

Part I of this paper discusses different practical aspects of the design of MERIT arrays and develops guidelines that can be used to collect good quality data. This part begins by describing problem of ambiguity or non-uniqueness in locating features that can arise when the deep and surface arrays are too widely separated. The effect of MERIT electrode location error is also described.

Part II of this paper introduces more advanced variations of MERIT techniques focused on solving challenging engineering geological problems. It introduces the application of 2D offset, parallel and intermediate MERIT arrays. We will
also evaluate The effectiveness of full 3D MERIT readings involving measurements taken using electrodes in different offset lines and MERIT electrodes is evaluated. Optimal offset spacing for MERIT3D surveys is also examined. Finally, field examples evaluating the application of the new techniques to solve complex engineering geological problems in Karst environment are discussed.

This chapter is an expanded version of a paper that is being prepared to be submitted to the journal Engineering geology.


**Chapter five: Summary and Conclusion**

This chapter summarizes the main objectives, results and limitations of the different chapters of the thesis.

**References**


53. Yeboah-Forson, A, Comas, X., and Whitman, D. 2014. Integration of electrical resistivity imaging and ground penetrating radar to
CHAPTER TWO:

IMPROVING RESISTIVITY SURVEY RESOLUTION AT SITES WITH LIMITED SPATIAL EXTENT USING BURIED ELECTRODE ARRAYS

This chapter is a modified version of an article published in the Journal of applied geophysics. It is included in accordance with the general agreement with the publisher which allows the free use of published articles for personal uses such as including in thesis or dissertation.

Abstract

Electrical resistivity tomography (ERT) surveys are widely used in geological, environmental and engineering studies. However, the effectiveness of surface ERT surveys is limited by decreasing resolution with depth and near the ends of the survey line. Increasing the array length will increase depth of investigation, but may not be possible at urban sites where access is limited. One novel method of addressing these limitations while maintaining lateral coverage is to install an array of deep electrodes. Referred to here as the Multi-Electrode Resistivity Implant Technique (MERIT), self-driving pointed electrodes are implanted at depth below each surface electrode in an array, using direct-push technology. Optimal sequences of readings have been identified with the “Compare R” method of Wilkinson. Numerical, laboratory, and field case studies are applied to examine the effectiveness of the MERIT method, particularly for use in covered karst terrain. In the field case studies, resistivity images are compared against subsurface structure defined from borings, GPR surveys, and knowledge of prior land use. In karst terrain where limestone has a clay overburden, traditional surface resistivity methods suffer from lack of current penetration through the shallow clay layer. In these
settings, the MERIT method is found to improve resolution of features between the surface and buried array, as well as increasing depth of penetration and enhancing imaging capabilities at the array ends. The method functions similar to a cross-borehole array between horizontal boreholes, and suffers from limitations common to borehole arrays. Inversion artifacts are common at depths close to the buried array, and because some readings involve high geometric factors, inversions are more susceptible to noise than traditional surface arrays. Results are improved by using errors from reciprocal measurements to weight the data during the inversion.

**Keywords:** Resistivity Inversion, Tomography, Optimized arrays, Sinkhole karst features, MERIT

**Introduction**

Electrical resistivity surveys suffer from fundamental limitations involving exponential decrease in resolution with depth and near the end of survey lines (Loke, 2001) as shown in figure 1 and figure 2. In this paper, we use a novel technique to enhance depth of investigation, with increased vertical and lateral resolution along the surface array length. This is done by implanting half of the electrodes at a depth closer to the subsurface target features, using an efficient direct-push technique. To make installation efficient and robust, deep pointed implant electrodes were designed to facilitate vibration resistance while being driven into the ground with minimal impact (Harro and Kruse, 2013). This array geometry is referred to as the multi-electrode resistivity implant technique, or MERIT. The presence of deep electrodes allows higher signal strength and sensitivity at depth even when the survey length is small. Even in areas where a longer survey would be feasible, a shorter MERIT array can avoid unwanted sensitivities to features off the survey line (e.g. Dahlin, 2001).
Figure 1. Typical pseudosection of a standard wenner array measured over a synthetic model with a block target. The 2D plot is prepared using the bulk apparent resistivity value for each array. The data points are placed at the center of the array for each ‘a’ spacing. The depth of the data point is also assigned based on an n value which depends on the ‘a’ the spacing.

Figure 2. Inverse model resistivity section for a synthetic model. The synthetic model constitutes a block placed at a shallow depth inside a relatively less resistive background.

MERIT arrays require more time and cost compared to conventional surface resistivity surveys. Hence, it is essential to use optimized arrays that will maximize the information gained from measurements taken using these surface and deep arrays. Although many practitioners use readings based on combinations of traditional arrays such as the dipole-dipole and Wenner arrays, a growing body of literature describes methods to find more efficient combinations of electrode selections. These ‘optimized’ arrays are mostly designed to maximize resolution of resistivity heterogeneities throughout the target volume (e.g. Cherkaeva, E. & Tripp, A.C., 1996; Furman et al, 2004; Stummer et al, 2004; Hennig, T. &...
Weller, A., 2005; Wilkinson et al, 2006a;2006b; Hagrey, S. A. al and Petersen, T., 2011). In this paper, optimal sequences of readings have been identified with the “Compare R” automatic array optimization techniques (Wilkinson et al., 2006b; 2012; Loke et al., 2015) to find optimal sets of readings that will capture the sub-surface geological heterogeneities between the surface and deep arrays and below the deep arrays. This improved approach is a novel application of the resistivity method to study complex subsurface geological features such as active sinkhole features in covered karst terrain.

**Method: Forward Models and Inversion**

Forward models are simulated using Res2Dmod and Res3Dmod from Geotomo Software. The outputs from both the 2D and 3D forward models are inverted using a modified version of Res2Dinv software, also from Geotomo Software. 2% Gaussian noise (Press et al., 2007) is added to the synthetic reading before inversion. The modification of Res2Dinv from the commercially available version permits the user to locally increase the smoothing factor in the vicinity of the buried electrodes. This modification has proven necessary to dampen inversion artefacts that otherwise are amplified close to buried electrode locations (Loke et al., 2015). Even after using geometric factor cut-offs for optimized sets of readings, inversions of field data sets with subsurface electrodes tend to have more noise and negative data points compared to conventional arrays (Wilkinson et al., 2008; Loke et al., 2014a). In order to suppress this effect, the inversion is done using the L1-norm constraint in Res2Dinv (Loke et al., 2003). L1 norm constrained inversion has higher stability and lower susceptibility to noise (Liu et al., 2015).

**Synthetic Models**

The potential advantages of the MERIT technique over conventional surface resistivity are first assessed by considering simple hypothetical subsurface
features. We compare MERIT and surface arrays in two ways: first, arrays with equal total number of electrodes; and second, arrays with equal electrode spacing.

**Cylindrical targets**

To compare conventional and MERIT approaches, 2D synthetic models containing several cylinders (radius=2 m) oriented perpendicular to the survey line are generated (Figure 3a). The models are designed to illustrate the effective depth of investigation, survey sensitivity, and resolution of both the dimension and the resistivity of the target cylinders. Models for surface surveys assume a conventional dipole-dipole array geometry (a=3 and n=6) with 203 measurements. The MERIT models employ an optimized set of readings generated via the method of Loke et al. (2015). All models assume a 52 m long electrode array with 2 m electrode spacing. The buried electrodes in MERIT models are at 8 m depth. 1000 Ωm resistive cylinders are embedded in a uniform 500 Ωm background. Cylinder center depths range from 3 to 12.5 m.

The differences between surface and MERIT surveys are shown clearly in the inversions for the buried cylinders (Figures 3b and e). The MERIT array detects the 5 deeper cylinders, which are not resolved in the surface-only array. Moreover, although the surface resistivity is able to detect Cylinder #3 just above the deeper electrodes, the MERIT array achieves better resolution of both shape and amplitude of the anomaly.

Targets like Cylinder #1 near the profile edges are not properly detected in the surface survey, even when at shallow depth (Figure 3b).
Figure 3. Comparison of surface (left column) and MERIT arrays (right column) over buried cylinders. (a) Forward model showing the locations and sizes of resistive cylinders ($\rho=1000\Omega\text{m}$, red) embedded in a uniform background ($\rho=500\Omega\text{m}$, blue). The numbers near the circles are used to label the cylinders. These cylinders are placed at locations of (5, 5.5), (11, 3), (29, 6.5), (45, 3), (5, 11.5), (11, 9.5), (23, 10.5), (29, 12.5) and (45, 9.5) meters across the array and meters deep respectively. Left column: results for surface dipole-dipole array with 2m electrode spacing and 203 total readings. Right column: results for optimized MERIT array with similar 2m spacing and 1203 total readings. (b) and (e) inversion results with data misfit of 1.2% and 2.2% respectively. (c) and (f) show sensitivity (d) and (g) show resolution.
This problem is ameliorated with the MERIT array (Figure 3e). Figure 3e shows that while the MERIT array significantly improves resolution of deep targets, it also suffers from inversion artefacts at depths just above the buried array. These inversion artefacts are addressed further below.

The improvement in the overall resolution and sensitivity at depth and near the edges with MERIT is also clearly illustrated in plots of model resolution and sensitivity for the inhomogeneous model (Figure 3f and g). Following the suggestion of Stummer et al. (2004) to define the depth of low resolution where model cells’ R drops below 0.05, the depth of low resolution of the conventional surface array is ~5 m. With the MERIT array, this depth of low resolution is pushed to ~5 m below the buried electrodes, for a total depth of ~13 m. Maps of resolution (Figure 3d and g) show the conventional surface array is less sensitive to features located near the edges of the survey line. A similar effect is observed in MERIT arrays below the deep electrodes, but between the surface and buried arrays there is good resolution to the ends of the profile (Figure 3g).

**Effect of a shallow conductive layer**

The benefits of buried electrodes can be even more striking in the presence of shallow conductive layers. Getting good penetration of electric current into underlying strata (for example limestone beneath clay in covered karst) is difficult as most of the current tends to flow through the conductive layer (Dahlin, 2001). Figure 4a shows the same 2D buried cylinders model as Figure 4a, with the addition of a shallow relatively more conductive (50 Ωm) layer between 1.5 and 3.5 m depth. The addition of this more conductive layer reduces the threshold depth of resolution of the conventional array from ~5m to ~4 m (Figure 3d and 4d). The mid-depth cylinder #3, below the conductive layer, is not detected by the surface array (Figures 4b, c, d). Yet the 13 m depth of
Figure 4. Comparison of surface (left column) and MERIT (right column) arrays over buried cylinders within and below a thin clay layer. (a) Forward model showing the locations and sizes of resistive cylinders ($\rho=1000\Omega\cdot m$, red) embedded in a background ($\rho=500\Omega\cdot m$, green) with a shallow low resistivity layer ($\rho=50\Omega\cdot m$, blue). The numbers near the circles are used to label the cylinders. Cylinder locations as in Figure 3. Left column: results for surface dipole-dipole array with 2m electrode spacing and 203 total readings. Right column: results for optimized MERIT array with similar 2m spacing and 1203 total readings. (b) and (e) inversion results with data misfit of 5.3% and 8.4% respectively. (c) and (f) show sensitivity (d) and (g) show resolution.
resolution of the MERIT array is relatively unaffected by the clay layer. Very similar resolution of cylinders is obtained in the presence and absence of the conductive layer (Figure 3g and 4g).

**Sinkhole structure**

Figures 2c and 2d show a sinkhole structure observed in west-central Florida. Figure 5 illustrates a synthetic model mimicking simple aspects of this structure. An uppermost sand layer (1500 Ωm) is underlain by a clay layer (50 Ωm), in turn underlain by a thick limestone (500 Ωm) with a thin transitional weathered layer (100 Ωm) (Figure 5a). The sediment-bedrock interface is disrupted at the center below a sub-surface depression in the sand and clay layers. Finally, the vertical feature cutting the clay layer is filled by sands raveling downward from the top layer. At this field site we infer that these raveling zones can be laterally elongated (Kruse, 2014) or can have small lateral extent with cylindrical conduit-like shapes (Kruse et al., 2006). Both scenarios are investigated, with a 2D model to simulate an elongated raveling zone, and a 3D model for a cylindrical conduit. As a conduit can have hydrologic significance as a breach in the clay semi-confining unit, resolution of this feature is a desired outcome. The conventional arrays comprise 27 surface electrodes spaced at 2m spacing while the MERIT arrays comprise 14 surface and 14 deep electrodes with 4m spacing thus fixing the total number of electrodes used in both methods close to 28 electrodes.

The resulting inverted images for 2D arrays are shown in Figures 5b,c,e, and f. Comparing the model resolution for the conventional arrays and MERIT shows that the depth of low resolution ($R < 0.05$) is located at 5.5m and 12.5m for the 2D forward model and at 6.5m and 13.8m for the 3D forward model, with surface and MERIT arrays, respectively. A noticeable decrease in model resolution is present at the center of the conventional array, due to the central resistive
Figure 5 Sinkhole structure. (a) Generalized synthetic sinkhole model showing resistivity variation in a sinkhole structure based on the geologic cross-section by Stewart and Parker, 1992. Sand unit (ρ=1500Ωm, green) is on the top and inside a raveling vertical conduit system. Below the sand is a clay layer (ρ=50Ωm, blue) with both the top and bottom contacts undulating. Weathered, clay rich limestone (ρ=100Ωm, orange) overlies the bottom fractured limestone (ρ=5000Ωm, light blue). Left column: results for surface dipole-dipole array with 2m electrode spacing and 203 total readings Right column: results for optimized MERIT array with similar 2m spacing and 1203 total readings. The 2D inversion results are labeled as 2D or 3D depending weather the readings are taken from 2D or 3D forward models. (b) and (e) 2D inversion of 2D forward model with data misfit of 2.6% and 2.8% respectively. (c) and (f) 2D inversion of 3D forward model with data misfit of 0.8% and 6% respectively. (d) and (g) Model resolution for 2D inversion of 2D forward model.
conduit. As seen for the cylinder models, resolution significantly decreases near the edges of the conventional arrays, but not for the MERIT array.

Figure 5 shows that both surface and MERIT methods are clearly able to detect the shallow contact and sub-surface depression between the top sand and clay layers. The inversion of the readings taken from the 3D forward model shows that this undulation is slightly less resolved in the MERIT array since the top electrodes have 4m spacing, compared to the conventional array which has 2m spacing. More significant differences are revealed in the identification of the vertical raveling zone. This raveling zone is manifested as a break in the continuity of the clay layer between 27 m and 32m and a sharp increase in resistivity compared to the resistivity of the clay layer (50 ohm-m). With the traditional surface array, the 2D conduit (elongate raveling zone) (Figure 5b) is better resolved than the 3D conduit (cylindrical raveling zone) (Figure 5c), in the sense that there is no indication of the raveling zone penetrating the limestone for the 3D cylindrical conduit. With the MERIT surveys, both the 2D and 3D versions of conduit are detected in the form of anomalies at limestone depths (Figures 5e and f). However, the 3D cylindrical conduit (Figure 5f) is clearly less accurately captured in the inversion. MERIT’s improvement over the surface array in resolving the 3D cylindrical conduit and its vertical continuity is novel and important in terms of helping to link the surface features with activities in the intermediate (overburden soil) and deeper (bedrock) activities. These linkages are keys to understanding hydrologic function and to properly mitigate karst-related sinkhole hazards.

Cavities in the limestone bedrock are themselves important targets. If the voids can be imaged, grouting can be done much more efficiently to mitigate the collapse of overlying sediments. Figure 6 shows a model with a top sand soil underlain by a clay layer that is in turn underlain by limestone.
Figure 6. Comparison of Data misfit with different bedrock resistivities. (a) Resistivity structure of Forward model. (b) Inverted resistivity image of highly resistive ($\rho=12000\Omega\text{m}$) bedrock with data misfit of 18.7% at iteration 8. (c) Inverted resistivity image of moderately resistive ($\rho=2000\Omega\text{m}$) bedrock with data misfit of 4.3% at iteration 8. (d) Inverted resistivity image of low resistive ($\rho=400\Omega\text{m}$) bedrock with data misfit of 7.3% at Iteration 4. (e) Inverted resistivity image of low resistive ($\rho=400\Omega\text{m}$) bedrock with data misfit of 1.2% at Iteration 10. Note that unlike the other figures in the paper, the color scale of resistivity varies from image to image.

In this model the sub-surface depression of the sand-clay contact is laterally offset from a deep dissolution cavity. The cavity is the original source of
hazard. Ideally, mapping of the raveling zone and shallow and deeper undulations could help in estimating the location of the associated limestone cavities. One way researchers have tried to map analogous sub-surface geological heterogeneities is through the injection of conductive tracers (e.g. Slater et al., 1997; Slater et al., 2000; Robinson et al., 2015). These conductive tracers are expected to follow preferential flow paths, such as the raveling zone. For resistivity surveys, the conductive tracers can preferentially enhance signal contrast, and ‘light up’ an area in time-lapse imaging. Here we examine such a scenario, simulating a void filled with conductive tracer.

In the 2D model in Figure 6a the conductive fluid is assumed to be concentrated in a cavity, while the overlying raveling zone has returned to background high resistivity. Figure 6b-d show inversion results for the same structure, with varying resistivity of the limestone bedrock (high=12000 Ωm, medium=2000 Ωm and low=400 Ωm). Also the bedrocks in all the models has good signal contrast compared to the overlying clay and the saline filled cavity. In all cases the MERIT array captures the sand depression, the low-resistivity cavity, and some anomaly in the vicinity of the raveling zone. All inversions show artefacts near the depth of the buried electrodes, which appear as the horizontal ‘stripes’ around the deep array. And because the method yields artefacts close to the buried electrodes, electrodes should ideally be buried above or below target depths – perhaps a distance on the order of the lateral spacing between electrodes.

