Redatuming borehole-to-surface electromagnetic data using Stratton-Chu integral transforms

Michael S. Zhdanov, University of Utah and TechnoImaging, and Hongzhu Cai, University of Utah*

Summary

We present a new method of analyzing borehole-to-surface electromagnetic (BSEM) survey data based on redatuming of the observed data from receivers distributed over the surface of the earth onto virtual receivers located within the subsurface. The virtual receivers can be placed close to the target of interest, such as just above a hydrocarbon reservoir, which increases the sensitivity of the EM data to the target. The method is based on the principles of downward analytical continuation of EM fields. We use Stratton-Chu type integral transforms to calculate the EM fields at the virtual receivers. Model studies demonstrate the effectiveness of the method.

Introduction

Over the past decade, there has been renewed interest in EM methods for oil and gas exploration and production. Most of this interest has been dominated by various marine EM methods, and cross-borehole EM methods. However, there has also been interest in borehole-to-surface EM (BSEM) methods that consist of a borehole-deployed transmitter, and a surface-based array of receivers (e.g., He et al., 2005, 2010). A recent pilot BSEM project in Saudi Arabia was able to successfully identify the oil-water contact in the water-injection zone of a carbonate reservoir (Marsala et al., 2011a,b). There is also interest in BSEM methods for monitoring carbon sequestration.

Fluids in the reservoir horizons represent the targets of BSEM survey. These reservoir horizons are deeply buried, implying that the surface responses are relatively weak. One method of overcoming this is to relocate the receivers from the surface to be closer to the reservoir horizons. However, this requires borehole receivers which may be expensive to deploy. In this paper, we propose a different approach based on downward analytical continuation of the observed EM data from the surface to a plane above the reservoir horizons.

Another major difficulty for interpretation of BSEM data could be caused by near-surface inhomogeneities. Significant variations in the resistivity of the overburden result in strong distortions of the recorded electrical field data on the surface. We demonstrate in this paper that the near-surface distortion effect can be removed prior to the downward continuation in order to generate a clear response from the deep target.

The principles of downward analytical continuation were originally introduced for the transformation of potential field data, and later on extended for the analytical continuation of EM and seismic data (e.g., Zhdanov, 1988). During the last decade, similar concepts have become popular in seismic processing as the “redatuming” of seismic data or seismic interferometry (e.g., Bakulin and Calvert, 2006; Schuster, 2009; Schuster and Zhou, 2006; Wapenaar et al., 2010). Recently, the same concepts were re-introduced for EM fields under the name of “electromagnetic interferometry” (e.g. Hunziker et al., 2009; Wapenaar et al., 2008). In this paper, we demonstrate that the theory of analytical continuation of EM fields based on classical Stratton-Chu type integrals can be effectively used for this type of problem.

Stratton-Chu integrals for redatuming BSEM fields

Let us consider a typical BSEM survey with the transmitter T_A located at some point A within a borehole, and the receivers distributed over the earth surface Σ at points with the radius-vector $\mathbf{r}'$ (Figure 1). Let us consider a horizontal plane P located at a depth z_0 in the ground (with the z axis directed downward). Note that point A of the transmitter location could be above or below the horizontal plane P. We also assume that the conductivity of the earth between the surface of the earth Σ and the horizontal plane P is known and it is equal to the background conductivity $\sigma_b(\mathbf{r})$. Below plane P, the conductivity $\sigma(\mathbf{r})$ is unknown and is characterized by some anomalous conductivity:

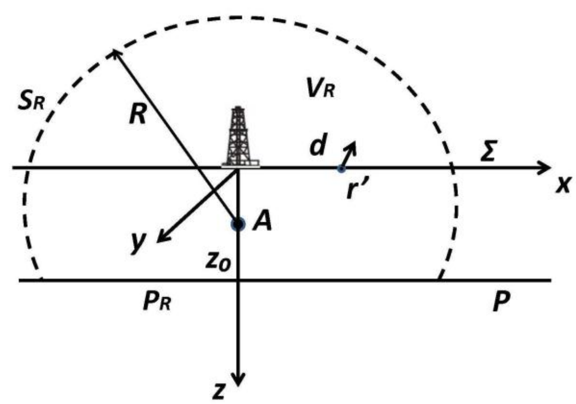

Figure 1. *A model of a typical BSEM survey with the transmitter T_A located at some point A within the borehole and the receivers distributed over the earth’s surface Σ with the radius vector* $\mathbf{r}'$.

