Redatuming of borehole-to-surface electromagnetic data at the Kevin Dome exploration site

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Summary

The method of redatuming the controlled-source electromagnetic data was introduced in Zhdanov and Cai (2012). The approach is based on a Stratton-Chu type integral and the Lorentz lemma to relate observed EM data on the earth's surface to EM data on some horizontal plane *P* located underground. By applying this methodology, we are able to calculate the EM scattering field at some depth from the observed data on the earth's surface. Once the EM field at some underground plane *P* is found, we can use these data for upward continuation and recomputing of the EM scattering data on the earth's surface. This upward continuation problem is always well posed. By doing this, we can place more virtual receivers at the earth's surface and within a much larger area. Compared to traditional interpolation and extrapolation techniques such as polynomial fitting or spline approximation, our method takes into account the physics of the EM field, which makes the redatuming more accurate than simple mathematical transformation. In this paper, we illustrate this method by redatuming of borehole-to-surface electromagnetic data at the Kevin Dome exploration site.

Introduction

Borehole-to-Surface Electromagnetic (BSEM) surveying is a new method of reservoir characterization and monitoring of oil and gas production and CO_2 sequestration in the deep reservoirs. In a typical BSEM survey, the EM electrical bipole source is located inside the borehole and it is usually placed close to a target reservoir to increase the sensitivity of the data to the geological target. A grid of receivers is located on the earth's surface to record the scattering electromagnetic field.

The resolution of the subsurface image obtained from the BSEM survey depends on the number of receivers placed at the earth's surface. In order to obtain a higher resolution of the subsurface formations, one should usually increase the number of receivers at the surface. However, the cost of the survey would also increase correspondingly. In this paper, we introduce a novel approach to solving this problem by placing additional virtual receivers at the observation surface, instead of the actual physical receivers. This approach is based on interpolation and extrapolation of the scattering EM field using the Stratton-Chu type integrals and the Lorentz lemma. We call this process a redatuming of EM data. The redatuming is different fromconventional interpolation and extrapolation techniques, such as polynomial fitting or spline approximation, because it is based on solving the Maxwell's equations for the EM field, and in this way it takes into account the physics of the EM field, which is ignored by traditional mathematical procedures.

We illustrate the effectiness of this redatuming method for the Kevin Dome site, located in Montana.

Stratton-Chu formulas for redatuming and interpolating the anomalous electromagnetic field for borehole-to-surface electromagnetic surveys

The borehole-to-surface EM (BSEM) survey consists of a borehole-deployed transmitter, and a surface-based array of receivers (e.g., He et al., 2005, 2010; Marsala et al., 2011a, b). Let us consider a typical borehole-to-surface electromagnetic survey with the transmitter T_A located at some point *A* within the borehole and the receivers distributed over the earth's surface Σ at points with the radius-vector **r**' (Figure 1). Let us assume that a horizontal plane *P* is located at a depth z_0 in the ground (with the axis *z* directed downward). 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 $\sigma_b(\mathbf{r})$; however, below plane *P* the conductivity $\sigma(\mathbf{r})$ is unknown and is characterized by some anomalous conductivity:

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

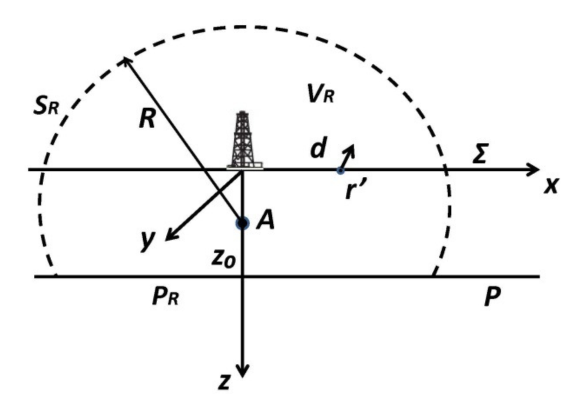

Figure 1: A model of a typical borehole-to-surface electromagnetic survey with the transmitter T_A located at some point A within the borehole and the receivers distributed over the earth's surface Σ at points with the radius-vector **r**'.

DOI http://dx.doi.org/10.1190/segam2013-0650.1

It was shown in Zhdanov and Cai (2012) that the anomalous EM field on the earth's surface can be computed from the anomalous field measured at the horizontal plane P using Stratton-Chu type integrals as follows:

$$\mathbf{d} \cdot \mathbf{E}^{a}(\mathbf{r}') = \iint_{P} \{ \mathbf{E}^{e}(\mathbf{r}'|\mathbf{r}) \times \mathbf{H}^{a}(\mathbf{r}) - \mathbf{E}^{a}(\mathbf{r}) \times \mathbf{H}^{e}(\boldsymbol{r}'|\boldsymbol{r}) \} \cdot \boldsymbol{ds} \qquad (1)$$

We can obtain a similar expression for the magnetic field as well.