Data RMS Misfit: Survey Design and Interpretation

The misfit between the data and the inversion results (presented as a percentage of the reading) is a commonly used gauge of the quality of the inversion results. Data misfits for MERIT surveys are typically higher than for surface surveys, as discussed in the introduction. In Figures 6b, 6c, and 6e the inversions
were run until the criteria for termination were satisfied. The criterion assumed in this paper is that the results of an inversion iteration vary by less than 0.1% from the previous iteration. At termination, the data misfits are 18.7%, 4.3% and 1.2% for the high, medium and low resistivity bedrock models respectively. Interestingly, the quality of the inversion is highly dependent on the presence of a highly resistive unit and absolute value of the resistivity contrast between the conductive clay and the resistive limestone. The higher the bedrock resistivity, the higher the data misfit and the poorer the recovery of the raveling zone and the void. Also, more artifacts with locally high or low resistivity values are introduced as seen in the model with the highest resistivity value and data misfit of 18.7%. Presumably this is because of: 1) the ease of current flow in the less resistivity bedrock models which allows better imaging of the void and 2) the negative effect of very high apparent resistivity values on the inversion. These high apparent resistivity values arise from array geometries that sample larger volume of the highly resistive bedrock. In L1-norm regularized inversion, these high resistivity readings would be more affected by the damping contributing to the bigger data misfit. This is an important factor since in most geological settings; the presence of more indurated, drier, resistive bedrock underlying softer, moister, less resistive sediment is a common state. Thus the deep arrays of MERIT, closer to the bedrock, tend to have higher data misfit.

Figures 6d and 6e illustrate the dangers of pushing the inversion process too far to lower the RMS misfit. Both figures share the same forward model; Figure 6d shows the inversion terminated at iteration 4 with 7.3% misfit; Figure 6e at iteration 10 with 1.2% misfit. The latter is below the 2% noise level; at this level the inversion is clearly amplifying artefacts as it fits the noise. The geological structures are equally identifiable in both cases. In summary, the results from MERIT arrays are reasonably expected to have a higher data
misfit especially in areas with more complex subsurface heterogeneity that includes highly resistive bedrocks. We suggest that these results should be accepted after a moderate effort to reduce error and an attempt to do ground-truthing and repeated or reciprocal measurements. Similar high data misfit while giving geologically reasonable results is observed in cross-borehole surveys as shown by Wilkinson et al. (2008) and Loke et al. (2014a).

The data processing approach used in the field studies in this paper to reduce data misfit includes eliminating bad data points in a sequential manner involving inversion and removal of noisy data points. In the inversion, reciprocal measurements are used to suppress noisy data using a data weighting matrix.

**Laboratory Experiments**

Two laboratory experiments were carried out to investigate the effectiveness of MERIT in a controlled environment. Both experiments were designed to be slightly similar to the synthetic models discussed above. In the first experiment (Figure 7), 5 resistive rods were placed in a water tank, creating a scenario similar to the cylinder synthetic model of Figure 3. In a second experiment (Figure 8), a small analogue sinkhole model was created to roughly mimic the sinkhole cross-section of Stewart and Parker, (1992), Figure 2c. In both experiments deep electrodes were implanted directly beneath surface electrodes.

**Rectangular rods**

In this experiment, 5 small insulated prisms were fixed at known locations (Figure 7). Data were collected for a conventional array with 28 electrodes spaced at 1cm and a MERIT array with 14 surface and 14 deep electrodes spaced at 2 cm. Deep electrodes were mounted at 5 cm depth. All rods except 2 and 3 had dimensions of 3.5 x 3.5 cm in the plane of the survey and 80cm perpendicular to the survey centered in the middle of the rods. Rod 2 and rod 3 had dimensions
of 2 x 4 x 80 cm and 6 x 3.5 x 80 cm, respectively (Figure 7). Holes drilled in blocks 2, 4 and 5 served as passages for the deep electrodes. Rods 1 and 5 are located close to the edges of the survey line while the rest are located closer to the center. Rods 2 and 4 mostly lay between surface and deep electrodes, rod 5 is close to the deep electrodes and rods 1 and 3 are located below the deep electrodes.

Figure 7. Experimental Rods. (a) Experimental setup of 5 rectangular rods in a water medium. The rods are made of wood insulated by plastic tape. The green dotted lines in rod 1 indicates that only part of rod one is shown in (b) and (c). Resistivity measurements are carried out using a SuperSting R1 resistivity meter. Both the surface and deep electrodes are made of copper wires with insulated and stripped sections. (b) Inverted resistivity image using conventional surface arrays (average noise level = 0.67%, data misfit error= 3.6%). (c) Inverted resistivity image using MERIT arrays (average noise level = 0.39% and data misfit error =7.5%).
The surface array detected only the shallow rods 2 and 4 (Figure 7b and 7c) but poorly resolved the dimension of the smaller rod 2. The MERIT array (Figure 7d) detected the shallow rods 2 and 4 and also better resolved the smaller rod 2. It also detected the deep rod 3 and rod 5 near the edge. Unlike the MERIT array, the surface array was not able to detect rod 5 near the edge and above the deep electrodes.

The MERIT array suffers a similar limitation below the deep arrays, where rod 1 near the edge is not detected. While the MERIT array has doubled the depth of resolution of the surface array, it suffers from inversion artefacts (at depth, right side) and near the deep electrodes. It also slightly mis-located rod 2 which is probably due to its smaller size and the presence of several target prisms to resolve.

**Sinkhole analog model**

An experimental sinkhole analog model was constructed mimicking a sediment-covered sinkhole structure such as the one studied by Kruse et al. (2006) (Figure 2c). The model has top layer of loose fine to medium sand underlain by cohesive clay soil (Figure 8). Below the clay, in order to mimic the weathered undulations in resistive bedrock, limestone blocks were emplaced over insulated foam padding. Weathered limestone chips mixed with a small amount of clay were used to mimic the weathered top of limestone. Three sand-filled “conduits” were created along the midline of the tank through the sand and clay with 4.5cm diameter plastic tubing with sand which was then removed, and the conduit filled with sand. Two conduits are vertical, one is inclined at an angle of ~70 degrees (Figure 8). In the middle of the tank just below these conduits, construction bricks with limestone chip and sand-filled cavities further simulates the bedrock that has undergone complex dissolution.
Figure 8. Sinkhole analog model based on the geologic cross-section of a covered karst sinkhole (Stewart and Parker, 1992). (Left) Photo taken during construction. Resistive foam padding lines the tank base. A limestone bedrock with limestone chip and sand-filled vertical fractures is created over the base, and overlain by fragmented limestone. In the middle, red construction bricks with chip and sand-filled voids simulate a more heterogeneous zone. A clay layer overlies the fragmented limestone and dips down over the bricks. Two vertical conduits and one inclined conduit are created in the clay layer with plastic tubing. The tubing was removed, the conduits filled with sand, and a poorly saturated sand layer was overlain on the top of the clay. The gray lines show the location of the two resistivity lines with 2.54cm (top) and 5.08cm (bottom) electrode spacing. The left edges of the lines correspond to the starting point of the survey lines. (Right) Resistivity setup for the study with 5.08cm electrode spacing; 14 at the surface and 14 buried at 8 cm depth.

Two electrode geometries were tested. The first array (A, Figure 8) had 14 surface electrodes and 14 deep electrodes buried at 8 cm depth; with 5.08cm horizontal spacing between electrodes. The array was centered over a central vertical raveling zone. Clearly resistivity readings will be affected by the edges of the tank (Loke et al, 2014b), but were neglected for the purposes of this simple experiment. The second (B, Figure 8) had 14 surface and 14 deep electrodes buried at 5cm depth with a 2.54 cm horizontal spacing. Array B was centered over the inclined raveling zone far enough (half the survey length) from the tank edges that edge effects should be small.

Figure 9a shows the inversion results from the experiments. The first figure shows the inversion result from the array A, the longer array with deeper electrodes across a vertical conduit. It can be seen that most of the longer wavelength sinkhole features are well resolved. The sub-surface depression in
the sand-clay contact and the top of bedrock are well imaged. Moreover, the narrow vertical raveling zone penetrating the clay layer is also detected. However, the continuation of this zone into the redbrick as sand filled cavity is not properly resolved, presumably due to the smaller resistivity contrast between the sand and the redbrick.

Figure 9b, over an inclined conduit, shows similar results. The effective depth of penetration is lower due to the shorter survey length. Nevertheless both the shallow contact between the sand and clay layer and the contact between the clay and the underlying limestone chips are seen. The inclined sandy conduit is not clearly imaged, but the offset between the lower depression centered at a distance of 0.125 m and sand-clay contact depression centered at 0.175 m is slightly captured.

Both inversions show considerable fine scale complexities that are not intentionally included in the physical model. These features could be inversion artifacts or could also be small heterogeneities that arise during material mixing or watering. Although the result captures most of the target features, it has a very high data misfit (14.9% for Figure 9a and 28.05% for Figure 9b) that is extremely high compared to the noise in the data set determined from repeated measurements, which is less than 1% for both experiments. This high data misfit is possibly related to the presence of the highly resistive bedrock layers represented by solid rock blocks and insulated foam padding. These results are fairly consistent with the results from the numerical model (Figure 6b) involving a sinkhole structure with highly resistive bedrock (12000 Ωm).

For Figure 9b, an attempt made to reduce the data misfit by removing noisy data points resulted in lower misfit but more artefacts with less resemblance to the true analogue model.

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Field Case Study

Two field-scale case studies are described here.

Field case study 1: sinkhole related karst features

The first case study site is located in covered karst in-west central Florida, in the Geopark research site on the campus of the University of South Florida (Figure 11; location shown in Figure 2). This research site has been studied by Stewart and Parker (1992) and Kruse et al. (2006). Ground truth information includes drilling logs, standard penetration tests (SPT), cone penetration tests (CPT), geologic profiles, and GPR survey data (Figures 11-14). Two MERIT lines (Line A and Line B) were installed by implanting 14 deep electrodes on each line. The deep electrodes are implanted at 7.6 m depth with a 4 m spacing on Line A and at a depth of 5 m with 5 m spacing on Line B. Conventional surface resistivity surveys were conducted using a 2 m spacing on Line A and 2.5 m and 5 m spacing for Line B. In both survey lines, the main targets are common sinkhole-related features, including contacts between stratigraphic layers,
undulations at contacts, raveling zones and dissolution cavities (e.g. Figure 2b).

Figure 11. Map of Geopark research site at the University of South Florida, USA. The cyan lines indicate geologic profile lines studied by Stewart and Parker (1992) and present study. The location of this site is the same as for the GPR lines as shown in Figure 2. Resistivity surveys along Lines A and B are described in this paper. The start of both surveys is towards the bottom end of the lines.

The noise level of the field data can be described in two ways: first, as the percent difference between repeated measurements with the identical electrode locations, and secondly as the percent difference between reciprocal sets of readings, in which the current and potential electrode pairs are switched. (In theory reciprocal readings should produce identical apparent resistivities.) By the first metric (repeated measurements), MERIT arrays have generally higher
noise level compared to the surface arrays. On line A the average noise level in the field data are 0.58% and 2.1% for the surface and MERIT arrays respectively. On Line B, the same values are 1.6% and 1.7%. Reciprocal measurements were run for MERIT arrays on Line B; these show a wide range, with a minimum reciprocal error of 0.1%, and 75% of the reciprocal errors below 7.2%. During the inversion, errors associated with the reciprocal readings were used in the data weighting matrix. The average reciprocal error becomes 3% after filtering out the 25% of the data that has a higher reciprocal error above 7.2%.

![Figure 12](image.png)

**Figure 12.** Comparison of resolution of resistivity survey with 28 electrodes arrays across the surface (left graphs) versus 14 shallow and 14 deep electrodes (right graphs) for Line A (top) and Line B (bottom). (a) Line A using conventional surface arrangement. (b) Line A using MERIT arrangement with electrodes at 7.6 m depth. (c) Line B using conventional surface arrangement. (d) Line B using MERIT arrangement with electrodes at 5 m depth. Both lines run from south on left to north on right. See Figures 2 and 11 for locations.

The addition of the deep implant electrodes results in significant improvement in depth of investigation as characterized by resolution, in both line A and line B (Figure 12). Improvements are most significant in regions that have low resistivities, and on the edges of the array between surface and deep electrode
On both lines, sinkhole-associated features include loose sediments, presumably raveling zones, which have higher moisture content relative to the surrounding less disturbed soils (Figures 13a at 24 and 29 m and Figure 14b at 45 m). These raveling zones result in low resistivity areas around the sinkhole locations, especially during the rainy season. On Line A (Figure 13), the use of the deep electrodes enables four distinct improvements in the resistivity image. (1) There is better agreement with a depression in a GPR reflecting horizon identified from simple auger holes as an internal stratification within the top sand layer with a slightly cohesive internal layer of clayey silty sand and coring indications for the sand-clay contact (magenta line Figure 13). (2) The MERIT results show better agreement with the general attitude of bedding captured in the CPTs, SPTs, and wells (Figure 13).
On line B (Figure 14), a GPR profile shows 3-4m depressions in the depth to a clay-rich layer at 20 m and at 49 m. The GPR reflector depression at 20 m overlies a zone of thick clay, where limestone was not reached by a CPT to >14m (CPT16; Figure 14). In contrast the depression at 49 m overlies a zone of thickened sands, but limestone at 11.3 m depth (B4, Figure 14). The boring results show large lateral variability in the cover sediments; clearly the raveling process of sediments over limestone is highly locally heterogeneous. We infer that sediments infilled a limestone dissolution feature at 20 m, but that this is no longer a site of active dissolution. The overlying sediments have had time to be well compacted, as seen in the relatively high SPT values in B3 (Figure 14b). In contrast, above the GPR reflector depression at ~49m, a surficial lens of organic soil, 8 m wide and up to 80 cm thick, is seen in both GPR and B4 (Figure 14a and b). We speculate that the second sinkhole is active with loose soil populated by plant growth during wet seasons. The complex stratigraphy and low SPT values at B4 further suggest a zone of active raveling.

Both MERIT and surface-only resistivity arrays show good agreement with undulations in the sand-clay contact seen with both GPR and coring. Below this contact, the MERIT profile (Figure 14e) shows better agreement with geological results than the surface profile with equal 5 m spacing (Figure 14c), in that MERIT shows a thick low-resistivity zone coincident with the thick clay recorded at CPT16 at 20 m. The surface array with 2.5m spacing also partly shows the presence of thicker clay around 20m. The MERIT results suggest high-resistivity limestone that is breached at 20 m and again on the northern end of the line. Borehole B1 5 m from the northern end of the line (see Figure11 for location) shows possible dissolution cavities indicated by absence of bedrock, voids and loss of circulation fluid, and low densities determined by SPT tests up to 56m. Both features are not sufficiently imaged by the surface arrays because they
are located at depth and near the edge where the surface arrays suffer from poor sensitivity and resolution.

Figure 14. Geopark Resistivity result on Line B. (Continued to the next page).
Field case study 2: landfill site

This case study site is a storage facility in Tampa, Florida, undergoing differential settlement in an urban setting with limited access.
Figure 15. Differential settlement at a landfill constructed over an old lake, Water Melon Lake in Tampa, Florida, USA. The lake boundary is mapped from a 1957 aerial photograph and the landfill boundary from a 1968 aerial photograph. A 1972 aerial photograph shows that the landfill was extended north and west of the 1968 boundary. 27.3 indicate the distance in meters from the north edge of the resistivity line to the boundary of the infilled Watermelon Lake. The southern edge of the resistivity line is 6m from the edge of the old lake. The north edge of the line corresponds to the starting point of the resistivity survey.

The site was a landfill, active between 1968-1972 based on aerial photograph records (Figure 15). The landfill partially infilled an old sinkhole lake (Water Melon lake). The uppermost part of the fill is compacted and levelled. A borehole (BH1 on Figure 16, 32 m from the northern end of the resistivity line on Figure 15) shows the uppermost fill as asphalt and more compacted soil (possibly material reworked from the natural ground), underlain by relatively loose landfill material containing fragments of wood, red bricks and other materials. The drilling was terminated at 7.3 m due to complete water loss,
without reaching any kind of bedrock material. Historical records of the landfill construction also confirm similar information. The current structures on the site are simple, one floor storage buildings. The middle part of the building highlighted in green on Figure 15 has experienced significant settlement, with cracks and offsets in the roof.

A resistivity survey was carried out as part of an investigation of the cause of the differential settlement and its relation to the old landfill activity. The 65 m-long survey occupied the maximum available length on site (Figure 15). 14 deep electrodes were implanted at 6.57m depth and 5m spacing with a total installation time of 7 hr. The resistivity survey installation is located parallel to and 1 m east of a vapor extraction trench installed to monitor the environmental impact of the landfill, and ~1m east of the settling building. The old lake boundary is 27.3 m from the northern end of the resistivity line and is 6m from the southern end. The maximum differential settlement in the building is at ~ 32m. The proximity of the old lake boundary and maximum differential settlement suggests the landfill is significantly thicker over the old lake, than on surrounding material.

The average noise level in the surface field data is 0.9%. For the MERIT arrays, the field measurement included reciprocal readings and has an average noise level of 0.6% and an average reciprocal error of 0.4%. These reciprocal errors were used to weight the observed data during the inversion. The contact resistance for both surface and MERIT electrodes is also very comparable. For example, the maximum and average contact resistance for the surface electrodes is 456 Ω and 295 Ω and 484 Ω and 277 Ω for the MERIT electrodes. Also on Line B above (Figure 14), similar contact resistance was observed for surface and MERIT electrodes with maximum and average value of 3470 Ω and 1395 Ω for surface arrays and 4826 Ω and 1120 Ω for the MERIT arrays.
Figure 16. Resistivity results from the profile over an old landfill shown as yellow line on Figure 15. Inverted resistivity image using conventional array (left) and MERIT array (right). Data misfits are 3.1% and 3.7% for the conventional array and MERIT array respectively. White dots show electrode locations and left end of the line points towards north.

The results from both the surface and MERIT surveys (Figure 16) show the contact between relatively resistive asphalt and compacted top layer and a lower conductive unit of landfill material. Most importantly, both images show a sharp resistivity boundary at 8-10 m depth, interpreted as the contact between the landfill material and the higher resistivity bedrock. This deep high-resistivity layer is discontinuous; it is absent south of ~35 m from the surface resistivity
inversion, and absent between ~30 m and 55 m in the MERIT image. We interpret this gap in the deep resistive layer as a result of the old lake, subsequently filled. This interpretation is supported by the differential settlement described above. We can then assess the resistivity results against the known lake boundaries. The MERIT image shows a slightly better fit to the northern lake boundary. Notably, the MERIT array also shows the southern lake boundary, which is outside the zone of resolution of the surface array. This site is thus an example of the utility of the MERIT geometry in a setting where array lengths are limited. The data misfit comparison between the surface and MERIT arrays shows that the MERIT arrays have relatively higher data misfit compared to the conventional surface arrays (Figure 13 for Line A, Figure 14 for Line B and Figure 16 for Landfill site). For Line A and Line B, while both arrays do a good job of capturing the near-surface variations, they both have higher data misfit compared to the results at the Landfill site. This could be related to the difference in the degree of complexity of the underlying karst structure in the two sites.