SEG Las Vegas 2012 Annual Meeting
DOI http://dx.doi.org/10.1190/segam2012-0746.1

$$\sigma(\mathbf{r}) = \begin{cases} \sigma_b(\mathbf{r}), & z < z_0, \\ \sigma_b(\mathbf{r}) + \sigma_a(\mathbf{r}), & z > z_0. \end{cases} \quad (1)$$

Let us consider a semi-sphere S_R in the upper half-space with a center located at the transmitter, point A and a radius R. We will denote the domain bounded by this semi-sphere and a part P_R of the horizontal plane P as V_R. Applying the generalized Lorenz lemma to the anomalous fields, and the background fields due to an electric source, we obtain the following integral representation of the anomalous fields (Zhdanov, 2009):

$$\iint_S \{[\mathbf{E}^e(\mathbf{r}',\mathbf{r}) \times \mathbf{H}^a(\mathbf{r})] - [\mathbf{E}^a(\mathbf{r}) \times \mathbf{H}^e(\mathbf{r}',\mathbf{r})]\} \cdot d\mathbf{s} = \iiint_V [\mathbf{E}^a(\mathbf{r}) \cdot \mathbf{d}\delta(\mathbf{r}-\mathbf{r}')]dv = \mathbf{d} \cdot \mathbf{E}^a(\mathbf{r}'), \quad (2)$$

where $\mathbf{E}^a$ and $\mathbf{H}^a$ are the anomalous EM fields generated by the given transmitter T_A in the model with anomalous conductivity in the plane P; $\mathbf{E}^e$ and $\mathbf{H}^e$ are the background EM fields generated in the background conductivity model by an electric dipole with unit moment $\mathbf{d}$ located at the point with radius vector $\mathbf{r}'$.

Applying equation (2) to the domain bound by the closed surface $S_R \cup P_R$, we can write:

$$\mathbf{d} \cdot \mathbf{E}^a(\mathbf{r}') = \iint_{S_R \cup P_R} \{[\mathbf{E}^e(\mathbf{r}',\mathbf{r}) \times \mathbf{H}^a(\mathbf{r})] - [\mathbf{E}^a(\mathbf{r}) \times \mathbf{H}^e(\mathbf{r}',\mathbf{r})]\} \cdot d\mathbf{s}. \quad (3)$$

Equation (3) makes it possible to calculate the anomalous EM fields at any point in the subsurface Σ if we know the EM fields on plane P. Following Zhdanov (1988), the surface integral in equation (3) can be expressed by the Stratton-Chu type integral:

$$\mathbf{S}_S^e(\mathbf{r}') = \iint_S \left\{\left[\hat{\mathbf{G}}_E^e(\mathbf{r}',\mathbf{r}) \times \mathbf{H}^a(\mathbf{r})\right] + \left[\hat{\mathbf{G}}_H^e(\mathbf{r}',\mathbf{r}) \times \mathbf{E}^a(\mathbf{r})\right]\right\} \cdot d\mathbf{s}, \quad (4)$$

for which:

$$\mathbf{S}_S^e(\mathbf{r}') = \begin{cases} \mathbf{E}^a(\mathbf{r}'), & \mathbf{r}' \in V, \\ 0, & \mathbf{r}' \in CV. \end{cases} \quad (5)$$