Note that, in the last formulas $\{\mathbf{E}^{a}(\mathbf{r}), \mathbf{H}^{a}(\mathbf{r})\}$ is an anomalous EM field generated by a given transmitter T_A in the model with anomalous conductivity given on the horizontal plane *P*; $\{\mathrm{E}^{e}(\mathbf{r}'|\mathbf{r}), \mathbf{H}^{e}(\mathbf{r}'|\mathbf{r})\}$ is a background EM field generated in the medium with background conductivity σ_b by an electric dipole with the unit moment **d**, located at a point with the radius-vectors **r**'.

Equation (1) can be used for the downward continuation of the EM field from the earth's surface to some underground plane *P*. In this case, we will treat equation (1) an integral equation to solve for $\mathbf{E}^{a}$ and $\mathbf{H}^{a}$ Once $\{\mathbf{E}^{a}(\mathbf{r}), \mathbf{H}^{a}(\mathbf{r})\}$ are obtained, we will treat the above equation as integral formula to recompute $\mathbf{E}^{a}(\mathbf{r}')$ and $\mathbf{H}^{a}(\mathbf{r}')$ at a different receiver locations.

Thus, the interpolation and extrapolation of the EM field on the earth's surface can be achieved by two similar procedures: 1) redatuming of the observed field at an underground plane P from actual receivers, located on the earth's surface, and 2) upward continuation of the field from the surface P to virtual receivers at the earth's surface.

Kevin Dome project site

Kevin Dome is a large underground geological structure in Toole County, Montana. This structure was selected for the experimental work to test an integrated EM acquisition, processing and imaging system for the permanent monitoring, verification, and accounting of CO_2 in deep reservoirs (Zhdanov et al., 2013). The BSEM survey is designed primarily to monitor the CO_2 sequestration.

A 3D resistivity model for the Kevin Dome was constructed in Zhdanov et al. (2013) based on well-log data. This model contains 12 layers with a resistivity range between 30 and 150 Ohm-m. The CO_2 is injected into the Devonian Duperow formation which is the target layer. This layer extends from 1100 m to 1140 m in the vertical direction. Figure 2 shows a 3D resistivity model that we constructed from well-logging data for Kevin Dome. The dots in panel (a) of Figure 5 show the location of receivers on the earth's surface. The borehole is drilled at the center.

A vertical electric bipole is placed inside of the borehole to excite the EM fields. The background resistivity was chosen to be 33 Ohm-m.

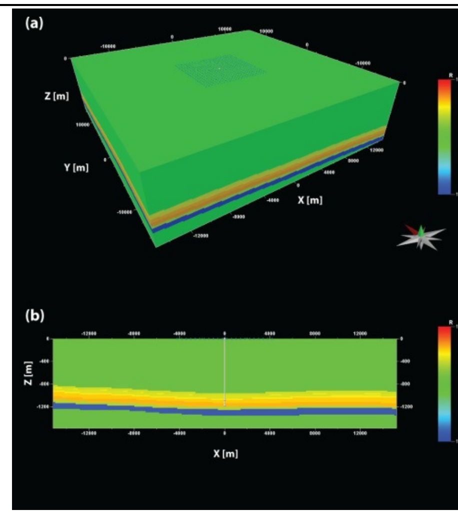

Figure 2: 3D resistivity model constructed from well-logging for Kevin Dome.

Interpolation and extrapolation of EM field data on the earth's surface

Originally, the EM receivers were placed on the earth's surface in a dense configuration, which is shown in Figure 3. The spacing between the receivers is 200 m in the *x* and *y* directions.

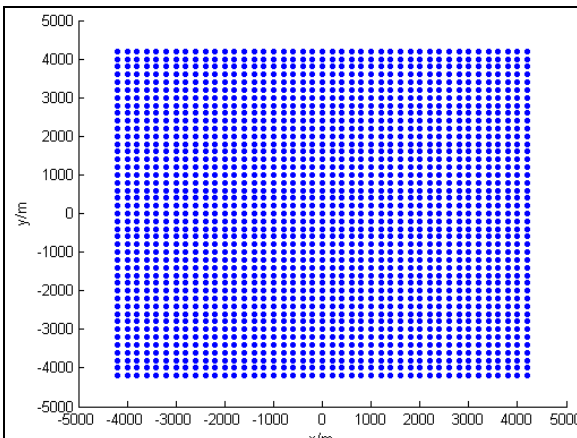

Figure 3: Configuration of original EM receivers on the earth's surface spaced at 200 m in the *x* and *y* / directions.