Comparing the data misfit of the MERIT inverted results from the Landfill site and Line B at the Geopark (Figure 14), it can be seen that the data misfit is significantly lower for the Landfill site although reciprocal error was used to suppress noisy data points on both. One explanation for that is the overall better data quality observed on the Landfill data compared to Line B. For example, the maximum contact resistance for Line B was 4826 Ω. Even though this number is lower than the commonly accepted value of 5000 Ω (AGI, 2005), it is 10 times greater than the maximum contact resistance value observed for the Landfill site (484 Ω). Similarly, the average noise level (1.7%) and average reciprocal error (3.0%) for Line B again are higher than what is observed for the Landfill site (0.6% and 0.4%).
Conclusion

2D surface resistivity surveys have fundamental limitations in depth of resolution, particularly at the ends of the array. These problems can limit the utility of the method at sites with limited working space. The problem is exacerbated by the presence of shallow conductive layers. Installation of a buried array of electrodes extends the depth of resolution and expands the zone of resolution to the ends of the array. This array geometry, referred to as multi-electrode resistivity implant technique (MERIT), is examined with synthetic models, laboratory experiments, and field case studies. In the field the deep electrodes are implanted using robust direct push technique using self-driving pointed electrodes. In practice, we find-

- Depth of resolution can be approximately doubled over that of a conventional surface array of equal length.
- Decrease in depth of penetration due to shallow clay layers is much less in MERIT arrays compared to conventional surface arrays.
- Good resolution is obtained up to the ends of the array, with some sensitivity (as expected) to features beyond the ends of the line.
- Improved resolution of geometries and absolute resistivity values are obtained for features between the surface and buried arrays.
- Because of geometric effects, the method is inherently somewhat noisier than surface arrays. Inversion artefacts appear close to the depth of the buried electrodes, analogous to the artefacts that appear close to electrodes in cross-borehole surveys.
- Inversion results are improved when reciprocal measurements are used to reduce the weight of noisy data in the inversion.
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3D electrical resistivity surveys are used where the need for better resolution of the subsurface outweighs the extra cost and time compared to 2D surveys. A well-planned 3D electrical resistivity will usually give a result that is superior to conventional 2D surveys by avoiding: 1) artifacts from offline objects and 2) misinterpretation of 3D features with low continuity perpendicular to the survey line. These 3D surface arrays suffer, however, from some of the same fundamental limitations of 2D resistivity surveys, namely a decrease in resolution and sensitivity with depth and near the edges. In this paper, we introduce a 3D resistivity method, called MERIT3D in which a 3D surface array is combined with a 2D rapidly-implanted buried electrode array. This method is an expansion of a previously described geometry in which a 2D buried array is installed directly beneath a 2D surface array (MERIT or MERIT2D). Once a deep array is installed, parallel surface arrays are set up laterally offset from the buried array. Results from numerical, laboratory and field studies are used to assess the technique with simple geometries and features of interest in covered karst, including caves and covered sinkholes. The MERIT3D approach is found to have significant advantages in resolution near the ends of the survey and at depth compared to both 2D MERIT and 3D surface resistivity arrays.
Introduction

Geoelectrical methods have evolved from classical 1D soundings to 2D profile and 3D grid studies of a wide variety of complex geological scenarios (Carpenter et al., 2010; Zohdy and Jackson, 1969; Dahlin, 1996; Kruse et al. 1998; Nyquist et al., 2005; Loke et al. 2015; Wilkinson et al., 2006a; Chambers et al. 2010; Kiflu et al. 2016). 2D resistivity methods are effective in areas where the geology can be reasonably assumed to vary primarily two dimensionally (Bentley et al., 2004). However, in areas with three-dimensional compositional or structural heterogeneities, 2D surveys can produce misleading interpretations (Park and Van., 1991; Loke and Barker., 1999a; Bentley and Gharibi, 2004). Bentley and Gharibi (2004) used synthetic and field studies at a remediation site to show that 2D resistivity measurements and inversions can be significantly affected by the offline heterogeneities, which they term a 3D geometric effect. In such settings, 3D electrical resistivity methods have proved to be important for capturing true geological heterogeneities (Dahlin et al. 2002; Gharibi & Bentley 2005; Chambers et al. 2006, 2012). Despite its limitations, however, 2D methods are still much more widely used, due to the lower cost, time and ease of field implementation. Several authors have given suggestions to overcome these limitations by finding efficient ways of collecting 3D field data (Dahlin et al., 2002; Loke and Barker, 1996; Loke et al., 2013).

In general, 2D resistivity surveys fail to fully resolve subsurface features that have a short dimension perpendicular to the survey line (Loke et al., 2013). While 3D surveys overcome these limitations, they still suffers from the 3D equivalents of other shortcomings of 2D surveys, namely exponentially decreasing sensitivity and resolution at depth and at near the edges of the line or grid (Loke et al., 2013). Cross-borehole surveys solve these problems
by increasing the resolution with depth, but usually the boreholes are placed close together, limiting the overall lateral coverage. Recently 2D techniques have been expanded into the depth dimension via the use of vertically buried horizontal arrays (referred to as MERIT or MERIT2D) (Harro and Kruse, 2013; Loke et al., 2015; Kiflu et al., 2016) or two horizontal layers of electrode arrays involving two horizontal boreholes (Danielsen and Dahlin, 2010) or combining a surface array and horizontal borehole (referred to as S2H) (Power et al., 2015). Each of these methods expands the range of traditional 2D surface surveys by overcoming the fundamental limitations on resolution at depth and at the ends of the profile, while still giving good lateral coverage along the profile, with a reasonable number of electrodes.

In this paper we explore the expansion one of the 2D surface-plus-deep electrode methods, the MERIT method, into the third dimension. Kiflu et al. (2016) describe the resolution of the MERIT method, which involves installation of a buried electrode array beneath a surface array. Electrodes are installed using a rapid robust direct-push technology that is much faster and cheaper than the conventional drilling required for cross-boreholes. Nevertheless, a MERIT array installation still requires additional cost and field time over that needed for a conventional surface array. In order to add more relevance to the increased cost and effort in a MERIT installation, we examine here the additional benefit that can be gained by the less incrementally expensive addition of parallel surface electrode arrays. Such arrays sequentially laterally offset to make both inline and offset measurements involving the surface and deep electrodes. We refer to this technique as MERIT3D.

In any 2D or 3D resistivity survey, choices must be made about which of the
thousands to millions of possible combinations of current and potential electrode pairs and readings to make. Methods to determine the optimal arrays, for maximum resolution for a given number of measurements, have been described in several studies (e.g. Furman et al, 2004; Strummer et al, 2004; Henning & Weller, 2005; and Wilkinson et al, 2006). Optimized arrays have also shown improved results in cross-borehole resistivity (Wilkinson et al, 2006a) and 3D resistivity (Loke et al., 2013a). In the MERIT3D development, we adopt a modified version of the Compare “R” method used for the 2D MERIT method described in Loke et al. (2015) and Kiflu et al. (2016).

In this paper we begin with synthetic numerical models to compare the capabilities of MERIT3D against the 2D MERIT technique detecting subsurface targets with short and long offline continuity. Then, as is commonly done, we example targets with simple shapes to compare conventional 3D surface resistivity grids against MERIT3D techniques for detecting features at depth and near the edges of a survey grid. Both numerical and laboratory studies are expanded to compare 3D surface resistivity and MERIT3D technique for a realistic complex shape of a cave. Finally, we will present field study results to explore the possible improvements of MERIT3D for imaging sinkhole features in study site located at Tampa, Florida.

**Methods**

In the MERIT approach, the subsurface electrodes are implanted using a Geoprobe® (Direct-Push) system (e.g. United States Environmental Protection Agency, 2005). The implanted electrode is an expendable drive point with an attached wire (Harro and Kruse, 2013). The drive point is placed in the lower end of a groundwater sampling sheath that is pushed downwards by percussion. When it reaches the desired depth, the sheath is withdrawn leaving the implanted
electrode joined to the surface by the attached wire. This installation is more rapid and less costly compared to vertical boreholes, with an average rate of installation of 20 m/hr. Cost wise, a MERIT array with 14 buried electrodes at 7.5 m depth is typically less costly than two cross-boreholes with 15-electrode string (United States Environmental Protection Agency, 1998) making it an attractive choice for deeper targets with large horizontal extent. In addition, compared to most drilling techniques, the MERIT approach minimizes the disturbance caused on the target itself by avoiding the use of circulation fluid and utilizing a small borehole radius (~2.5cm). The borehole radius itself is much smaller than the targets of the studies described here. The direct push rig has a controlled hydraulic system that permits vertical advancements in increments as small as 0.125cm. When the lengths of the push rods for installation are accurately measured, the vertical accuracy of the implanted electrodes is expected to be similar to that of an electrode mounted on a rigid support in vertical boreholes (e.g. Wilkinson et al., 2008). Following Paasche et al. (2009), the maximum horizontal deviation of the direct push rod from vertical is expected to be less than 5 degrees.

Figure 1. Field arrangement of 3D surface arrays with 4m electrode spacing and 4m offset interval (left) and MERIT3D arrays with 8m implant depth, 8m electrode spacing and 4m offset interval.
Once the MERIT implants are installed, surface electrodes are placed along the center line and sequentially on offset lines on both sides (Figure 1). Measurements are taken using 1) inline readings along the MERIT electrodes, 2) inline readings along the surface electrodes, and 3) optimized arrays between the surface and the MERIT electrodes. This process is repeated for all the offset line positions.

This deployment of MERIT electrodes and offset electrodes offers complex spatial geometries with opportunities to select optimal combinations of electrodes as current and potential pairs that would maximize information extracted per reading involving the offset surface and MERIT electrodes. The selection of optimal sets of readings for MERIT arrays is created using the modified version of the “Compare R” method with algorithms suitable to these new electrode arrangements and is described in detail in Loke et al. (2015) and Kiflu et al. (2016). The optimization algorithm works by efficiently selecting a predetermined number of stable arrays that will maximize the model resolution from a myriad of possible array combinations. The model resolution matrix R measures how well the resistivity of each model cell can be estimated from the observed data (Menke, 1984). The final 3D inversion will combine this offset measurements and inline and offline measurements taken only involving surface measurements.

**Numerical Studies**

Synthetic models are used to investigate the effectiveness of MERIT3D arrays compared to 2D MERIT results, and then MERIT3D against 3D surface arrays. Forward and inverse models are run with Res3DMod and Res3DInv software (Geotomo Inc., 2014; Geotomo Inc., 2016). We focus on the potential of MERIT3D to address challenging and practical engineering, karst, and geological scenarios.
Comparison of MERIT3D with MERIT2D techniques

A pair of models is used to evaluate the degree to which a MERIT3D survey could improve over a MERIT2D survey in the resolution of a feature with a short extent perpendicular to the survey line.

Figure 2. Comparison of MERIT2D and MERIT3D surveys over “2D” (left side) versus “3D” (right side) features. Synthetic model with inclined resistive planar body (a) and inclined conduit-like resistive body (b) with resistivity $\rho=1000 \ \Omega \cdot m$ and background resistivity $\rho=500 \ \Omega \cdot m$. (c) and (d) show the MERIT2D inversion results for the planar and conduit-like bodies respectively. (e) and (f) show cross-sections taken along the center of the 3D inversion results for MERIT3D for the planar and conduit-like bodies respectively.
The synthetic models incorporate a resistive feature, 2 meters thick that dips at an angle of ~35° from the surface to 13 meters depth. In model (a), the inclined feature is planar and continuous perpendicular to survey line all the way to the end of the model domain, including padding cells that are not shown in Figure 2a. In model (b), shown in Figure 2b, the inclined feature now is only 2 meters in thickness in the direction perpendicular to the plane of the profile, so it resembles a dipping conduit rather than a dipping plane. In both cases the model background has a resistivity \( \rho = 500 \, \Omega m \) and the inclined target feature has a higher resistivity of \( \rho = 1000 \, \Omega m \). The MERIT2D array is located at the center of the model domain and consists of a total of 651 readings between electrodes spaced at 4 m, with the deep electrode array implanted at 8 m depth. The MERIT3D array involves the same of arrangement with additional 7 offset lines on both sides of the MERIT implants, spaced at 1m intervals. The total number of readings used in the MERIT3D acquisition is 16921.

The inversion results for the MERIT2D survey (Figures 2c and 2d) show that the MERIT2D array was resolves the dimension, depth and even the absolute value of the resistivity of the 1000 \( \Omega m \) “planar” body quite well. In contrast, however, the MERIT2D process does not recover the continuity of inclined “conduit” (Figure 2d). Only sections that are close to the surface and to the deep electrodes are detected. The full depth extent of the body is also not well resolved. The result clearly the weakness of MERIT 2D surveys for fully resolving features with short extent perpendicular to the array.

In contrast, the MERIT3D process captures the continuity of the conduit, although the MERIT3D inversion underestimates the 1000 \( \Omega m \) resistivity of both the planar and conduit targets.
Comparison of MERIT3D with 3D surface resistivity surveys: simple shapes

Here, we investigate the effectiveness and improvements of the MERIT3D technique compared to conventional 3D surface surveys. We use two synthetic models, one designed to address in particular resolution of features at depth and near the edges of the survey lines; the other to address the resolution of a “cave”, a feature of interest in many karst resistivity investigations (e.g. Panek et al., 2010; Orfanos et al., 2011). The first synthetic model consists of 8 resistive spheres (radius=2 meters, $\rho =3000$ $\Omega$m) that are buried inside a lower resistivity ($\rho =100$ $\Omega$m) background (Figure 3). Four of the spheres (1, 2, 3 and 4) are located above the deep array implanted at 8m depth; four are located below the deep array (5, 6, 7 and 8). Two shallow (1 and 4) and two deep (5 and 8) spheres are located near the edges of the survey area. All the spheres are aligned along the central resistivity line containing the deep MERIT electrodes.

Figure 3. Synthetic models to assess resolution of “small” features at various locations. (a) 8 resistive 2-m radius spheres ($\rho =3000$ $\Omega$m) in a $\rho=100$ $\Omega$m background at shallow and deep locations and near the edges of the survey. (b) Survey grid for MERIT3D and 3D surface methods. Blue dots represent the offset surface electrodes used for both the MERIT3D and 3D surface arrays. The bottom red/black cones represent the MERIT electrodes used only on the MERIT3D surveys. The central lines simply indicate the coordinate system (red = $x$-direction, yellow = $y$-direction.

The 3D surface arrays in this synthetic model consist of 15 parallel 2D dipole- dipole arrays, with 28 electrodes each. The spacing between each of
Figure 4. Inversion result of sphere models. (a) 3D inversion result of the 3D surface arrays with a data misfit value of 0.17%. Left side shows the volume rendering. Model spheres with no resistivity response appear red; purple rendering shows resistivity signature above a threshold value; where purple resistivity signature surrounds it, the model sphere appears pink. Right side shows vertical cross-sections along the X and Y directions overlaid by the cross-sections of the model spheres shown in white. (c) 3D inversion result of the MERIT3D arrays with a data misfit value of 0.57%. Left side shows the volume rendering of the detected spheres shown in purple overlaid over the model spheres shown in red. Right side shows vertical cross-sections along the X and Y directions overlaid by the cross-sections of the model spheres shown in white.

the parallel 2D arrays is 1 meter (y-direction on Figure 3); along each 2D array the electrode spacing is 2 meters (x-direction on Figure 3). This combination requires of a total of 2842 surface measurements. To simulate
the MERIT3D array, a set of 14 electrodes implanted at 8 meters depth with an electrode spacing of 4 m are added below the center line of the surface array (Figure 2b). Readings are computed between each 2D surface array and the deep MERIT electrodes, inline along the surface lines and inline along the deep implant array, for a total 18051 measurements. The resistivity inversion results for both the 3D surface and MERIT3D arrays are shown in Figure 4. The 3D surface array detects the four shallowest spheres, with the best resolution of the shallowest spheres, including # 4 located near the edge. Least well resolved is sphere #1, at the edge of the survey. The surface arrays do not detect any of the deep spheres located below the buried electrodes. On the other hand, the MERIT3D arrays clearly resolve both the shallow and deep spheres, excluding only the deep sphere # 5 located near the edge. This is expected, as the MERIT3D array is expected to suffer similar edge effects as the surface arrays, with the effects simply translated to depths below the deep array.

Comparison of MERIT3D with 3D surface resistivity surveys: cave

Resistivities are widely applied to cave and void detection. The following numerical investigation mimics a geologically realistic dissolution cave. The model is based on an existing cave, Legend cave, in Citrus County, Florida that is studied by McCrackin (2012) using a 3D surface resistivity method. Here, we used their cave map to produce a 3D CAD model of the cave which we then resampled to create an input file for Res3Dmod software (Figure 5). The resistivity of the cave is assumed to be 1000 Ωm while the background is assumed to have lower resistivity of 100 Ωm. The shape of the cave is irregular, having sections with varying dimensions and depth, including a narrow section leading from one larger void space to another. The purpose of this study is to test the
effectiveness of 3D surface and MERIT3D arrays in terms of resolving: 1) the three-dimensional propagation of deeper features 2) narrow sections of the cave.

Figure 5. Synthetic model mimicking Legend cave, west-central Florida. a) 3D model. Two larger voids are connected by narrow vertically and horizontally winding sections. Cave resistivity is set to 1000 Ωm; surrounding background to 100 Ωm. Resistivity electrode locations are partially shown: the blue cones represent offset surface electrodes used for the 3D surface and MERIT3D arrays. Red cones indicate deep MERIT electrodes used only in the MERIT3D arrays. b) Full survey grid layout used for synthetic model resistivity surveys. Both the offset lines and the MERIT electrodes are perpendicular to the principal direction of the cave. The deep MERIT electrodes are located slightly above the bottom of the cave.