It follows that:

$$\mathbf{E}^a(\mathbf{r}') = \mathbf{S}_S^e(\mathbf{r}') = \iint_S \left\{\hat{\mathbf{G}}_E^e(\mathbf{r}',\mathbf{r}) \cdot [\mathbf{H}_{\boldsymbol{\tau}}^{\boldsymbol{a}}(\mathbf{r}) \times \mathbf{n}] + \hat{\mathbf{G}}_H^e(\mathbf{r}',\mathbf{r}) \cdot [\mathbf{E}_{\boldsymbol{\tau}}^{\boldsymbol{a}}(\mathbf{r}) \times \mathbf{n}]\right\} \cdot ds, \quad (6)$$

where we take into account that $d\mathbf{s} = \mathbf{n}\, ds$, and $\mathbf{n}$ is a unit vector of the normal to the surface P directed downward, and $\mathbf{E}_{\boldsymbol{\tau}}^{\boldsymbol{a}}$ and $\mathbf{H}_{\boldsymbol{\tau}}^{\boldsymbol{a}}$ are the tangential components of the anomalous EM fields on the surface P. Equation (6) can be used for redatuming anomalous EM fields. This equation transforms the anomalous EM fields from the underground surface P to the observation surface Σ. The same equation can be used for downward analytical continuation of the anomalous EM field from the observation surface Σ to the horizontal plane P located at a depth z_0 in the subsurface from the observed values of the horizontal components of the electric field at the surface. The Statton-Chu integral equation (6) can also be derived for magnetic receivers.

Different methods for the downward analytical continuation of EM fields were discussed by Zhdanov (1988). In this paper, we have developed a technique based on the regularized conjugate gradient (RCG) method. In this framework, the Stratton-Chu integral equations for electric and magnetic receivers can be written as:

$$\begin{bmatrix} \mathbf{E}^{\Sigma a} \\ \mathbf{H}^{\Sigma a} \end{bmatrix} = \begin{bmatrix} \mathbf{G}_H^e & \mathbf{G}_E^e \\ \mathbf{G}_H^m & \mathbf{G}_H^m \end{bmatrix} \begin{bmatrix} \mathbf{E}_\tau^{\Sigma a} \\ \mathbf{H}_\tau^{\Sigma a} \end{bmatrix}, \quad (7)$$

where $\mathbf{G}_{E,H}^e$ and $\mathbf{G}_{E,H}^m$ are the Green's operators:

$$\mathbf{G}_{E,H}^e \mathbf{f} = \iint_S \hat{\mathbf{G}}_{E,H}^e(\mathbf{r}',\mathbf{r}) \cdot [\mathbf{f} \times \mathbf{n}] \cdot ds, \quad (8)$$

$$\mathbf{G}_{E,H}^m \mathbf{f} = -\iint_S \hat{\mathbf{G}}_{E,H}^m(\mathbf{r}',\mathbf{r}) \cdot [\mathbf{f} \times \mathbf{n}] \cdot ds. \quad (9)$$

Equation (7) can be written in the compact form:

$$\mathbf{M}^\Sigma = \mathbf{\Gamma} \mathbf{M}^P, \quad (10)$$

where six-vectors, $\mathbf{M}^\Sigma$ and $\mathbf{M}^P$, represent the anomalous EM fields on the surfaces Σ and P, respectively, and $\mathbf{\Gamma}$ is the matrix of Green's operators (8) and (9). Equation (10) is ill-posed, so to obtain a stable solution, we minimize the Tikhonov parametric functional (Zhdanov, 2002):

$$P^\alpha(\mathbf{m}, \mathbf{M}^\Sigma) = \|\mathbf{\Gamma}\mathbf{M}^P - \mathbf{M}^\Sigma\|_{\boldsymbol{M}}^2 + \alpha\left\|\mathbf{m} - \mathbf{m}_{apr}\right\|_{\boldsymbol{m}}^2 \rightarrow min, \quad (11)$$

where $\mathbf{m}_{apr}$ is some a priori vector of the anomalous EM fields in the subsurface. The minimization of equation (11) is based on the regularized conjugate gradient method (RCG) with adaptive regularization (Zhdanov, 2002).