DOI http://dx.doi.org/10.1190/segam2013-0650.1

As we mentioned before, this kind of dense receiver configuration is expensive. In our approach, we construct a survey with a lesser number of receivers and in a smaller area to recover the scattering EM field at the original locations shown in Figure 3. We first introduce an auxiliary horizontal plane *P* located 500 m under the earth's surface. The EM field in this plane is determined by solving the Stratton-Chu integral equation (1). In the next step, the EM field on the earth's surface at any location can be computed by applying a linear upward continuation operator to the field observed at the underground horizontal plane *P*. Figure 4 shows the maps of the observed anomalous EM field data recorded in the original network of the dense receivers.

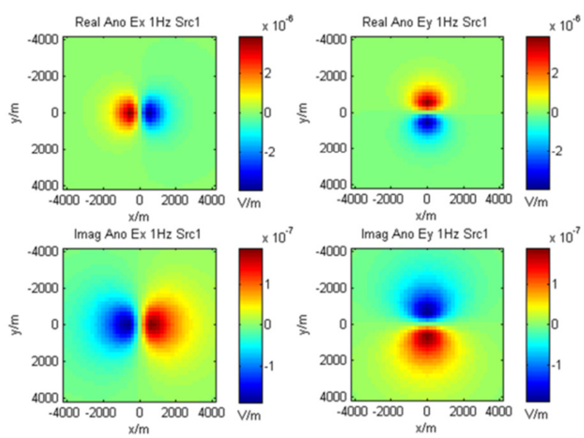

Figure 4: Observed anomalous EM field in the original network of the dense receivers. The left panels show the real and imaginary parts of the anomalous E_x field. The right panels show the real and imaginary parts of the anomalous E_y field.

Case 1: Interpolation/extrapolation from receivers spaced at intervals of 400 m

In this case, we set the spacing between the EM receivers on the earth's surface to be 400 m in the *x* and *y* / directions, which is twice as the spacing of the original EM receiver configuration (Figure 5). Figure 6 and figure 7 presents the profiles of the interpolated/extrapolated data (red curve) compared with the true data (blue curve) for the original dense receiver configuration at y=-1000m and y=1000m. We can see that the interpolated/extrapolated EM data based on our redatuming method are very close to the true data.

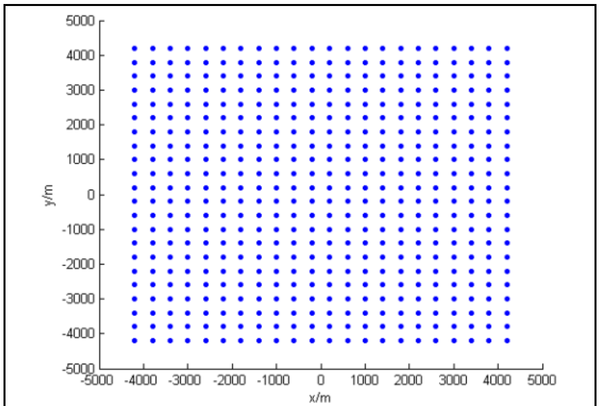

Figure 5: Configuration of EM receivers on the earth's surface spaced at 400 m on the earth's surface.

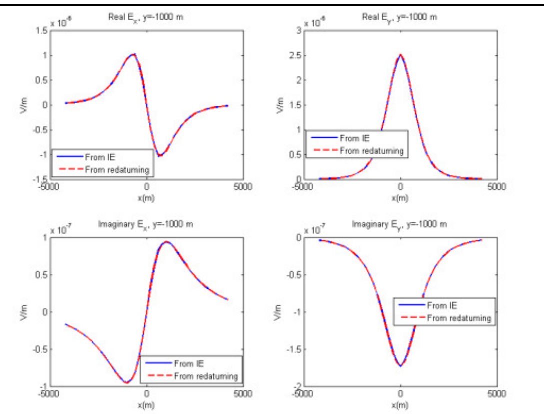

Figure 6: Comparison of original data and interpolated/ extrapolated data from redatuming (case 1) at *y*= -1000 m.