The 3D surface arrays for the cave model consist of dipole-dipole arrays along nine parallel X- direction profiles (perpendicular to the cave; red direction in Figure 5) with 28 electrodes each, with electrodes set at 4m intervals along each line. These lines are also offset 4 meters from each other in the Y direction. In total 1827 measurements are simulated. The MERIT3D array incorporates the same surface arrays with 14 additional implants beneath the middle line at 24 m depth with an electrode spacing of 8 m (Figure 5b). The MERIT3D array has a total of 10830 measurements taken along the offset lines, along the deep array, and between the offset and the deep array.

Figure 6 shows the resistivity inversion results for both the 3D surface (left column) and MERIT3D (right column) arrays. Both methods resolve the two large shallow rooms in the cave. However, the MERIT3D array better resolves the
Figure 6. Inversion results of a synthetic cave model. Left column shows result for 3D surface arrays (data misfit = 0.25%) and right columns shows inversion results for MERIT3D arrays (data misfit = 0.98%) for noise-free synthetic data. (a) and (b) show a voxel image of the inversion result using a resistivity threshold values of 40 $\Omega$m and 350 $\Omega$m (purple) overlaid over the actual 3D cave model (gray). The upper right diagrams in both (a) and (b) show the shape of the cave based on the inversion result for each array. (c) and (d) show horizontal cross-sections of the inversion results overlaid by the horizontal cave boundary at the same elevation (black lines) and vertical cave boundary across the center of the cave (pink lines). (e) and (f) show the vertical cross-section of the inversion results overlaid by similar vertical cross-section of the cave model (white line) at the same area. The narrower sections of the cave and better resolved the general shape of the cave. The narrow sections at the center of the caves are too narrow to resolve compared...
to the electrode spacing used in the study. This is an incremental improvement over the surface 3D array, as even with the MERIT3D, the finer details of the cave structure are incompletely resolved with the electrode configuration used in the simulation. It is important to note here that resistivity inversion methods fundamentally limit resolution of a sharp boundary (Loke, 2003; Nguyen et al., 2005), and that MERIT3D technique still suffers from these basic limitations of resistivity method. In addition, the inversion suffered from poor resolution and produced strong artifacts near the edges of the model domain.

**Laboratory Experiment: Cave Geometry**

A laboratory experiment was set up using a water tank filled with tap water and a small amount of salt as background and a plastic cave model as target feature. The water tank has a dimension of 80cm x 80cm x 80cm and is made of clear plexiglass material. The average resistivity of the water used in the experiment was 15.33 ohm-m. The laboratory “cave” is a modified version of the 3D CAD model for Legend cave described in the previous numerical modeling section. The plastic “cave” is made with a 3D printer (Figure 7) using 300 micron polylactide (PLA) thermoplastic filament, such that the long dimension of the cave is ~40 cm. Internally the cave is supported by a honeycomb structure that has voids. The cave is printed as two pieces that are connected using a wire support and glue. Inside the water tank, the cave is pervious and the voids inside the cave are partly filled by the water from the tank. Thus the actual resistivity of the bulk cave volume is not known, but is generally higher than the resistivity of the water. This lab model is similar to the numerical model of the previous section, but with the orientation adjusted relative to the electrode arrays. The primary differences are that the deep electrode array lies beneath the cave, that the edge of the cave rather than the cave center is
overlies the deep array, and that the cave is set at an angle such that one room is deeper and the other is shallower. The latter adjustment is made in order to test the capability of the MERIT3D arrays in resolving the cave at a range of depths. Figure 7 shows the cave design and experimental setup. Both the surface electrodes and the deep electrodes are constructed from an insulated steel wire where ~3mm of the

Figure 7. Laboratory model for a resistive “cave” based on the Legend cave geometry as in Figures 5 and 6. a) Vertical cross-section of the CAD design used in 3D model printing. b) and c) Laboratory setup of the experimental plastic cave model in water-filled tank. b) tank viewed from side. C) tank viewed from above. The electrode arrays are prepared by stripping a steel wire.

wire is stripped to expose the tip. These electrodes, along with the cave, are mounted from a wood support bar such that the deep electrodes are placed at a depth of 10 cm. A total of 14 deep and 14 surface electrodes are used for the study with an electrode spacing of 4 cm for both. As described above, most of the cave lies on one side of the electrode array, a small portion extends
between the 4th through 6th electrodes from the right side of the array as shown in Figure 7. The offset surface electrodes for both the 3D surface and MERIT3D measurements are placed at both sides of the deep array at 1 cm spacing. In addition to the measurements taken at the center line, additional 9 offset arrays are used for both the 3D

Figure 8. Inversion results from laboratory “cave” experiment. Left column: MERIT3D; Right column: 3D surface arrays. Black line grid illustrates plastic “cave”. Black dots show surface electrodes; white dots show buried MERIT electrodes. a) View from top of MERIT3D results. b) View from top of 3D surface array results. Data misfit for the inversion is 14.27% and 14.61%, respectively. Front view of the inversion result for c) MERIT3D arrays and d) 3D surface arrays. Color scale for (a), (b), (c), and (d) shown with bottom color scale. Isosurface map of the inversion results for MERIT3D arrays (e) and 3D surface arrays (f). Color scale for (e) and (f) shown with top color scale.

surface and MERIT3D arrays. A total of 507 dipole-dipole measurements are made
for the 3D surface arrays and 8879 measurements for the MERIT3D arrays.

The inversion results for the lab experiment are shown in Figure 8. Both 3D surface arrays and MERIT3D arrays clearly show that the general cave location (Figures 8a and b). Both methods are also able to detect the two bigger sections of the plastic cave model (Figure 8c and d). However, on the results from the 3D surface array, the deepest cave portion and the parts of the cave near the edges of the profile at \( x = 0.4-0.48 \) meters are not detected. Although both surveys indicate the connectivity of the two large sections, the MERTI3D arrays arguably better capture the complex nature of this connecting path. Similarly, the larger room located between \( 0.08 \)m and \( 0.28 \)m extends deeper near \( ~0.28 \)m, rises, near \( ~0.22 \)m and deepens again between \( 0.14 \)m to \( 0.08 \)m. This form is slightly captured by the MERIT3D arrays. Generally, the larger room located between \( 0.08 - 0.28 \)cm is clearly lower in elevation compared to the larger room located between \( 0.32 \)m - \( 0.48 \)m on the MERIT3D inversion. However, in the 3D surface array results, this is not, and both sections appear as if they have the same elevation. Finally, although the MERIT3D arrays are able to capture relatively more complex characteristics of the cave, neither method captures the finer details of the cave. The cave in the inversion results appears larger and smoother in the than the laboratory model.

**Field Study: Covered Karst**

A field study designed to compare 3D surface and MERIT3D surveys was carried out at the Geopark research site on the campus of the University of South Florida, Tampa, Florida. The area is characterized by the presence of several active and passive sinkholes in clay and sand-covered karst. Some of these sinkholes have been previously studied by Stewart and Parker (1992), Kruse et al. (2006), and Bumpus and Kruse (2014). In this study, we focused our study along a previously studied line (Line B, described in Stewart and Parker (1992)
and Kiflu et al. (2016)) that crosses two known sinkholes as shown in Figure 9. Kiflu et al. (2016) studied Line B using the MERIT technique in a 2D mode, with buried array

Figure 9. Geopark sinkhole research site at University of South Florida, Tampa, Florida. White lines xx show profiles described in Stewart and Parker (1992). Green Line A is described in Kiflu et al. (2016) and blue Line B shows the location of MERIT electrodes implanted and described here. The arrow tip shows the direction of increasing distance in x-direction on Figures 10, 11, and 12. Upper right map shows the state of Florida, USA. Elevations derived from a bare earth LiDAR data (Source: https://coast.noaa.gov).
directly beneath a single surface array. The 2D MERIT study showed characteristics of the bedrock undulations and detail in overlying sand and clay, with good correlations with geotechnical drillings along the line. Here, we describe similar resistivity measurements using MERIT3D and 3D surface resistivity techniques. The main objective of this study is to show examine MERIT3D survey results at a field scale to assess the possible improvements compared to a 3D surface survey.

![Diagram of borehole lithology, ground penetrating radar profile and electrode locations shown in 3D perspective along Line B (location shown in Figure 9). All axes show distances in meters. The subsurface depressions of the bright GPR reflector, observed at x = 18 m and 48 m along the profile, are indicators of sinkhole activity.](image)

Figure 10. Borehole lithology, ground penetrating radar profile and electrode locations shown in 3D perspective along Line B (location shown in Figure 9). All axes show distances in meters. The subsurface depressions of the bright GPR reflector, observed at x = 18 m and 48 m along the profile, are indicators of sinkhole activity.

The total length of the survey line on Line B is 65 meters (Figure 9). A total of 14 MERIT electrodes are implanted at a depth of 5m with 5m electrode spacing. The MERIT3D arrays consist of a single deep MERIT array along Line B, with
surface arrays with 14 electrodes each along line B, and 4 offset surface arrays on each sides of the MERIT array, with a 1.5 m offset spacing. The 3D surface arrays are also carried out along the same survey lines using only the surface arrays. The 3D surface measurements alone used 812 standard dipole-dipole readings; the MERIT3D measurements involved an optimized sequence of 3685 optimized arrays.

Figure 10 shows the location of and lithologies encountered in boreholes drilled along or close to line B. The geology of the area is generally characterized by an upper fine sand layer underlain by a silty sand or clayey sand unit which is in turn underlain by a clay layer, weathered limestone and competent limestone at lower depth. Depressions in a bright reflector captured on a ground penetrating radar (GPR) survey that correspond to the top of a clay layer, indicate that there are two sinkholes centered at 18 m and 48 m. The drilling data from BH4 near x = 48 m confirm that the sinkhole located at 48 m is an active sinkhole, as characterized by the presence of a raveling zone with very loose soil. This loose raveling zone is consistently found in the overburden soil in the depth ranges of 2.7 m to 8.2 m, 10.3 m to 10.4 m and between 12.8 and 13.4 in the bedrock. In contrast, the sinkhole located at 18 m seems currently less active near the surface because drilling data from BH3 indicate loose raveling conditions only at depths between 10 m and 11.9 m. Elsewhere near the line, drilling results from CPT 16 near x = 21 m and BH1 just past the northern (x = 66 m) end of the line show locally deep bedrock depressions. At BH1, the bedrock was not reached until a depth of 17.7 m. Similarly, on CPT16, no bedrock was found until a depth of 15 m. The inversion results for both 3D surface measurements and MERIT3D measurements are shown in Figures 11 and 12. The results from MERIT3D reveal some details about the sinkhole features. First, the result shows that the MERIT3D arrays are able to image subsurface
undulations related to the sinkhole activity at 18 m and 48 m (Figure 11). The width and depth

Figure 11. Borehole lithology, ground penetrating radar profile, center profile electrode locations, and resistivity inversion results along Line B (location shown in Figure 9). All axes show distances in meters. a) 3D inversion perspective. b) Cross-section along the center line of the survey grid where the MERIT implants are located.

of these depressions are in good agreement with the GPR data (shown as magenta lines) and reasonable agreement with the borehole logs (discussed further below). Additionally there is good agreement between the MERIT3D inversion and the GPR profile and from the drilling data at the northern end of the line (x = ~60–65 m) where the upper sand layer gets thicker.

As seen in Figure 11, the limestone unit below the clay layer has a resistivity intermediate between that of the upper sands and the conductive clay. There are noticeable misfits between the depth to top of limestone recorded in the drilling and the depth of the corresponding resistivity contrast, which is generally deeper, and diverges somewhat for example at ~x = 58 m. Based on the drilling data, we believe this is due to the fact that the top part of the
limestone bedrock is highly fragmented and weathered and often characterized by loss of drilling fluid.

Figure 12. Inversion results for MERTI3D (left) and 3D surface (right) resistivity measurements. The top shows a vertical slice of the 3D inversion results along the different offset lines spaced at 1.5m. Bottom shows vertical slices of the 3D inversion result at selected positions perpendicular to the X-axis.
and borehole collapse. Hence, the boundary between this upper weathered bedrock unit and the overlying clay and sandy clay layers is probably gradational. Resolving the boundaries of gradational contacts is usually difficult (Nguyen et al., 2005). Nevertheless, the overall presence of bedrock undulations around 20m and past 60m are clearly indicated. Also, the resistivity inversions seem to capture the subtle rise in bedrock elevations at ~ x = 40m and drop at ~x = 50m.

Figure 12 illustrates a comparison of the 3D surface resistivity survey with MERIT3D. In both the X and Y cross-sections, it can be seen that the 3D surface resistivity array only detects the contact between the upper more resistivity sandy layers and the lower more conductive clay layers. The MERIT3D cross-sections suggest some important three-dimensional aspects of the bedrock and the sinkhole features. For example, the bedrock resistivity signature becomes deeper and the clay layer becomes thicker in the positive y-direction, especially around x = 40-50 m (Figure 12 lower left diagram). This is the area recognized as the zone of sinkhole activity in the drilling data.

Discussion
These numerical models and laboratory and field case studies illustrate that for 3D targets, expanding a surface array by adding a single central deep (MERIT) array of electrodes offers significant benefits. These benefits are primarily depth of resolution (demonstrated in the all the examples: sphere, cave, and covered sinkhole), resolution of finer-scale features (demonstrated in the dipping slab and cave examples), and resolution at the edges of the grid (demonstrated all examples). The improvement in depth of resolution can be particularly significant in a setting like that shown for the covered sinkhole field study, where the conductive clay layer focuses current flow from surface measurements, and limits resolution of underlying structure. The numerical and
laboratory cave example suggests MERIT3D would be a promising approach to explore cave-connectivity karst related studies (e.g. Florea, 2006).

Although the focus of this manuscript is primarily an analysis of the benefits of the addition of the deep array to a surface 3D array, the dipping slab model (Figure 2) shows a scenario where the MERIT3D improves resolution over a 2D MERIT survey with a single surface transect underlain by a deep array. We note that in the numerical example of the spheres (Figure 4) and the numerical and laboratory examples considering a cave (Figures 6 and 8), that the y-direction (perpendicular to the MERIT array) extent of these features would simply not be resolved without the addition of the offset surface arrays. The lateral extent of features even below the deep array can be resolved, as seen particularly in the sphere numerical study (Figure 4b, cross-sections in lower right).

**Conclusions**

Resistivity surveys are used to image an exceptional range of geological, environmental and engineering targets. 3D surface resistivity surveys are used when it is necessary to understand the three dimensional aspects of the subsurface target features. The primary factor that limits the effectiveness of 2D resistivity surveys is when the target feature has limited continuity perpendicular to the survey direction. However, even when 3D surface surveys are conducted, they suffer from some of the limitations that characterize 2D surveys: lack of resolution at the edges of the grid beneath the outermost electrodes, and lack of resolution at depths greater than ~one quarter of the line length.

In this study, we introduce a new 3D resistivity technique, MERIT3D, which is an extension of the 2D MERIT technique. In the 2D MERIT method, an array of electrodes are implanted at depth using a robust direct push technique with
self-driving pointed electrodes. These implanted arrays are centered across the target of interest with an overlying surface array. In the 3D MERIT method additional sequentially offset surface arrays are placed on the ground on both sides of the buried MERIT electrodes. Measurements are taken using optimized arrays that involve the offset surface electrodes and the deep MERIT arrays.

Numerical, laboratory and field studies described here demonstrate the possible improvements of this new technique compared to 2D MERIT and 3D surface resistivity surveys. First, we show that the implementation of MERIT3D technique can improve on the limitations faced by MERIT2D technique in terms of resolving features with limited continuity perpendicular to the survey line (Figure 2). Second, we compare MERIT3D with 3D surface resistivity and showed that the inherent limitations of 3D surface resistivity in terms of resolving subsurface features located near the edge and at depth of the resistivity surveys can be significantly improved by simply adding a single line of buried MERIT electrodes (Figure 4). Third, we use numerical and laboratory based cave models with complex geometry to show the improvements of MERT3D in terms of resolving these complex geometries compared to 3D surface resistivity (Figure 6). In terms of resolving the complex geometries of the cave model, MERIT3D showed a small incremental improvement compared to 3D surface arrays. Finally, we conclude our study by showing a field case study result where MERIT3D technique is used to investigate the three-dimensional characteristics of a sinkhole feature located in our sinkhole research site (Figures 11 and 12). The results observed from MERIT3D correlate well with the geotechnical drilling data collected on the site. The study reveals the prominent zones of sinkhole activity and the three-dimensional elevation variation of the underlying weathered limestone.
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CHAPTER FOUR:

PRACTICAL ASPECTS OF MULTI-ELECTRODE RESISTIVITY IMPLANT TECHNIQUE

Abstract

The implementation of deep buried arrays in multi-electrode resistivity implant technique (MERIT) has proved to be an effective way of enhancing resolution at depth and near the edges of a survey area. However, buried electrodes generally are susceptible to problems of non-uniqueness and geometric location error of the deep arrays. Also, the depth of implant of these arrays controls the level of blurring phenomenon and misinformation that may arise from poorly resolving subsurface features. Some of resolution problems mentioned above can be improved by implanting additional parallel and intermediate arrays. We studied the effect of non-uniqueness on measurements taken using the deep arrays and found that standard arrays suffer from non-uniqueness problem depending on the vertical resolution characteristics at the target location. Optimized arrays are less susceptible to such problems. We also found that the MERIT deep arrays are sensitive to high vertical geometric location error. The result showed that vertical mis-location error from the installation equipment is very low while significant vertical mis-location due to human error is a major problem. We developed a guideline to determine resolution cut-off values and optimal depth of implant to resolve targets depending on the target size, target resistivity and resistivity contrast. We compared additional techniques that can be applied to further improve resolutions at the edge and at depth in terms of resolving complex sinkhole structures and narrow vertical features. We used numerical
studies to determine optimal offset spacing for MERIT3D arrays. Measurements taken between the deep MERIT arrays and inline offset surface electrodes are compared to measurements taken between deep MERIT arrays and offset surface electrodes involving multiple offset lines. The results suggest that the addition of the cross-line MERIT3D measurements showed only little improvement. Finally, field measurements were taken using more advanced field implementation of MERIT arrays using intermediate and parallel MERIT implants.