Model study

In the following model study, we consider redatuming BSEM data. The first model we consider consists of a 1 km thick upper layer of 0.1 S/m conductivity, a 400 m thick second layer of 0.2 S/m conductivity, and a basement of 0.1 S/m conductivity. A resistive (0.01 S/m) reservoir target is embedded in the second layer. The EM fields were

DOI http://dx.doi.org/10.1190/segam2012-0746.1

simulated for a vertical electric dipole transmitter at 700 m depth in the borehole, at a frequency of 5 Hz (Figures 2 and 3). In the first study, we have assumed that the EM fields are observed in the set of virtual receivers located on the horizontal plane *P* at a depth of 500 m. No noise was added to the data. The intent is to transform the anomalous EM fields upward from the horizontal plane *P* to the surface of the earth Σ. Modeling was performed using the 3D IE method (Hursán and Zhdanov, 2002). As shown in Figure 4, the result of the IE modeling and the upward analytical continuation of the EM fields using the Stratton-Chu integral transform are, for all intent and purpose, identical. This particular model study validates the approach of our method.

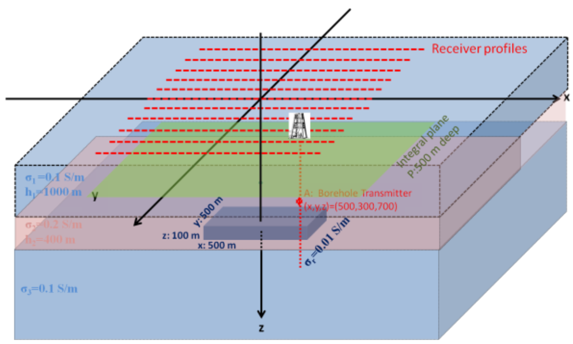

Figure 2. *3D perspective view of the reservoir target embedded in a layered host. The actual and virtual receiver profiles are shown, along with the borehole and BSEM transmitter location.*

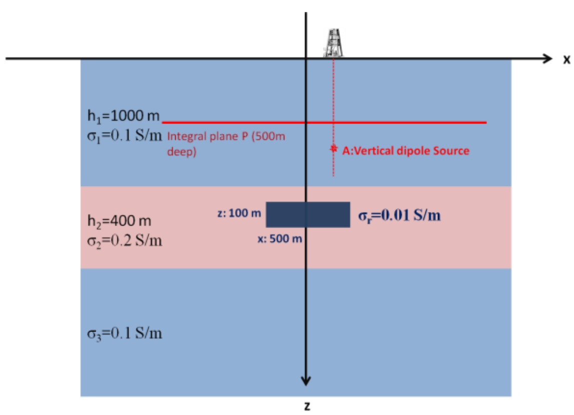

Figure 3. *Vertical cross section of the reservoir target embedded in a layered host. The actual and virtual receiver profiles are shown, along with the borehole and BSEM transmitter location.*

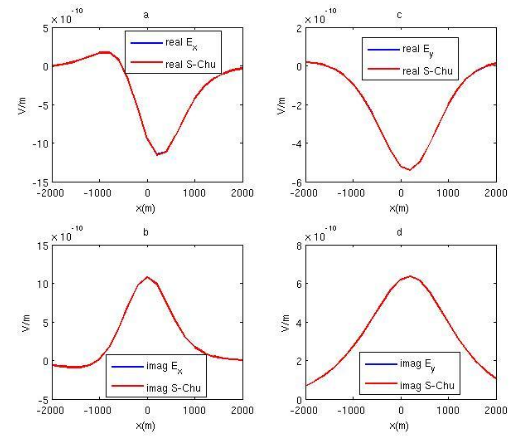

Figure 4. *Comparison between the horizontal components of the electric field at the Earth's surface computed using IE modeling (blue) and by the Stratton-Chu integral transform (red).*

In the second study we consider, we assume that the EM fields are observed on the earth's surface Σ. The intent is to transform the anomalous EM fields downward from the earth's surface Σ to a horizontal plane *P* that is 500 m below the surface. In this case, the EM fields on the earth's surface were contaminated with 5% random noise. Figure 5 shows the results of the IE modeling and the downward analytical continuation of the EM fields using the Stratton-Chu integral transform, and one can see there is very good agreement between them. Note also that we have many more virtual receivers on the plane *P* than the number of the actual receivers on the earth's surface Σ.