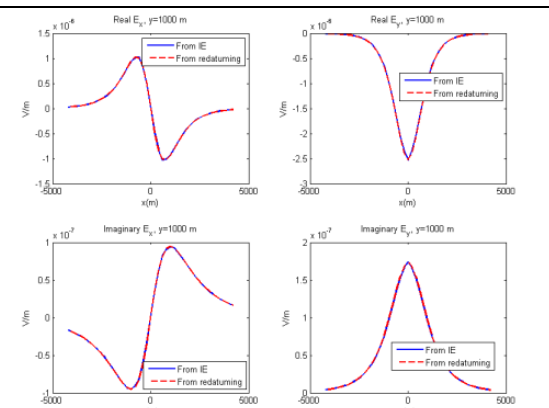

Figure 7: Comparison of original data and interpolated/ extrapolated data from redatuming (case 1) at *y*= 1000 m.

DOI http://dx.doi.org/10.1190/segam2013-0650.1

Case 2: Interpolation/extrapolation from receivers spaced at 800 m intervals

In this case, we set the spacing between the EM receivers on the earth's surface to be 800 m in the *x* and *y* / directions which is four times as the spacing in the original EM receiver configuration. Also, the area covered by a new set of the receivers extends from -3200 m to 3200 m only in both *x* and *y* directions, which is smaller than the area covered by the original receivers. Figure 8 shows the receiver configuration. Figures 9 present the profiles of interpolated/extrapolated data compared with the true data for the original dense receiver configuration. For this case, it seems that we begin slightly loosing accuracy for the interpolation and extrapolation since the number of available receivers is much less than the number of the original receivers shown in Figure 3.

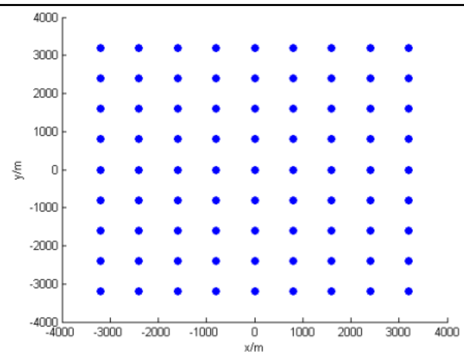

Figure 8: Configuration of EM receivers on the earth's surface spaced at 800 m.

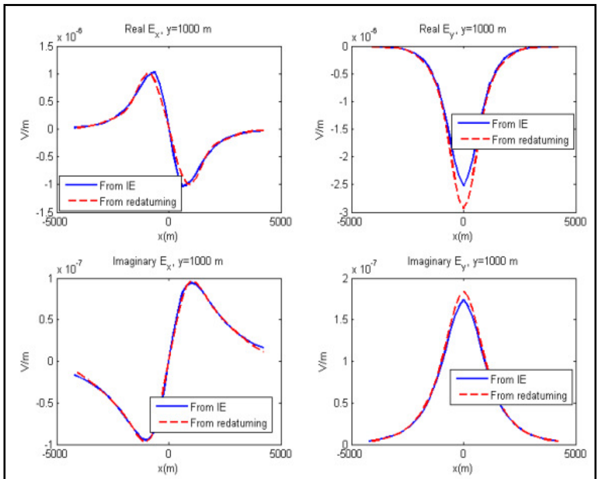

Figure 9: Comparison of original data and interpolated/ extrapolated data from redatuming (case 3) at *y*= 1000 m.

Conclusion

We have developed a method of redatuming observed EM data from a sparse set of actual receivers, located on the earth's surface into a dense set of virtual receivers.

The method is based on using Stratton-Chu type integral transforms. The redatuming is achieved by using the regularized conjugate gradient method of solving an ill-posed inverse problem. The application of the regularization theory makes it possible to apply this method to noisy observed data.

We have considered an application of this method for redatuming BSEM data. By placing the auxiliary receivers at some horizontal plane located underground above the anomalous domain, we can calculate the anomalous EM field at this plane by solving the Stratton-Chu integral equations. The obtained anomalous field can then be used for upward continuation to compute the anomalous EM field in a dense set of virtual receivers located on the earth's surface. This is achieved by an upward continuation, which is a well-posed problem. As a result, we can place a signiÞcant number of virtual receivers on the earth's surface within a much larger area. Contrary to the traditional polynomial interpolation and extrapolation techniques, the developed redatuming method takes into account the underlying physical laws governing the behavior of the observed EM field, which makes the interpolation and extrapolation much more accurate.

This new method for EM field data interpolation and extrapolation was illustrated for the synthetic EM data computed for a model of the Kevin Dome site.

Acknowledgments

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

http://dx.doi.org/10.1190/segam2013-0650.1

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