Introduction

The success of electrical resistivity tomography surveys depends on factors such as type of array, available working space, and subsurface geological conditions, as well as equipment used, field quality control, and the data processing technique. After a resistivity image is generated, it is critical for the interpreter to understand the fundamental and site specific limitations of resistivity method. This paper addresses many of these issues specifically in regard to a recently described resistivity survey arrangement, called MERIT, which is especially useful in sites with limited extent of survey area (Loke et al., 2015; Kiflu et al., 2016). In this introduction we place MERIT (multi-electrode resistivity implant technique) in the context of the incremental developments in resistivity tomography methods. The chapter then describes aspects of data acquisition and interpretation to help practitioners better assess the utility and resolution of the MERIT, as well as other resistivity survey arrangements, and to optimize survey design.

Two-D and 3D electrical survey design has two components: first, a specified number of electrodes must be arranged in space. Second the user must define which combinations of electrodes will be used to constitute pairs that inject and extract current, while other pairs simultaneously make readings of
electrical potential. In dealing with the first component for a 2D surface survey, electrodes are typically uniformly spaced along a line at the surface. Larger electrode spacing and hence longer total array length gives a deeper depth of investigation, while smaller electrode spacing gives better spatial resolution at the cost of shallower depth of penetration (e.g. Loke, 2010). Hence, in the conventional survey design phase, a compromise has to be made between the total survey length and electrode spacing, unless time permits multiple surveys or the use of a system that can access more electrodes. Forward model simulations using anticipated field conditions are generally recommended to help in the deciding the most feasible survey design.

The appropriateness of a 2D survey must also be considered. Subsurface geologic conditions can significantly vary from having simple 1D structure (e.g. horizontally layered strata) or 2D structure (e.g. vertical dikes) to complex 3D structures (e.g. sinkhole structure in karst areas). The use of a 2D resistivity profile in a heterogeneous ground with complex geologic structure can suffer from 3D geometric effects (Bentley and Gharibi, 2004; Loke et al., 2014). On the other hand, the use of 3D surveys in an area with strongly 2-dimensional structures is inefficient. Hence the expected nature of the subsurface geologic structure will drive the choice of the most economical yet effective resistivity method (Bentley and Gharibi, 2004; Loke and Barker., 1996a; Park and Van., 1991; Dahlin et al., 2002).

After consideration of all the above factors, the effectiveness of a resistivity survey can still be limited by site-specific conditions. The fundamental limitations often have to do with site access: a 3D grid of surface electrodes may simply not be possible. Commonly, even a 2D array may be limited in line length by lot size or terrain limitations. Two-D profiles suffer from decreases in sensitivity and resolution both at depth (as mentioned above) and at the
ends of a survey line. As a consequence in a site that has limited available work space area, the depth of investigation of surface electrical resistivity method is inherently limited and targets located near the boundary or at depth may not be resolved or detected (e.g. Loke et al., 2015; Kiflu et al., 2016). This can also further be complicated by the presence of surface materials with high contact resistances, or combinations of shallow conductive or highly resistive layers that focus and can significantly decrease the depth of current flow (Dey and Morrison, 1979; Neguen et al., 2005).

From the above discussions, it can be seen that modifications in the placement of resistivity electrodes could improve the resolution of resistivity imaging. One recent proposal for an incremental change is the use of a multi-electrode resistivity implant technique (MERIT) in which an array of deep electrodes is buried directly below an array of surface electrodes (Harro and Kruse, 2013; Loke et al., 2015; Kiflu et al., 2016a; Kiflu et al., 2016b). In MERIT technique, the deep electrodes are implanted using a novel robust direct-push technology. Kiflu et al. (2016a) has shown that a deep implant arrays addresses the fundamental limitations of surface resistivity method by increasing the resolution at depth and near the ends. In particular this technique is effective at sites with limited working area and when thick conductive materials are found at shallow depth. Similar advantages are also observed for 3D MERIT surveys as compared to conventional 3D surface resistivity surveys (Kiflu et al., 2016b). The simplicity of the geometric layout makes a MERIT array similar to a horizontal cross-borehole survey, and allows lessons learned from cross-borehole resistivity surveys to be applied to thinking about MERIT arrays. In particular, Wilkinson et al., (2008) illustrates the extreme sensitivity of cross-borehole surveys to errors in the location of downhole electrodes.
Oldenborger et al., 2005a also studied the sensitivity of resistivity to electrode position errors.

The second key aspect of survey design involves the selection of array geometries, or the combinations of electrodes used to make a given number of readings in order to optimize resolution of the ground resistivity structure. Two-D surface resistivity surveys are commonly carried out using adapted versions of traditional four-electrode geometries used in 1-D soundings (e.g. Loke, 2010). More recently the advantages of using specially optimized arrays have been clearly shown (e.g. Cherkaeva, E. & Tripp, A.C., 1996; Furman et al., 2004; Stummer et al., 2004; Hennig, T. & Weller, A., 2005; Wilkinson et al., 2006b; Hagrey, S. A. al and Petersen, T., 2011). Dahlin and Zhou (2004) used numerical studies to compare the resolution and effectiveness of 10 standard arrays by considering signal-to-noise ratio and their capabilities in terms of imaging different geological structures. Wilkinson et al. (2006) compared the resolution capabilities of arrays generated using different optimization techniques. Other authors have used point spread function to evaluate the resolution of subsurface features (Oldenborger et al., 2009; Loke et al., 2015). 2D cross-borehole data can also be collected using standard arrays (Zhou and Greenhalgh (2000)) or optimized cross-borehole arrays (Wilkinson et al., 2006b; Loke et al., 2014a). Similarly, 3D resistivity data are often collected using standard pole-pole arrays with varying field implementations (e.g. Loke and Barker, 1999a; Dahlin et al., 2002; Nyquist et al., 2005; Loke et al., 2013), but there are advantages of optimizing arrays for 3D resistivity surveys also (Loke et al., 2014b). Loke et al. (2015) computed and described the advantages of optimal arrays for MERIT surveys.

Once data are collected in the field, the readings are then inverted to arrive at the subsurface resistivity structure that best reproduces those data.
The accuracy of the inverted result depends on the choice of the inversion method (e.g. Loke and Barker 1996) and, of course also the 2-dimensionality of the setting, if a 2D survey is used (Bentley and Gharibi, 2004) and the noise in the data. Oldenborger and Li, 2005b gives a detailed discussion of the problem of non-uniqueness in resistivity inversion. A comparison of different inversion methodologies can be found for 2D inversions of surface arrays in Loke et al. (2002; 2003) or for inversions of 3D surface data in Loke and Baker (1996).

In the inversion process the resolution “R” of any cell in the resistivity model can be computed (e.g. Wilkinson et al., 2006; Loke et al., 2015) Similarly the resolution for the homogenous model or formal resolution (Stummer et al., 2004) can also be computed and usually will be slightly different from the resolution calculated for the inverted model depending on the resistivity structure of the model. Resolution measures how well the resistivity of each model cell can be estimated from the observed data (Menke, 1984).

The model resolution matrix R is calculated from Jacobian (sensitivity) matrix G. G describes the sensitivity of the observations to the resistivities of each model cell \( G_{ij} = \frac{af_i}{\theta_j} \), where \( f_i \) = the ith model response and \( \theta_j \) = the jth model parameter. In common 2D resistivity inversions, G is used in the linearized least-squares equation as

\[
(G^T G + \lambda C) \Delta r_i = G^T d - \lambda C r_{i-1},
\]

where \( \Delta r_i = r_i - r_{i-1} \) with \( \Delta r_1 \) represents the model parameter change vector between consecutive iterations. C is the roughness filter constraint, \( \lambda \) is the damping factor and d is the data misfit vector.
The model resolution matrix is then given by

$$R = BA$$  \hspace{1cm} (2)$$

where \( A = G^T G \) and \( B = (G^T G + \lambda C)^{-1} \) and the main diagonal element of \( R \) are used to estimate the model cell’s resolution.

Stummer et al., 2004 used a resolution cut-off value of 0.05 to delineate area of the poor resolution for surface arrays. In their study, this low resolution occurred below a depth of 30m which corresponds to one fifth of the survey length. They used this result to design their experiment focusing on the depth above this low-resolution depth.

In this chapter, we use numerical studies to investigate the resolution of the MERIT technique as a function of the depth of the buried array using vertical resolution characteristics curves (RC curves). We describe the depth of low-resolution as depth of resolution break. We will examine the effect of resolution contrast on resolution cut-off values and depth of resolution break in order to determine the most appropriate MERIT implant depth for different target sizes.

Part I of this paper discusses different practical aspects of the design of MERIT arrays and develops guidelines that can be used to collect good quality data. This part begins by describing problem of ambiguity or non-uniqueness in locating features that can arise when the deep and surface arrays are too widely separated. The effect of MERIT electrode location on the data errors is also described.

Part II of this paper introduces more advanced variations of MERIT techniques focused on solving challenging engineering geological problems. It introduces
the application of 2D offset, parallel and intermediate MERIT arrays. We will also evaluate the effectiveness of full 3D MERIT readings involving measurements taken using electrodes in different offset lines and MERIT electrodes. We will also examine the optimal offset spacing for MERIT3D surveys.

Part III of this paper will present field examples to evaluate the application of the new techniques to solve complex engineering geological problems in Karst environment.

PART I: Factors Affecting the Quality of MERIT Surveys

The problem of non-uniqueness near the deep implant electrodes

A survey with MERIT electrodes can be considered the sum of measurements involving only the surface electrodes, only the deep electrodes, and measurements between the deep and the surface electrodes. The current flow from the surface electrodes is constrained by infinitely resistive air and is treated as hemispherical flow near the injection electrode in a homogeneous medium. In contrast the equivalent current flow from a buried MERIT electrode is treated as spherical flow. In the 2D inversion process, while the surface arrays coincide with the model boundary, the deep arrays are placed inside the model domain. If readings were only taken with very deep electrodes, a problem of non-uniqueness or ambiguity is anticipated for targets close to the deep electrodes: even for 2D targets, it could not be determined whether the target were below or above these deep electrodes. Clearly this non-uniqueness can be eliminated by placing the deep array within the zone of resolution of the shallow array and combining readings. However, what this means in practice is examined systematically here for the first time. A suite of synthetic models is used to better understand necessary conditions for eliminating this non-
uniqueness. For all models, the inversion is run using L1-norm inversion and 2% random noise is added to the measurements.

The synthetic model used for the study involves a simple model with a uniform low resistivity (10 ohm-m) background and a resistive (100 ohm-m) 4m by 4m square block being imaged with a combined surface array and deep array. The block lies just below the center of the deep array (Figures 1a, g). In the first model suite (Figures 1a-1f), the buried array is 8m deep (Figure 1a). Figure 1b shows the inversion result for fully combined surface and deep arrays, assuming 14 surface electrodes and 14 buried electrodes with a 4-m electrode spacing, using the optimal arrays following Loke et al. (2015) incorporating a total of 651 readings. The full optimized array with total array length of 51 m and MERIT electrodes buried at 8 m depth clearly resolves the block position as below the buried array (Figure 1b). Figures 1c-1f illustrate the non-uniqueness which can arise with fewer readings, however. Figures 1c and 1e show inversions from measurements only involving traditional arrays of 28 buried electrodes at 2-m spacing. Figure 1c shows a Wenner array (107 readings), Figure 1e a dipole-dipole array (203 readings). The standard arrays using only deep electrodes indicate (falsely) two blocks, one above and one below the deep arrays. Figures 1d and 1f show the results if inline readings from an equivalent surface array are added to the inline readings from the buried array. The Wenner surface plus deep combination (Figure 1d; 214 readings) still shows the block location non-uniqueness, but the dipole-dipole combination (Figure 1f; 406 readings) shows the non-uniqueness problem nearly resolved. On the other hand, when the implant depth is increased to 12m, both the Wenner and dipole-dipole arrays suffer from ambiguity even when both the surface-surface and deep-deep measurements are combined (Figure 1i and 1j). With the block at 12 m depth, the optimized array (Figure 1h) still recovers the true block position.
Figure 1. Non-uniqueness problems that can arise from deep MERIT electrodes. 
a) Forward model with a high resistivity block ($\rho = 100 \text{ ohm-m}$, 4m x 4m) located below 8m-deep MERIT electrodes against a 10 ohm-m background. b) Inversion result using full optimized MERIT arrays. c) Result using Wenner array only at the deep electrodes. d) Result using Wenner readings along the surface electrodes and deep electrodes. e) Result using dipole-dipole array only at the deep electrodes. f) Result using dipole-dipole readings along the surface electrodes and deep electrodes. 
Forward model with same resistivity block located below 12m-deep MERIT electrodes. 
h) Inversion result using optimized MERIT arrays. i) Result using Wenner readings along the surface electrodes and deep electrodes. 
j) Result using dipole-dipole readings along the surface electrodes and deep electrodes.
To understand these results, the resolution matrices of the corresponding array geometries are examined. Figures 2a–e show the resolution cross-section for the Wenner inline surface and buried arrays, dipole-dipole inline surfaced and buried arrays and optimized inline surface, buried, and crossline arrays for 8m and 12m implant depths. Comparing the results of Figures 1 and 2, it is clear that the problem of non-uniqueness arises when the cumulative resolution in Region I drops below a low resolution value of ~0.05. We note that this resolution value is the same as the one suggested by Stummer et al., 2004 to focus their study above the depth of this low resolution value.

We conceptualize the inversion domain as two regions: the first, region I, is the area between the surface electrodes and the deep electrodes. The second, region II, is the area below the deep electrodes. The cumulative resolution in region I reflects the contribution of the measurements taken: 1) along the surface electrodes 2) along the deep electrodes and 3) between the deep and the surface electrodes (for the case of the optimized full array). On the other hand, region II is mostly constrained by the measurements taken along the deep arrays and partly by the measurements taken combing the deep and surface electrodes. To quantitatively illustrate the relative contribution of surface-surface, deep-deep (=MERIT-MERIT) and surface-deep (=surface-MERIT) readings to Region I and Region II, we define a vertical resolution characteristics curve (RC curve) as shown in Figure 3. These RC curves are vertical slices through the resolution matrices equivalent to those shown in Figure 2.

Figure 3 shows how the resolution characteristics vary with depth 4m in from the edge of the array (leftmost two columns) and at the center of the array (rightmost two columns) and depth of implant for Wenner (top row), dipole-dipole (middle row) and optimized arrays (bottom row).
Figure 2. Resolution plots for measurements taken using surface and deep MERIT electrodes. a) Inline Wenner arrays with implants at 8 m depth. b) and c) dipole-dipole inline arrays for 8m and 12m-deep implants respectively. e) and f) full optimized arrays (inline and combined surface and deep electrodes) for 8m and 12m implants depths respectively.

For example, with dipole-dipole readings taken using only the deep MERIT-MERIT implants at 8m depth (Figure 3e pink dashed line) resolution falls well below the apparent 0.05 threshold value in both Region I (above MERIT implants) and Region II (below MERIT implants) and suffers from ambiguity in (Figure 1e). But when both the surface-surface and MERIT-MERIT measurements are
Figure 3. Resolution characteristics curves (RC curves) 4 meters from the edges of the survey line (leftmost two columns) and at the center of the line (rightmost two columns). (a) and (b) for inline Wenner arrays with MERIT implant depths of 8m, (c)-(f) for inline dipole-dipole arrays with MERIT implant depths of 8 m and 12 m, (g)-(j) for full optimized arrays with implant depths of 8 m and 12 m.

combined the problem of ambiguity disappears (Figure 1f) while the cumulative resolution in region I exceeds 0.05 (Figure 3e red dashed line with dots). Hence the surface array is contributing to effectively constrain the absence of any
block between the deep and the surface arrays. However, when the implant depth is increased to 12m, once again a resolution break is observed as cumulative resolution at the center of region I drops below 0.05 even with the presence of the surface-surface arrays (Figure 3f red dashed line with dots) and hence the reappearance of the problem of ambiguity (Figure 1j). The optimized arrays in both 8 m and 12 m depth cases don’t show the ambiguity in block depth, and are characterized by higher cumulative resolution in region I (> 0.05). This is partly because the optimized arrays have measurements that involve readings between the surface and the deep arrays which further maximizes the resolution in regions I and better constrains the inversion process.

In practice the ambiguity in target location can also arise if the user constrains the inversion process to only solve for the resistivity in region I. (This is analogous to a cross-borehole inversion in which only the space between the two boreholes is considered during inversion.) Figure 4 illustrates such a scenario, with a 4m x 4m resistive block between arrays as described in Figure 1, with the deep array at 12 m depth. The traditional arrays (Figure 4 c and d) still suffers from non-uniqueness where both still show the block as if it is present above the deep arrays although it is present below the deep electrodes. On the contrary, for the full optimized MERIT array, inverted only for region I (Figure 4b) doesn’t show any problem of non-uniqueness. The high anomaly just at the electrodes is in fact an actual anomaly as the electrodes are in contact with the upper edge of the block at that location. However, measurements taken using the optimized arrays are sensitive to the presence of a block in region II. And when the inversion is carried out only in region I, the presence of the block outside the model domain will act as a noise and result in spurious anomalies during the inversion process as shown in figure 4b. This is also seen by the increase in data misfit from 1.2% for the inversion
domain containing both regions I and II (figure 1h) to a data misfit of 4.5% when the inversion is only carried out using regions I. This shows the robustness of optimized arrays even with the problem of model inadequacy.

These models indicate that once region I is well constrained with cumulative resolution above 0.05 then the problem of target location ambiguity will disappear, even though Region II may have areas of low resolution. Whenever the RC curve crosses the low resolution cutoff line in Region I, a resolution break occurs and the problem of ambiguity starts to appear. There may be cases where the RC curve does not fall below the threshold at the center of the profile, but does near the edge. In such a case ambiguity, could be expected near the edge. Figure 2 indicates the falloff in resolution near the edges is less for the optimized array than for the shallow+deep combinations of traditional arrays.