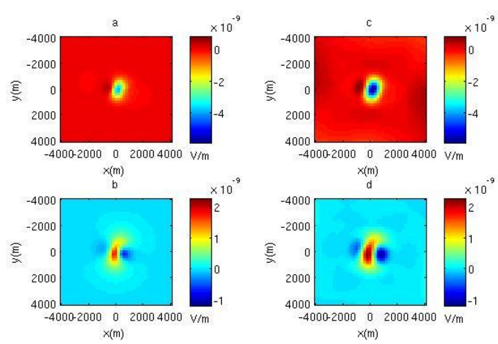

Figure 5. *A comparison between the real (upper panels) and imaginary (lower panels) components of the x-directed electric field on a plane P located at 500 meters below the earth's surface Σ computed using IE modeling (left panels) and by the Stratton-Chu integral transform (right panels).*

DOI http://dx.doi.org/10.1190/segam2012-0746.1

We now modify our 3D earth model to include near-surface inhomogeneities (Figures 6 and 7). Again, we assume that the EM fields are observed on the earth's surface Σ and our intent is to transform the anomalous EM fields downward from the earth's surface Σ to a horizontal plane P that is 500 m below the surface. Figure 8 shows the results of the IE modeling and the downward analytical continuation of the EM fields using the Stratton-Chu integral transform, and again, one can see there is very good agreement between them.

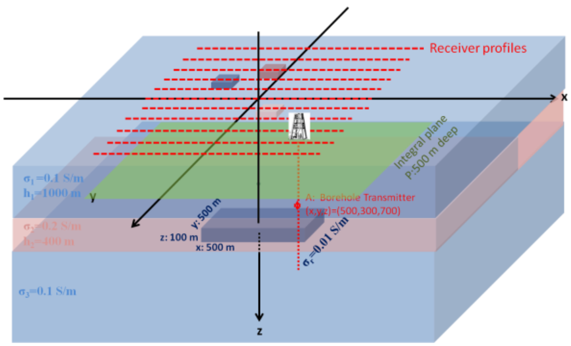

Figure 6. *3D perspective view of the reservoir target embedded in a layered host with near-surface inhomogeneities. The actual and virtual receiver profiles are shown, along with the borehole and BSEM transmitter location.*

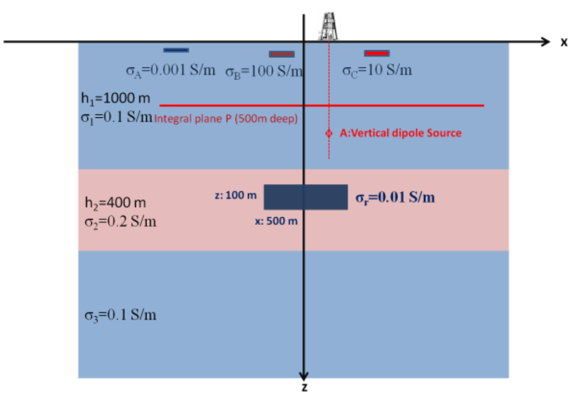

Figure 7. *Vertical cross section of the reservoir target embedded in a layered host with near-surface inhomogeneities. The actual and virtual receiver profiles are shown, along with the borehole and BSEM transmitter location.*

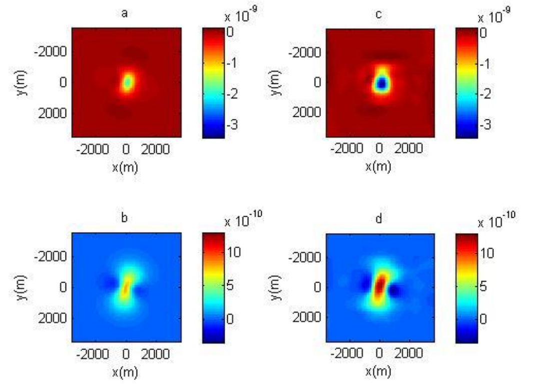

Figure 8. *A comparison between the real (upper panels) and imaginary (lower panels) components of the x-directed electric field on a plane P located at 500 meters below the earth's surface Σ computed using IE modeling (left panels) and by the Stratton-Chu integral transform (right panels).*