**Figure 4.** Non-uniqueness problems arising when the inversion model is limited to Region I (between the surface and the deep electrodes). a) Forward model with a resistive block \((r=100 \text{ ohm-m}, 4 \text{m x 4m})\) located below 12m deep MERIT electrodes. The masked region below the deep electrodes is excluded from the inversion domain. The actual forward model domain extend to 24m. b) Inversion result using optimized MERIT arrays. c) Result using Wenner arrays along the surface and deep electrodes. d) Result using dipole-dipole readings along the surface electrodes and deep electrodes.
Effect of the depth of the implant array on resolution

For deepest possible imaging, a user might seek to implant the buried array as deeply as feasible. However, the resolution characteristics curves in Figure 3 show that when the buried array is deep, critical resolution may be lost in the intermediate portion of Region I between surface and implant array. The following suites of models systematically simulate block-shaped targets throughout Regions I and II to help the user assess this trade-off between total depth of investigation and resolution loss. The model results are then characterized and compared against the RC curves.

We are interested in the resolution capabilities for two kinds of features: the first is small-scale heterogeneity, the second the presence of an isolated feature. To understand the first, we assess resolution as the ability to detect, locate, and differentiate multiple closely spaced blocks, with spacing between blocks comparable to the block thickness. To understand the resolution of isolated features, models with isolated blocks of varying size are simulated at the central location between the surface and MERIT electrodes where the resolution reaches a local minimum.

For the study of repetitive heterogeneity, blocks are described in terms of the ratio of their width W to the MERIT electrode spacing S. Blocks having W:S ratio of 0.5 (half blocks), 1.0 (full blocks) and 2.0 (double blocks) are simulated. The suites of models were run involving a vertical stack of half blocks, full blocks and double blocks. Selected examples of model runs are shown in Figure 6. In all cases the simulated electrode spacing is 4 m with total survey length of 52 m. The half blocks have a width of 2m and thickness of 2m. The full blocks have a width of 4 m and thickness of 3m. The double blocks have a width of 8 m and thickness of 3 m. All blocks are stacked vertically using a 3m spacing. Models simulate a range of implant depths, from
Figure 6 Examples to illustrate blurring phenomena. The models contain multiple blocks stacked vertically with a spacing equal or greater than the block thickness. The half blocks have a width equal to half of the electrode spacing. Full blocks and double blocks have widths equal to the electrode spacing and twice the electrode spacing respectively. Inversion result (top) and model resolution (bottom) with resolution contrast of 10 a) to c). Inversion result for resolution contrast of 2 d) and resolution contrast of 10 e) and f). The inversion result a to d use resistive blocks (2000 ohm m) and e and f use conductive blocks (100 ohm m).

3m to 40m. To investigate the effect of resistivity contrast, three distinct suites were run. In the first suite the blocks ($\rho=2000$ ohm-m) are 10 times more resistivity than the background ($200$ ohm-m). In the second suite the blocks ($\rho=2000$ ohm-m) are just 2 times more resistive than the 1000 ohm-m background.
In the third suite blocks ($\rho=100$ ohm-m) are 10 times more conductive than the 1000 ohm-m background.

The modeling demonstrates that as the depth of the implant array is increased a blurring phenomenon develops between the inversion images of adjacent blocks. Figure 6 shows a summary of the four observed variations of blurring scenarios: (a) a slight blurring effect whereby each block can be located as it has its own resistivity peak centered at the block, but two or more blocks share a common blurred or diffuse boundary between them (Figure 6d); (b) a moderate blurring effect in which one of the blocks can be located having a central resistivity peak while the other block appears as a tail with a diffuse boundary (Figure 6f); (c) a strong blurring effect with a single peak centered midway between the blocks (Figure 6b); and (d) an extreme blurring effect with no clear peak and in cases a continuous vertical band of anomalous resistivities (Figure 6c). Hence, depending on the depth of the implant array, size of blocks and resistivity contrast, target blocks may be 1) not detected, 2) detected but completely blurred or banded together and whereby individual blocks cannot be located, 3) located but poorly resolved with diffused boundary and low peak resistivity value, or 4) located and well resolved. When individual blocks are poorly resolved, it means that the center of the blocks is still detected and located but the boundary is diffused and its peak has lower value.

To examine the relationships between the depth of the implant array, the model resolution, and the blurring phenomenon, the resolution characteristics curves were extracted along the half blocks, full blocks and double blocks. The blurring, or lack thereof, was then categorized for all the target blocks in the model. Figure 7 shows a summary of these RC curves for each block type and the block blurring phenomena for selected implant array depths ranging from 8 m to 40 m, using the model with resistive blocks with 10 times the background
resistivity. In Figure 7 green blocks represent blocks in category (4) above: detected and resolved. Red blocks indicate blocks in categories (2) and (3): detected but poorly resolved. Finally, black blocks indicate those not detected.

By looking at a sequence of simulations with increasing depths to the buried array (i.e. a row of Figure 7), the deep array location is identified for which there begins to be a loss in detection or resolution of blocks in Region I. For example, in the top row in Figure 7, all blocks are resolved with the implant array at 10 meters depth, but at 14 meters depth blocks in the central part of region I cannot be resolved. The implant array depth at which resolution in Region I starts to break down is termed the “depth of resolution break”. The value of the RC curve at this depth is then identified, this RC curve value is then called the resolution cut-off value.

The practical significance of this resolution cut-off value (figure 7) is that they can be used as an option to exclude the regions of the inverted model that falls below this resolution value to avoid misinformation during data interpretation of an actual field survey. For example, Stummer et al., 2004 used a resolution cut-off value of 0.05 for surface arrays and used that threshold value to exclude the area below that depth and focused their experimental study above the depth of low resolution. Current commercial software such as Res2Dinv (Geotomo software, 2014) give an option to blank out part of the model using resolution cut-off values and the results from this study can be used as a guide line to choose the right cut-off value depending on the survey design. Similarly, the resolution break depth for the different target sizes, target resistivity and resistivity contrast can be used as a guideline for better planning of the design of MERIT arrays depending on the anticipated site condition.
Figure 7. Resolution characteristics curves the inverted model (“x”) for the base model with resistive blocks (ρ = 2000 Ωm) and resolution contrast of 10. Black solid lines indicate RC for homogenous model. Top shows the RC curves for the multiple half blocks and for different depth of implants. Resolution break occurs at the minimum depth where the blocks are not detected (black) or are strongly or extremely blurred together without being located (red). Resolved blocks are shows as green. Middle shows the RC curves for Full blocks and bottom shows the RC curves for Double blocks.
For example, if one plans to investigate a study area with an anticipated resolution contrast of 10 and target of interest having a dimension equal to the MERIT electrode spacing of 4m, then we can use figure 7 to find the maximum allowable depth of implant for the survey, i.e. 16m and the maximum effective depth of investigation will be 22m. During the data interpretation, a resolution cutoff of 0.046 can be used to put less emphasis on regions of the inverted model below this value.

Figure 8. Comparison of resolution characteristics curves and resolution cutoff values for base model (resistive blocks with resistivity contrast of 10) with other models having lower resolution contrast of 2 (top right) and conductive block with resolution contrast of 10 (lower left).

Figure 8 shows the same analysis with a lower resolution contrast (factor of 2) with resistive targets and with a factor of 10 resolution contrast but with conductive targets. A summary of the resolution breakout depths vs resolution cutoff value is shown in (Figure 9).
From the RC curves of the base model, it can be seen that in many cases a loss in resolution occurs, evidenced in zones where blocks are not detected or exhibit strong blurring effects, as shown with black or red blocks in Figure 7. This is observed in region I for MERIT implant depths of 14m, 16m and 18m for the half blocks, full blocks and double blocks respectively. In region II below the implant depth, it can be seen that most of the time, similar resolution loss occurs as the RC curve crosses. Hence, the resolution cut-off value can possibly be used as a rough estimate also in Region I.

![Figure 9. Summary of resolution breakout depths vs resolution cut-off value for different target sizes. Results with different resolution contrast and block conductivity are compared with the base model.](image)

From the result, for the half blocks, when the resolution contrast decreased from 10 to 2 for the resistivity blocks, the resolution break or strong blurring effect also occurred earlier at a depth of 10m compared to 14m for the base model. The resolution cutoff value also increased from 0.069 to 0.116 which
means strong blurring effect is more likely to be observed even at a higher resolution value when the resolution contrast is lower. Similarly, while keeping the resolution contrast the same, when the study is made using conductive blocks instead of resistive blocks, again the resolution break occurred at shallower implant depth of 12m compared to 14m for the base model. Similarly, the resolution cutoff value also increased from 0.069 to 0.086. For the full blocks and double blocks the resolution break depth was the same for all models (16m and 18m) respectively but similar increase in resolution cutoff value with decrease in resistivity contrast or increase in target conductivity is observed. The resolution cutoff values for the base model, conductive target models and lower resistivity contrast model is (0.046, 0.049, 0.057) for the full blocks and (0.028, 0.036, 0.039) for the double blocks respectively. The low resolution cutoff value of 0.05 suggested by Stummer et al, 2004 is closer to the value observed for the full blocks (0.46 - 0.057).

Figure 10. Inversion (top) and resolution (bottom) plots for isolated block models with varying MERIT implant depths and resistivity contrast. In the figure titles, “I” represent Isolated, “C10” or “C2” represent a resistivity contrast of 10 and 2 respectively and “-A” followed by a number indicates the depth of implant.
The above study involving multiple blocks is more appropriate for geological and engineering problems involving multiple smaller subsurface targets (e.g. buried utilities, consolidation grouts, grout columns, boulders, archeological features etc). However, most geological problems usually require resolving a few isolated subsurface targets (e.g. dissolution voids, sand lenses etc). Hence, we conducted a second study involving isolated half, full and double blocks located at the center of regions I for different implant depths (Figure 10). The blocks have a resistivity of 2000Ωm and a resistivity contrast of 10 and 2 is used for comparison.

**Effect of geometric location error arising from mis-location of MERIT implants**

MERIT electrodes are implanted using a robust direct-push technique. The installation method has an accuracy of less than 5° deviation from vertical (Paasche et al., 2009). For an 8m depth of MERIT implant this will correspond to a maximum horizontal deviation of ~0.67 m and a vertical deviation of ~0.03 m. Here, we will try to explore the effect of these horizontal and vertical geometric location errors on the overall quality of the MERIT data assessed by the results of the inversion models. We will also compare the effect of similar geometric errors on the surface electrodes of MERIT arrays and standard surface dipole arrays. Since the above mentioned maximum vertical deviation of 0.03m is too small, we used a slightly higher value of ~0.25m to test the effect of vertical geometric error on the overall data quality. Accordingly, to study the worst and best case scenarios, we conducted two studies with maximum geometric location error of 0.25m and 1.5m for both the horizontal and vertical electrode location errors.

The model used for this study involves a shallow resistive small block (4mx4m, ρ=100 Ωm) located at shallow depth near the edge, a conductive larger block
(8mx4m, $\rho = 1 \ \Omega m$) located at depth and an inclined resistive elongated dike feature (4mx10m, $\rho = 100 \ \Omega m$) located at depth and a background resistivity of 10 \Omega m (Figure 11a and Figure 12a).

Figure 11. Inversion results with maximum geometric location error of 0.25m. a) Forward model. b) dipole - dipole and c) optimized MERIT arrays with no geometric location error. d) dipole-dipole and e) optimized MERIT arrays with maximum vertical geometric location error of 0.25m on surface electrodes. f) Optimized MERIT arrays with vertical geometric error on the deep MERIT electrodes. g) dipole-dipole and h) optimized MERIT arrays with maximum horizontal geometric location error of 0.25m on surface electrodes. i) Optimized MERIT arrays with horizontal geometric error on the deep MERIT electrodes.

In the first study, we examined the effect of a geometric error of 0.25m. This value is higher than the maximum vertical installation error and is lower than the maximum horizontal installation error for the study. The design survey geometry is adjusted by adding a random value with in the range of -0.25 to 0.25 to the design electrode spacing and design implant depth. Then measurement is taken by using the adjusted survey geometry. Finally, we do comparisons between measurements taken without any mis-location error with one taken using the “as built” MERIT geometry with mis-location error (Figure 11 and Figure 12).
Figure 11 shows the results using a maximum geometric location error of 0.25m. Figure 11b and c show the ideal condition where the measurement is taken using the design survey and is inverted with the same design geometry for surface dipole-dipole array and MERIT arrays respectively. Figure 11d and e show the inversion results for measurements taken using the “as built” survey geometry with vertical location errors of 0.25m applied to the surface electrodes. Both the surface dipole-dipole and MERIT results show that the vertical location error of 0.25m on the surface electrodes has no effect in the overall result. When the same vertical location error is applied to the deep MERIT electrodes (Figure 11f), the mis-location error has a slight impact on shape of the shallow resistive block but the model can be reasonably assumed to be equivalent to Figure 11c.

The effect of maximum horizontal geometric location error of 0.25m is shown in Figure 11g to i. Similar to what is observed in the case of the vertical geometric location error, no effect was observed due to the horizontal geometric error for both the dipole and MERIT arrays regardless of whether the vertical location error of 0.25m is applied to the surface or deep electrodes. To study the worst-case scenarios, a second study is carried out using a maximum geometric location error of 1.5m (Figure 12). When a vertical geometric error of 1.5m is applied to the surface electrodes for the dipole-dipole arrays, a slight effect near the edge of the shallow resistive block is observed (Figure 12d). On the other hand, the addition of this horizontal geometric error on the surface electrodes of MERIT didn’t show any significant effect (Figure 12e). Figure 12f shows the effect of 1.5m vertical geometric location error to the MERIT electrodes. It can be clearly seen that at this point, the inverted result is extremely noisy and a lot of bigger artifacts are introduced and the interpretability of the image has been significantly compromised.
Figure 12. Inversion results with maximum geometric location error of 1.5m. a) Forward model. b) dipole-dipole and c) optimized MERIT arrays with no geometric location error. d) dipole-dipole and e) optimized MERIT arrays with maximum vertical geometric location error of 1.5m on surface electrodes. f) optimized MERIT arrays with vertical geometric error on the deep MERIT electrodes. g) dipole-dipole and h) optimized MERIT arrays with maximum horizontal geometric location error of 1.5m on surface electrodes. i) optimized MERIT arrays with horizontal geometric error on the deep MERIT electrodes.

Similarly, for a horizontal geometric error of 1.5m applied to the deep MERIT arrays (Figure 12g), several anomalies are introduced and the interpretability of the result is moderately affected. However, when all the inversion is carried out again after removing all the noisy points, the results improved for horizontal geometric error as compared to those with vertical geometric error. In general, the vertical geometric location error seems more relevant in the extreme cases compared to horizontal geometric error. The result suggests that a strong effort should be carried out on the field to do an accurate installation of the MERIT electrodes to avoid any additional human errors. The installation errors from the direct push techniques are very small (~0.03m) and negligible.
based on the results of the lower geometric location error used in this study i.e. 0.25m.

PART II: Advanced Field Implementation Techniques

In this section, we will explore the various possible ways that we can implement MERIT technique on the field in order to effectively increase the amount of information gained. Since this usually involves adding more MERIT implant or offset lines, we will also evaluate the importance of the information gained by the additional works compared to the extra effort required for the field implementation. Accordingly, in the sections below, we will try to explore: 1) the application of parallel MERIT lines to resolve the propagation direction of complex karst features 2) the advantages of adding intermediate arrays to resolve the full extent of narrow vertical deep features 3) the effect of offset spacing in MERIT 3D surveys 4) the advantages and limitations of full 3d MERIT measurements. Finally, we will present results from two case study sites focused on investigating complex sinkhole related features.

Application of parallel MERIT arrays to resolve the geometry of complex deep features

In MERIT3D applications, MERIT electrodes are implanted at a depth preferably along the center of the anticipated subsurface target and multiple sequentially offset surface arrays are used to make measurements between the deep MERIT and the offset surface electrodes. These will give a better opportunity to study the three-dimensional variation of subsurface geologic features. However, although MERIT3D technique does have a better resolution than 3D surface resistivity methods, it may still suffer from some resolution limitations when the target features are more complex or are found below the MERIT electrodes and are located near the edges of the survey grids as discussed in Chapter 3.
Here, we will try to test the advantage of adding additional parallel MERIT line to further improve depth resolution.

Figure 13. Synthetic sinkhole model with bending dissolution conduit. a) shows the different sinkhole and karst features included in the synthetic model by separating them out. The actual thickness of the layers has been decreased to expose the karst features. The model layers from top to down are sand layer (r=1500Ωm), clay layer (r=50Ωm), weathered limestone r=800Ωm and limestone (r=1000Ωm). The dissolution conduit is filled with groundwater (r=50Ωm) and bends towards the northeast corner of the survey line.

For this purpose, we used a synthetic model comprising complex karst features such as sinkhole, bedrock undulation and a dissolution conduit (Figure 13). The model has an uppermost sand layer (1500 Ωm) underlain by a clay layer (50 Ωm), in turn underlain by a weathered limestone (800 Ωm) and relatively less weathered limestone (1000 Ωm).

In addition, the different sinkhole and karst related features include subsurface depressions between the sand and clay layers and a vertical sand filled raveling zone penetrating the clay layer, and undulation at the clay-
bedrock interface and a dissolution conduit connecting to the vertical raveling zone. The horizontal dissolution conduit is assumed to be filled with groundwater and have a resistivity of 50 Ωm. To add more complexity to the study, the dissolution conduit will bend towards the northeast corner of the model.

The 3D surface arrays for this synthetic model consisted of multiple dipole-dipole arrays along 14 offset lines with 1m spacing along the Y-direction (Figure 13 c). Electrode spacing for the surface arrays is 2m along X direction. This consisted of a total of 2842 measurements. The single implant line MERIT3D array is also along the same line with additional implants at 8m depth with an electrode spacing of 4m along the X-direction in the middle line (Figure 13c). The single implant MEIRT3D array has a total of 18051 measurements. These measurements involve readings taken between the offset surface electrodes and the deep MERIT electrodes, along the surface offset lines and along the deep MERIT electrodes. The MERIT3D line involving two parallel MERIT lines has similar design but the two MERIT lines are located at Y= 5m and Y=9m compared to Y=7m in the case of the single MERIT line. Hence, while the single MERIT line is located across the center of the sinkhole, the parallel MERIT lines are located on either side of the sinkhole. The parallel MERIT lines have a total of 33260 measurements.

The resistivity inversion result for the 3D surface, MERIT3D with single MERIT line and MERIT3D with double line are shown in figure 14. Both the single MERIT line and two parallel MERIT line configurations (figure 14 c and d respectively) showed significant improvement over the 3D surface resistivity methods (figure 14b). The results from the two MERIT surveys are similar and does a good job of predicting the actual sinkhole geometry compared to the forward model (figure 14a and e). For example, both MERIT3D surveys were able to detect the contacts
between the major units, the surface depressions and the bedrock undulations. The raveling zone penetrating the clay layer is also detected by both methods. The major difference between the two methods is that the measurement taken using parallel MERIT arrays has better resolved the horizontal dissolution cavity which diverts its propagation directions towards the northeast corner of the model near the end of the survey line. The MERIT 3D measurement taken using the single MERIT line however was only able to resolve the first half of the dissolution conduit which is closer to the center of the MERIT line and were not able to detect the propagation of the bending section of the conduit. On the result of the single MERIT line survey (figure 14c and 14f), the presence of the bending section of the conduit is manifested as a slight extension of the straight section of the conduit which gives misinformation. Also, generally the results from the MERIT3D with parallel merit lines generally show less inversion artifacts and the contacts are better defined compared to the single MERIT line surveys.

Figure 14. Inversion results of sinkhole model with horizontal conduit. a) Vertical cross-section along the center of a) synthetic model b) 3D surface arrays c) MERIT3D with only one MERIT line d) MERIT3D with two parallel MERIT lines. Horizontal slices of e) synthetic model f) MERIT3D with single MERIT line g) MERIT3D with two parallel MERIT lines.
In summary, the result showed that MERIT3D measurements taken using a single line generally reveal most of the important information that we want to learn and since the installation of MERIT lines is costly, the additional parallel MERIT lines are only relevant in few special cases requiring to refine the results of the single MERIT line especially for resolving smaller heterogeneities and deep subsurface features located near the survey edges. The parallel MERIT lines could also be useful when installing the MERIT line along the target of interest is not an option (e.g. due to the presence of engineering structures or access limitations) in which case two parallel MERIT lines can be installed on either sides of the target of interest.

**Application of intermediate MERIT arrays to resolve deep narrow vertical features**

The depth of implant of MERIT arrays is determined by the survey length. For a successful measurement, the MERIT electrodes should be implanted at a depth that is shallow enough to avoid resolution break between the surface and the deep electrodes (occurs when the resolution drops below a resolution cutoff value described in the Part I of chapter 4). However, some sites may only allow a limited working space for the survey but the target feature could be located at depth below the allowable MERIT implant depth. Such challenges can be ameliorated by increasing the depth of MERIT implants towards the target feature and then installing intermediate MERIT arrays midway between the surface and the deep electrodes to avoid the resolution break.

To investigate the advantage of this approach, we used a synthetic model mimicking a deep ( > 360 feet deep) vertical dissolution sinkhole or shaft that occurred in the New Wales phosphate mining plant of IMC-Agrico company located in Polk county near Mulberry, Florida (Fuleihan et al, 1997) shown in figure
15 a and b. Similar large sinkhole feature has also recently occurred in a Mosaic phosphate mining site located in Polk county, Florida. The deep sinkhole in the New Wales plant suddenly occurred at a phosphogypsum stacking facility and formed a vertically extending deep shaft having a width of 110ft. The effective determination of the extents of such problems is relevant to avoid the possibility of contaminating the groundwater by the water from the gypsum stack facility that usually carries water with high pH and high percentage of fluoride, phosphate, sodium and sulfate dissolved from the waste material.

Figure 15. Deep dissolution sinkhole. a) Geologic cross-section of a deep dissolution shaft in a potassium mining site (after Fuleihan et al., 1997). b) Photograph of the sinkhole opening at the gypsum stack site in 1994.

(Fuleihan et al., 1997). In order to achieve this, remediation works should be carried out to re-establish the confining layers (Hawthorn formation) so that surficial water from the mining plant will not flow down to the intermediate aquifer (Tampa limestone) and the main Floridian aquifer (Suwannee limestone). Remediation measures such as grouting and backfilling can be effectively carried out if the depth and lateral extent of this features are well resolved. Figure
15a shows a geological profile section along the deep sinkhole that formed in the New Wales plant. Although some deep narrow vertical geological features such as the above dissolution shaft are important geological problems, resolving the full extent of narrow vertical features is a common challenge to most existing resistivity techniques. Hence, we selected this model in order to test if a modified MERIT technique would be able to determine the full vertical extent of the narrow vertical shaft. In the presence of the intermediate arrays, the deep MERIT arrays can be implanted at lower depth without compromising resolution.

The geologic units used in the synthetic models have comparable thickness to the actual observations and include a thick gypsum stack (0 ft - 100 ft) underlain by a thin sand unit or cast overburden (100 ft - 140 ft) which is again underlain by a thick Hawthorn formation (140 ft - 280 ft). Below the Hawthorn formation there is a thick limestone layer (280 ft - 460 ft) comprising the Tampa limestone and Suwannee limestone where a thin Tampa clay layer (360 ft - 380 ft) intercalates between the two limestone units. The dissolution conduit has a diameter of 30 ft between a depth of (0 ft - 240 ft) and a diameter of 60 ft between the depth of (240 ft - 360 ft). The diameter of the conduit is intentionally chosen to be smaller than the actual diameter of the sinkhole to add an increased level of difficulty to the numerical study. The groundwater level (GWL) is assumed to be at a depth of 140 ft resulting in an air-filled resistive section of the sinkhole shaft (3000 Ωm) above the GWL and a groundwater filled conductive section (10 Ωm) of the sinkhole void. The resistivity of the different units is assumed to be 100 Ωm for the gypsum, 1000 Ωm for the sand, 1000 Ωm for the Hawthorn formation, 1500 Ωm for the limestone and 500 Ωm for the thin clay layer.
The survey grid comprises two parallel MERIT arrays on either side of the sinkhole feature. Each MERIT line has 28 intermediate and 28 deep implants at 100ft and 200ft depth respectively. The electrodes are spaced at 40ft interval. The offset surface electrodes are spread over 14 offset lines with an offset spacing of 40ft except along the sinkhole where there are no electrodes.

Figure 16. Inversion result of a synthetic model mimicking a deep dissolution sinkhole shaft. a) Design of synthetic model mimicking the actual dissolution sinkhole. The blue cones represent the surface, intermediate and deep MERIT electrodes along the two MERIT lines and the red cones represent the offset surface electrodes. c) vertical cross-section along the center of the forward model d) vertical cross-section along the center of the inversion result. The white lines indicate the boundary of the model shaft. e) 3D isosurface of the dissolution sinkhole.

The inversion result, figure 16c, show that the 3D offset measurements taken using the intermediate and deep MERIT arrays along two parallel MERIT lines were able to resolve the full extent of the elongated vertical shaft. Moreover, the lateral dimension of the void was resolved very well. The result is better
portrayed in the isosurface map of the dissolution shaft from the inversion result in figure 16d. The isosurface map is prepared by using a resistivity threshold value of 550 Ωm and 600 Ωm. The lithologic contacts between the lower layers were not resolved due to the low resistivity contrast between the units or because some of the units are very thin (e.g. clay layer). The addition of the intermediate arrays has allowed to successfully increase the depth of the deep implants which in turn resulted in better resolving the full extent of the sinkhole. Although the required field effort for implementing a survey grid like the one shown in figure 16a requires a significant effort, the results show that it can be a feasible method to address large complex engineering geological problems that may require advanced field investigations such as the approach discussed above.

**Determining the optimal offset spacing required to detect narrow subsurface features**

MERIT3D technique uses sequentially offset surface electrodes. One question may arise is the optimal or minimum offset spacing required to conduct a successful survey without significantly compromising resolution. We used a synthetic model consisting multiple jet grout columns with different sizes to test the optimal offset spacing. Grout columns are engineering structures that are made by drilling a hole and injecting a high-pressure cement into the borehole (Stark et al, 2014). The turbulence created by the high pressure and the rotation will result in simultaneous erosion of the soil around the borehole and mixing it with cement. This forms a soil-cement mix grout and as the drilling rod is gradually raised, it will end up creating a grout column that is usually used as a foundation support. Individual grout columns shown in figure 17 a and b have a radius ranging from 1.4m to 2m.

The synthetic model contains different sized two shallow (#1 and #3) and one
deep (#2) vertical grout columns (r=1500 Ωm) where the shallow grout column #1 is located near the edge (figure 17c). The two shallow grout columns have a radius of 2m and extend from surface to 7m depth just 1m above the top of bedrock. The deep grout column is made of two overlapping grout columns, each having a radius of 2m. It extends from 4.5m to 10m where the bedrock depth at this location is 10m. The overburden soil has a low resistivity of 50 Ωm while the bedrock has a resistivity of 500 Ωm. The dimensions of the grout columns are setup up to be equal to the electrode spacing (#1 and #2) and twice the electrode spacing for overlapping grout column #3. These dimensions are also reasonable compared to the actual field observations of excavated out grout columns by Stark et al, (2014).

Figure 17. Synthetic model with Grout columns. (a) and (b) Excavated out single and overlapping jet grout columns with radius ranging from 1.4m to 2m and upto 10m depth. Modified from Stark et al, (2014). (c) Synthetic model with 3 vertical jet grout columns (r=1500Ωm) constructed in an overburden soil (r=50Ωm) overlying a resistive bedrock (r=500Ωm).
First the 3D surface resistivity and MERIT3D measurements were taken using a closely spaced offset line with 1m offset spacing along the Y direction which is equal to one fourth of the MERIT electrode spacing along the survey lines. The 3D surface arrays consisted of multiple dipole-dipole arrays along 12 offset lines with 1m spacing along the Y-direction. Electrode spacing for the surface arrays is 2m along X direction. This consisted of a total of 2842 arrays. The MERIT3D array is also along the

Figure 18. Forward model with 2 shallow individual and one deep double - overlapping jet grout columns. (a) shows 3D volume model of the grout columns (r=1500Ωm) buried in a low resistivity overlying soil (r=50Ωm) and underlain by resistive bedrock (r=500Ωm). Right: shows vertical cross-section along X direction showing the extent and position of the grout columns. (b) Full 3D inversion result of the 3D surface arrays with volume rendering of the detected grout columns and (c) shows vertical cross-section along the X direction. (d) and (e) show results of MERIT3D with 1m offset spacing. (f) and (g) show MERIT3D results with 1m offset spacing and full 3D readings involving multiple offset lines and MERIT electrodes. (h) and (i) show MERIT3D results using 4m offset spacing. (j) and (k) show MERIT3D inversion with 7m offset spacing.

same line with additional implants at 8m depth and an electrode spacing of 4m along the Y-direction. Since the MERIT electrodes can’t be installed over the grout column structures, the MERIT line is positioned on the side of the grout
columns at $Y=9m$ while the grout columns are centered at $Y=7m$. For the MERIT3D, two measurements are taken where the first measurement includes 18051 readings taken between each offset line and the deep MERIT electrodes and a second measurement involving full 3D measurements taken between the surface electrodes in the different offset lines and the deep MERIT electrodes resulting in a total of 21810 arrays.

The resistivity inversion result for both the 3D surface and MERIT3D array measurements with 1m offset spacing are shown in figure 18 b to g. The two shallow grout columns (1 and 3) are detected by the 3D surface and both MERIT3D arrays. While the vertical extent of column #3 is detected by both methods, the 3D surface technique was not able to resolve the vertical extent of column #1 which is located near the edge. Moreover, the shape of both grout columns is not well resolved in the case of the 3D surface arrays and the deep grout column (#2) is not detected at all. On the contrary, all the grout columns including the deep grout column are well resolved in the case of both MERIT3D arrays showing the effectiveness of the technique to resolve the extent of vertical features. It can also be seen that although the MERIT implants are not located along the target features, the grout columns were properly imaged. From this numerical study, it can be observed that the results from both MERIT3D results are very similar. Although the second MERIT measurement involves relatively more complex readings between MERIT and different offset lines, it didn’t show significant improvement in this study. It is also worth noting that measurements involving full 3D arrays would require more systematic planning and their field implementation isn’t as straightforward as the sequentially offset MERIT3D measurements.

When using offset arrays for MERIT3D, a question of optimal offset spacing may be crucial as it will affect the field survey time. Here we will try to
investigate the effect of varying offset spacing and number of offset lines for the synthetic model. As mentioned above, grout columns #1 and #3 have a dimension that is equal to the MERIT electrode spacing and grout column #2 has a dimension that is twice that the MERIT electrode spacing. Since the grout columns are vertically continuous (grout column 1 and 3 extend from 0m - 7m and grout column 2 extend from 4.5m - 12m), this can also be used to evaluate the effect of offset spacing on resolving the depth extent of each grout column.

The MERIT3D arrays with 1m offset spacing have a total of 12 offset lines including the surface electrodes along the MERIT implants. For comparison, two additional MERIT3D readings were carried out by approximately using an offset spacing equal to the MERIT electrode spacing of 4m and 7m which is nearly twice the spacing of the MERIT electrodes. The readings include: 1) an offset spacing of 4m, with 4 offset lines, 6739 readings and 2) an offset spacing of 7m on one side and 4m on the other side which corresponds to the end of the model domain, 3 offset lines, 5828 readings. The results for these two measurements are shown in figure 17 h to k. Based on the result the measurement taken using an offset spacing equal to the MERIT spacing (4m) was able to equally resolve the feature as the measurement taken using 1m offset spacing with 12 offset lines. It was able to resolve the full extent of the grout column sections at different depths. We believe this is an important finding because it will significantly decrease the amount field effort and time required to collect the data. Similarly, the results from the measurements taken using an offset spacing twice that of the MERIT spacing shows a reasonable result as it was able to resolve all three grout columns. However, grout column #1 which is located near the edge was slightly less resolved. Since the models used in this study are vertical targets that are relatively more challenging to resolve, we suggest from the result that an offset spacing equal or twice the spacing of MERIT electrodes
could be a reasonable assumption for field studies especially involving less complex subsurface targets. Clearly, the result also show that an offset spacing of 1m is very conservative at least for the synthetic model that was studied.

PART III: Field Case Studies

The field case studies presented in this section are focused on karst related sinkhole activities in Florida. Karst environments usually possess several complex subsurface features with varying geometries and resistivity structures which will make them a perfect target to test the capabilities of MERIT surveys. The case study areas are characterized by mantled karst terrain where the deep karst features are mantled by clastic sediments with thickness ranging from 10m to 70m near west-central Florida and thicker towards south Florida (Sinclair and Stewart., 1985; Tihansky, 1999). The bedrocks constitute carbonate and evaporate sedimentary rocks that are deposited under marine environment setting during the formation of the Florida platform. These karst features developed due to the fluctuation of sea level resulting in different cycles exposing and flooding the Florida platform (Tihansky, 1999). The most common karst features are dissolution cavities, fractures, caves, bedrock undulations and sinkhole activities arising from the raveling of overburden sediments into dissolution cavities or fractures.

In this section, first we will present a study involving the use of 2D offset survey in a known large sinkhole site at Wekiva parkway, Lake county, Florida. Later we will present a detail characterization of subsurface engineering geological problems using MERIT3D technique from a case study site located at Geopark sinkhole research site, at the university of South Florida, Tampa (Kruse et al., 2006; Loke et al., 2015). Finally, we will present a study that shows the field application of combined parallel MERIT and Intermediate MERIT lines.
to characterize the three-dimensional aspects of a sinkhole features located at the Geopark field site.

**Wekiva parkway case study site**

Field studies using 2D MERIT and 2D offset measurements is carried out at the Wekiva parkway study site located in Lake county, Florida (figure 19). The study site is part of a 2.5-mile road realignment project. The site is characterized by an open pastoral land with very limited number of trees. Hence, the common problem of limited survey area that is observed in most urban areas of Florida is not an issue in this case. However, the sinkhole of concern is a very deep sinkhole (> 60m) and is of very concern for the road project because over 26 drilling data, SPT and CPT field tests showed that there is a very thick peat and organic soil underlying the thick sand layer. The aim of the study was to investigate the depth and extent of this deep sinkhole feature and characterize the different units. Accordingly, a MERIT array constituting 28 implants at a design implant depth of 48ft were installed. The electrode spacing used for the study is 40ft. During the installation of MERIT arrays, some of the implants were not installed at the design depth of 48ft and the actual depth was carefully documented for each borehole to avoid geometric location error during the data processing phase. Two offset lines were also setup to investigate the three-dimensional characteristics of the different units and the sinkhole. A total of 1995 measurements were taken between the surface electrodes and the MERIT implant electrodes along the center line.

Figure 20 shows the inversion result of the measurement taken along the center MERIT line only. The CPT results are overlaid to ground truth the result. The results from the MERIT readings strongly correlate with the information observed from geotechnical field investigation. The result shows that the sinkhole feature is characterized by a thick sand layer that extends up to a depth of
Figure 20. Inversion results of Wekiva parkway study site. a) Location map of study site. b) 2D inversion result along the center MERIT line, AA’. c) 2D inversion result for the offset lines WW’ and EE’.

90m. This is underlain by a very thick conductive soil which is confirmed from...
the drilling data as organic peat or clay or silt soil. The CPT values show tip resistance value in a range of 0 to 25. The organic peat and clay or silt dominated soils are manifested by smaller tip resistance as shown in RS25, RS23 and RS19. Moreover, the result shows complex characteristics of the bedrock topography which tends to be irregular and filled by conductive peat or organic soils or abruptly drop vertically to a large depth. For example, at 280ft, the bedrock drops abruptly from depth of 100ft to depth of 170ft. In addition to the large depression at 240ft, another significant bedrock complexity was observed at a distance of 440ft which could possibly be a large failed dissolution void that is filled by overlying sediment. The evidence for that comes from the abrupt interruption of the continuous conductive (clay or peat) layer which can be seen filling the void like feature in the bedrock. It can also be seen that the overlying sand layer at this location gets thicker indicating the occurrence of some collapse feature in the past that was later filled by the overlying sand sediment.