Conclusions

We have developed a method of redatuming EM data from actual receivers located on the earth's surface to virtual receivers located in the subsurface. This method is based on Stratton-Chu type integral transforms of the observed EM data, whereby the redatuming is achieved by solving an ill-posed inverse problem with the regularized conjugate gradient method. In this paper, we have demonstrated the method for BSEM surveys. By being able to place virtual receivers in the subsurface, closer to reservoir target, we are able to generate EM data which may subsequently be inverted. We have shown that one of the advantages of our particular redatuming method is that the number of virtual receivers can be much larger than the number of the actual receivers on the earth's surface. We have also demonstrated that the method can be used in the presence of near-surface inhomogeneities. However, in this case, a priori knowledge of near-surface inhomogeneities is required.

Acknowledgements

The authors acknowledge support of the University of Utah's Consortium for Electromagnetic Modeling and Inversion (CEMI), and TechnoImaging.

http://dx.doi.org/10.1190/segam2012-0746.1

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2012 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Bakulin, A., and R. Calvert, 2006, The virtual source method: Theory and case study: Geophysics, **71**, no. 4, SI139–SI150.

Berdichevsky, M. N., and M. S. Zhdanov, 1984, Advanced theory of deep geomagnetic sounding: Elsevier.

He, Z., W. Hu, and W. Dong, 2010, Petroleum electromagnetic prospecting advances and case studies in China: Surveys in Geophysics, **31**, no. 2, 207–224.

He, Z., X., Liu, W. Qiu, and H. Zhou, 2005, Mapping reservoir boundary by borehole surface TFEM: Two case studies: The Leading Edge, **24**, 896–900.

Hunziker, J., E. Slob, and K. Wapenaar, 2009. Controlled source electromagnetic interferometry by multidimensional deconvolution: Spatial sampling aspects in sea bed logging: Presented at 71st Annual International Conference and Exhibition, EAGE.

Marsala, A. F., M. H. Al-Buali, Z. A. Ali, S. M. Ma, Z. He, T. Biyan, G. Zhao and T. He, 2011a, First borehole to surface electromagnetic survey in KSA: Reservoir mapping and monitoring at a new scale: Presented at Annual Technical Conference and Exhibition, SPE.

Marsala, A. F., M. H. Al-Buali, Z. A. Ali, S. M. Ma, Z. He, T. Biyan, G. Zhao and T. He, 2011b, First pilot of borehole to surface electromagnetic in Saudi Arabia: A new technology to enhance reservoir mapping and monitoring: Presented at 73rd Annual International Conference and Exhibition, EAGE.

Schuster, G. T., 2009, Seismic interferometry: Cambridge University Press.

Schuster, G. T., and M. Zhou, 2006, A theoretical overview of model-based and correlation-based redatuming methods: Geophysics, **71**, no. 4, SI103–SI110.

Stratton, J. A., 1941, Electromagnetic theory: McGraw-Hill.

Wapenaar, K., D. Draganov, R. Snieder, X. Campman, and A. Verdel, 2010, Tutorial on seismic interferometry: Part 1 — Basic principles and applications: Geophysics, **75**, no. 5, 75A195–75A209.

Wapenaar, K., E. Slob, and R. Snieder, 2008, Seismic and electromagnetic controlled-source interferometry in dissipative media: Geophysical Prospecting, **56**, 419–434.

Zhdanov, M. S., 1988, Integral transforms in geophysics: Springer-Verlag.

Zhdanov, M. S., 2002, Geophysical inverse theory and regularization problems: Elsevier.

Zhdanov, M. S., 2009, Geophysical electromagnetic theory and methods: Elsevier.