Additional offset lines were measured to study the lateral continuity of the shallow organic or clay\silt layer on either sides of the MERIT line. Accordingly, two offset measurements are carried out with offset lines located at 40ft offset spacing on both sides of the MERIT line. The results are shown in figure 20c. Based on the result, the shallow peat layer is still continuous to a significant distance on either side of the center MERIT line. Also both offset measurements showed similar results where the sand unit gets significantly thicker at the first 280ft of the survey line and starts to get shallower passing a distance of 280ft. This study demonstrates the practical use of the 2D offset arrays whenever it is required to investigate if a certain geologic feature is continuous on either side of the main MERIT line. We believe that this technique would be more useful in identifying the continuity and
propagation direction of linear features such as tunnels, caves etc.

**Geopark study site**

At the geopark research site, along line B (figure 21), a single line MERIT electrodes are installed along a known area characterized by two sinkholes. The survey length for this MERIT line is 65m and 14 MERIT implants are installed at a depth of 5m with an electrode spacing of 5m. Also, 6 offset lines were setup at 1.5m spacing in order to collect MERIT3D data.

![Figure 21. Map of Geopark research site at the University of South Florida, USA. The cyan lines indicate geologic profile lines studied by Stewart and Parker (1992) and present study. Resistivity surveys along Lines A and B are described in this paper. The start of both surveys is towards the bottom end of the lines.](image-url)
The aim of this study was to investigate and characterize the different sinkhole related subsurface features of the most active sinkhole located at 48m. The main features of interest in this study are the zones of the overburden soil that are affected by the sinkhole activity and dissolution fractures or voids that could possibly be present at depth.

Figure 22. Geologic cross-section along Line B based on 10 borehole logs and 1cpt log. Red graphs show SPT values from the field tests carried out on each of the 10 boreholes.

On Line B, to characterize the engineering geological properties of the soil, a total of 10 boreholes were drilled and in situ standard penetration test (SPT) and split spoon sampling was carried out. Based on the result, the site is characterized to have generally a top fine sand layer (SP), underlain by transitional clayey sand and silty sand layer (SC and SP-SM) which is further underlain by a conductive clay layer (CH or CL) above the bedrock. The bedrock is characterized by a highly weathered and fractured yellowish to brownish limestone that tends to cave in and frequently result in loss of fluid circulation during drilling. Below this transition zone, there is a slightly
less weathered limestone that is creamy to white in color. The groundwater level in the area is around 2.43m. A summary of the drilling result and a geologic cross-section is shown in figure 22.

The figure shows two sinkholes located at 20m (sinkhole 1) and 49m (sinkhole 2) and both sinkholes are first identified using GPR surveys and other drilling data (Stewart and Parker, 1992; Kiflu et al., 2016). Borehole BH3 and BH4 are located close to the centers of the two sinkholes. Structurally both sinkholes share similar features such as subsurface clay depression, thick sand layer and deeper bedrock undulations as identified both in the GPR and drilling data. The area just outside the end of the resistivity line near BH1 also share similar characteristics to what is observed at sinkhole 1 and sinkhole 2. Also, at BH1 the bedrock was not found until depth of 17m while generally, the characteristic bedrock depth in the area is shallower than 12m. Similarly, near sinkhole 1, based on the cone penetration test done at CPT16, bedrock was not found even below the depth of 15m. At BH4, although the bedrock gets deeper, it was still intercepted within a reasonable depth by boreholes drilled at Sinkhole 2 including BH4, BH6, BH7 and BH8.

However, the occurrence of a void at the bedrock was detected by BH6 at a depth of 10.36m, where the drilling rod suddenly dropped for 1.5m after intercepting a bedrock. At BH4, a significant portion of the drilling at different depths (4.8, 7, 10.3, 10.6, 12.8) was characterized by weight of rod (WR) or weight of hammer (WH) conditions where the rod simply drops by the weight of the rod or by the hammer weight during an SPT test. In sinkhole susceptible areas, this is commonly interpreted as a raveling zone in cover-subsidence sinkholes or as subsurface void in the cohesive soil in the case of cover collapse sinkhole. The raveling zone is characterized by loose sediment that is gradually migrating or being washed away into the subsurface dissolution voids.
Figure 23. Inversion result at Line B. a) shows a vertical cross-section facing west. The loose raveling or soft void in the overburden has a low resistivity below 10 Ωm (gray) and correlates with loose zone detected as WR/WH (gray cylinders) during drilling test. The shape of this zone mimics the subsurface sinkhole depression. b) Horizontal slice of the model along the raveling zone. Gray in cylinders on the borehole logs indicate the WR/WH condition. c) Vertical cross-section overlaid by an isosurface bounding the low conductivity (<10 Ωm) zone. d) Volume rendering of the inversion result using multiple isosurface maps. The isosurface maps clearly show the sinkhole depressions (pink and yellow) and the change in bedrock topography across the survey line (green).

While similar condition was observed on BH1, the only WR condition observed on BH3 was near the bedrock and all the SPT results above that indicate a more compacted overburden. Hence, we assume that sinkhole 2 is more active sinkhole as identified by the continuous presence of low SPT values and WR/WH conditions in 4 boreholes that are drilled over it. Moreover, results from BH4 and GPR images show the presence of a thin 80cm thick organic layer (OH) at sinkhole 1. We speculate this is due to the presence of loose soil that gets easily populated by plants during wet season.

The results from MERIT3D on line B strongly correlate with geological characterization of the site which is done based on an intensive drilling and
field testing work. These results show the two sinkholes and the boundaries of the depression strongly correlates with the drilling and GPR data (figure 23 a and c). The results from the MERIT3D also show the bedrock undulation and absence of shallow bedrock contact at CPT16 and BH1. The result also reveals some additional three-dimensional aspects of the sinkhole structures. For example, the bedrock topography generally dips towards the west and hence clay thickness also increases toward west (figure 23 d).

More importantly further analysis of the resistivity results clearly reveals the zone of the overburden that is highly affected by the sinkhole activity (figure 23 a to d). This distinct very low resistivity zone (shown in gray or blue) is characterized by a very low conductivity below ~10 Ωm and is very consistently present during the data inversion. Figure 23c shows the isosurface map of this zone using a threshold value of 10 Ωm. This zone also greatly coincides with the WR/WH conditions observed in 4 boreholes located at the same location at sinkhole 1. Generally, it mimics the shape of the subsurface sinkhole depression along the survey lines and is mostly located towards the western edge of the model grid. We believe this low conductivity zone delineates the volume of soil that has become soft, loose or void due to the sinkhole activity resulting in a highly porous zone. For example, at this zone, out of the SPT tested section of BH4 between depths of 2.7m to 11.5m, 40% of the length is characterized as WR/WH condition. Similarly, 30% of the tested section in BH7 is characterized as WR/WH condition. This indicates the development of subsurface void in the overburden soil. While the sinkhole is clearly active, so far no surface subsidence is manifested. These characteristics are consistent with cover-collapse sinkholes described by Tihansky, 1999. Cover-collapse sinkholes occur in areas having a thick clay layer over the limestone cavity which is consistent with stratigraphy of Line B. We believe, the resistivity
image is delineating a zone of active subsurface void development in the overburden soil. This zones also provide a preferential flow path for infiltration and groundwater movement.

Loose soil conditions or voids like this are generally treated using geotechnical remedies such as consolidation and compaction grouting to fill the voids and densify the soils or using chemical grouting to fill the porosities and consolidate the soil. Such plans usually are costly and require a well-planned design. Techniques such as MERIT are relevant in this cases because they can be used to delineate the area and have a more effective and targeted grouting of this loose and preferential flow path zone. Similarly, the same method can be used to verify if the grout is going to the expected regions to effectively mitigate the problem.

Figure 24. Inversion result at Line A. a) shows the inversion result from a resistivity survey involving two parallel MERIT lines and where the first MERIT line (at Y=0m) has also an intermediate MERIT arrays. b) Geologic cross-section along line A (Source: Kruse et al., 2006).

The MERIT3D array on line A consists of two parallel MERIT arrays with
MERIT3D implant depth of 7.62m and electrode spacing of 4m. The two lines are located at 0m and 1.5m along the Y direction. The first MERIT line that is located at 3m also has an intermediate array installed at 1.5m depth with similar 4m electrode spacing. A total of 5 offset lines are setup with an offset spacing of 1.5m. The total measurement includes 4107 readings which are taken sequentially between the offset surface electrodes and the MERIT implants at the two lines.

The sinkhole structure along the Line A has been previously studied and has been described in detail by Stewart and Parker, 1992; Kruse et al., 2006; Loke et al., 2015. The aim of this study is to investigate the three-dimensional characteristics of the sinkhole by using MERIT3D technique. Figure 24b show the geological profile along Line A modified from Kruse et al., 2006. This line corresponds to the offset location of 1.5m in the MERIT3D array. The geology is characterized by a top sand layer underlain by silty clayey sand and sandy clay layer. The overburden sediments are further underlain by thicker weathered limestone and relatively less weathered but fractured limestone with vertical dissolution cavities. The bedrock is characterized by undulations and dissolution fractures below the sinkhole. The raveling zone penetrates the sandy clay layer is generally composed of silty sand soil.

The results from Line A are shown in figure 24a. The result reveals the major lithologic units including the top sand layer, clay layer and the limestone bedrock. The transitional silty clayey sand layer is manifested simply as a gradational contact between the more resistive sand unit and the low resistivity clay unit. It can also be seen that the MERIT3D array is able to capture the gradual thinning of the sand layer towards the end of the survey line. The result also reveals some of the main sinkhole related features observed during the geological investigation. For example, in the geologic profile, the clay
layer becomes discontinuous near the sinkhole and it will drop down vertically joining the silty sand raveling zone and the dissolution fracture as shown in Figure 20b. Similar results are observed in the MERIT3D images where the clay layers start to become discontinuous and drops down vertically near a distance of 28m where the sinkhole is located. This is mostly pronounced starting from offset location of 0.75m near the second MERIT line close to the geologic profile line. Although some of the dissolution cavities look distinct (e.g. between 0.75m -1.5m) and clearly located in the bedrock, we believe in most of the sections it is not easy to decipher between the down dropping clay and the dissolution fractures. The result also shows how the bedrock has significant variability in resistivity and shows significant undulation, perhaps much stronger than what is portrayed in the geologic profile based on uni-directional information from drilling data. It can be clearly seen that the bedrock is more indurated and resistive towards the beginning of the line and is most weathered with undulation near the center of the survey line where the sinkhole is located. Across the profile line, i.e. along the offset direction, the sinkhole feature is more pronounced with discontinuous clay layer and possible raveling zone towards the east especially at offset=1.5m, which passes through the center of the sinkhole. Towards the west, the clay layer is continuous at the distance where the sinkhole is located. Between the offset distances of -1.5 to 0m, the clay layer becomes very deep towards the first half of the survey line. The above results show that a better understanding of the three-dimensional characteristics of the subsurface sinkhole features can be attained by implementing intermediate and the parallel MERIT arrays.

Conclusions
In this chapter, we used numerical studies to investigate possible limitations and possible advanced field implementation of the MERIT technique. Part I of
this chapter discussed some of the limitations of MERIT that arise due to the new configuration that involves deep buried arrays. These problems include: 1) artifacts near the deep electrodes 2) high sensitivity due to vertical geometric location error 3) problem of non-uniqueness 4) blurring phenomenon due to increased spacing between the surface and the deep electrodes and 5) data is relatively noisier.

The problem of artifacts near the deep electrodes can be significantly decreased by using a damping factor near the deep electrodes (Loke et al., 2015) and the effect of the increased noise level in MERIT measurements can be decreased by using reciprocal measurements to weight the data during the inversion process. We also learned that the deep electrodes are more sensitive to vertical location error than horizontal location error. Hence, we found out that the effect of vertical location error was significant when it was in the higher range (~1.5m). The instrumental error during the installation is around 0.03m for the vertical error. Hence, we concluded that the installation error has little to no effect on the measurement and the major source of geometric location error would be human error. Hence, we recommend that a high degree of care should be taken during installation of the deep MERIT arrays.

We also learned that the problem of non-uniqueness occurs only when standard array measurements are used. This occurs whenever there is a resolution break between the surface and the deep electrodes which happens when the cumulative resolution in region I drops below the resolution cut-off value of 0.05 as suggested by Stummer et al., 2004. We defined resolution characteristics curve to study the effect of blurring phenomenon that occurs when two targets are closely placed but the resolution is low at that location to resolve the objects. Based on this, we developed a guideline that can be used to select optimal depth
of implant depending on the anticipated target size, target resistivity and resistivity contrast.

Part II of this paper introduces more advanced variations of MERIT techniques focused on solving challenging engineering geological problems. It introduces the application of 2D offset, parallel and intermediate MERIT arrays. We also evaluated the effectiveness of full 3D MERIT readings involving measurements taken using electrodes in different offset lines and MERIT electrodes. We examined the optimal offset spacing for MERIT3D surveys. Finally, we presented field examples to evaluate the application of the new techniques to solve complex engineering geological problems in Karst environment.

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Reference


CHAPTER FIVE:

SUMMARY AND CONCLUSION

This thesis introduced a novel 2D and 3D resistivity surveying method using Multi-electrode resistivity implant technique (MERIT). The MERIT technique uses a fast and robust direct-push technique to burry a self-driven pointed MERIT electrodes at a depth that is closer to the subsurface target of interest. This study finds this technique to be an effective method to increase depth of investigation especially in urban areas where the survey length is usually short due to limitations of available free space to spread longer survey lines. Measurements using this technique are taken using optimized arrays that maximize the resolution between the surface and the deep electrodes and below the deep electrodes. The optimized arrays are generated using a modified version of (Loke et al., 2015) the “Compare-R” algorithm of Wilkinson et al., 2006. The advantages gained by using this technique are tested by using several numerical studies, laboratory experiments and field studies involving complex subsurface structures that are usually challenging for traditional resistivity methods.

Accordingly, most of our studies focused on studying complex karst related features mimicking actual scenarios observed in the mantled karst environment of Florida. Karst process involve multiple dissolution episodes that produce complex features in carbonate or evaporate rocks. When this features are further overlaid by thin layer of soils some geohazards such as sinkhole tend to develop. Some of the karst related features include sinkholes, raveling zones, subsurface
depressions, bedrock undulation, dissolution cavities and conduits, caves and vertical dissolution shafts. We also evaluated the effectiveness of this new technique in terms of resolving narrow vertical targets such as jet grout columns.

The MERIT2D technique was compared to traditional standard surface resistivity survey along the same survey length. From numerical and laboratory experiments involving simple shapes placed at different locations, we found that the addition of deep arrays has significantly improved the resolution at depth and near the edges of the survey lines. This is an important improvement because traditional surface resistivity method fundamentally suffers with exponential decrease in resolution at depth and near the edges. We also did the survey using more realistic targets involving complex sinkhole related features such as the one studied by Stewart and Parker, 1992. We compared MERIT2D with standard 2D resistivity survey using numerical models, laboratory experiments and field studies involving complex sinkhole structures. The result shows significant improvement compared to traditional surveys.

Similarly, the results comparing MERIT3D with standard 3D surface resistivity surveys showed that the addition of the deep MERIT arrays significantly increases resolution at depth and near the edges of the survey grid. The MERIT3D technique involves using a sequentially offset surface electrodes where measurement is carried out between each offset line and the deep MERIT electrodes sequentially. For more complex scenarios, we also tested measurements taken using electrodes in multiple-offset lines and the deep electrodes. This was tested in the same manner like the 2D case using simple shapes such as multiple spheres placed in different locations and using complex shapes such as irregularly shaped caves. The study for the cave model was based on an actual
cave, Legend cave, found in Florida (Mccrackin, 2012). The cave model has irregular shape involving two larger rooms that tapers toward each other and make a narrow pathway that connects them. The numerical model was created using a 3D cad model of the cave and laboratory experiment was setup using a 3D printed plastic model of the cave immersed in a water tank. The result showed that the MERIT3D technique can detect features that can’t be detected using standard 3D resistivity method. These features are mostly located at depth and near the edges. The MERIT3D method was able to capture irregularity and narrow sections that can be reasonably captured by the electrode spacing used in the study.

While MERIT technique has its advantage, there are some issues that will come due to the new configuration that involves deep buried arrays. The problems that may arise due to the deep electrodes include: 1) artifacts near the deep electrodes 2) high sensitivity to vertical geometric location error 3) problem of non-uniqueness 4) blurring phenomenon due to increased spacing between the surface and the deep electrodes and 5) data is relatively noisier. We investigated all these problems and we found out that the problem of artifacts near the deep electrodes can be significantly decreased by using a damping factor near the deep electrodes. We also learned that the deep electrodes are more sensitive to vertical location error than horizontal location error. Hence, we found out that the effect of vertical location error was significant when it was in the higher range (e.g. 1.5m). The instrumental error during the installation is around .03m for the vertical error. Hence, we concluded that the installation error has little to no effect on the measurement and the major source of geometric location error would be human error. Hence, we recommend that a high degree of care should be taken during installation of the deep MERIT arrays not to cause large vertical mis-location errors. We also learned that
the problem of non-uniqueness occurs only when standard array measurements are used. These occurs whenever there is a resolution break between the surface and the deep electrodes which happens when the resolution drops below the resolution cut-off value of 0.05 as suggested by Stummer et al., 2004. We defined resolution characteristics curve to study the effect of blurring phenomenon that occurs when two targets are closely placed but the resolution is low at that location to resolve the objects. Based on this, we developed a guideline that can be used to select optimal depth of implant depending on the anticipated target size, target resistivity and resistivity contrast. We also studied the source of noise in the MERIT arrays. We found out that the MERIT arrays are relatively noisier due to 1) higher geometric factor used in the arrays 2) the arrays are not standard and 3) because most of the deep arrays are closer to resistive bedrocks. In this thesis, we discussed and showed the effect of the above factors. We also used reciprocal measurements to suppress the effect of measurements depending on the reciprocal error.

Finally, we explained possible advanced field implementation methods of the MERIT technique. We showed that the results of MERIT3D technique can be further enhanced by using additional parallel MERIT implants and intermediate implants as required depending on the site condition. We conducted both numerical and field studies using parallel and intermediate arrays. The results showed that difficult subsurface targets such as narrow, long, vertical dissolution shafts can be imaged using this advanced field setups and their full extent and lateral dimension could be well resolved. We also applied this techniques to study complex sinkhole features in more detail.
References


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APPENDIX A

Permission Access for Chapter 2

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