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The field is analyzed in the frequency domain, we further consider that the field is oscillatory. The Green's function for solving the diffusion equation is known. The Green's function can be used to calculate the wavelength, phase velocity, amplitude and phase at any given point. Equation (2) states that for a single frequency, diffusion also admits solutions with a specific direction of propagation. Therefore, it is logical to apply the synthetic aperture concept to diffusive fields in the frequency domain. Since in the current CSEM the field is analyzed in the frequency domain, we further apply the synthetic aperture concept in CSEM.

A general formula for constructing a synthetic aperture $S_d$ is:

$$S_d(r, \omega) = \sum_{n=1}^{N} a_ne^{i\phi_n}s(r, r_n, \omega).$$

At a single angular frequency $\omega$, a synthetic source at location $r$ is a superposition of the sequentially distributed sources that are located from $r_1$ to $r_N$ with an amplitude weighting $a_n$ and a phase shift $\phi_n$.

We show an example of a 10 km synthetic aperture with field steering using the Green's function $G(r, r_n, \omega) = \pi/\sqrt{r - r_n}$ for equation (1) [Mandelis, 2001]. We use the diffusivity of electromagnetic field in sea water $2.4 \times 10^5$ m$^{-1}$ (D = 1/(µσ), where µ is the permeability and σ is the conductivity). The frequency used in this example is 0.25 Hz. The Green's function from the synthetic aperture is defined as:

$$G_d(r) = \int_{-5km}^{5km} e^{-ic_1n\Delta x}e^{-ic_2n\Delta x}G(r, x, \omega)dx.$$  

where $c_1$ is a coefficient to control the steering angle, $c_2$ is a coefficient to compensate the energy loss due to the diffusion, and $\Delta x = 1x + 51$ km is the distance between each source and the left edge of the aperture. In this particular example we use $c_1 = 0.7$, which corresponds to a steering angle of $\theta = \pi/4$ (angle between the steering direction and vertical axis). The steering angle is related to $c_1$ by $\theta = \sin^{-1}(c_1)$. The coefficient $c_2$ is set to be the same as $c_1$ because the coefficient $c$ corresponding the field decay is the same as that for phase in equation (2). Figure 1 (top) shows the Green's function from the synthetic aperture. Figure 1 (bottom) is the ratio of the field amplitude with a phase steering to the field amplitude without the phase steering, defined as:

$$R = \frac{\int_{-5km}^{5km} e^{-ic_1n\Delta x}e^{-ic_2n\Delta x}G(r, x, \omega)dx}{\int_{-5km}^{5km} e^{-ic_2n\Delta x}G(r, x, \omega)dx}.$$  

This ratio is the largest at angle $\pi/4$ from the synthetic aperture. This example illustrates that we can indeed steer a diffusive field to a designed angle. Although we only show the field steering aspect of synthetic aperture in this paper, general synthetic aperture concepts can be applied much more widely. For example, a quadratic phase shift applied to the source signal can, in principle, be used to focus the field.

3. Synthetic and Field Data Example

3.1. Synthetic Data Example

In the numerical model shown next we use a hydrocarbon reservoir (centered at the origin with horizontal extent of 5 km in the x and y directions and a thickness of 100 m) located 1 km below the sea floor. The sea water is 1 km deep with a resistivity of 0.3 Ωm. The subsurface background is a half space with a resistivity of 1 Ωm. The resistivity of the reservoir is set to be 100 Ωm. The receivers are located at the sea floor and a 100 m dipole source with a current of 100 A is continuously towed 100 m above the receivers. The source current oscillates with a frequency of 0.25 Hz. All the analysis in this research are in the frequency domain using 0.25 Hz data.

In this example, we focus on the construction of a synthetic aperture source with the field steered toward the target direction. Figure 2a shows the inline electrical fields with the reservoir (dashed line) and without the reservoir (solid line) from a single 100 m dipole whose center is located at $x = -6.5$ km. There is a slight increase in the field around the position $x = 0$ km when the reservoir is present. This 20% difference is shown by the ratio of the field with the reservoir to the field without the reservoir (black solid curve in Figure 2e).

Similarly superposing the 50 employed sequential sources, is equivalent to setting $a_n = 1$, $\phi_n = 0$, and $N = 50$ in equation (3). This superposition gives a 5 km long dipole source with a current of 100 A. The total $E_0$ field is given by Figure 2b. The ratio of the fields with and without the reservoir is shown by the red dashed curve in Figure 2e. Although the overall signal strength increases compared to
The attenuation of a diffusive field, causes the sources on the left side to give a smaller contribution to the synthetic aperture construction because they propagate a greater distance. In order to have a more effective steered field, we use an energy compensation term $a_n = e^{-c_2 n \Delta s}$ as we used in equation (4), where $c_2$ is a constant that controls the amplitude weighting. Although we used $c_2 = c_1$ in the homogeneous medium shown in equation (4), in this layered model the anomaly due to the reservoir is largest when $c_2$ is 0.1 m$^{-1}$. The optimization of $c_1$ and $c_2$ will be further investigated and presented in a more detailed paper. After we include this energy compensation, the difference between the models with and without the target further increases, as shown in Figure 2d. This difference is quantified by the ratio of the fields with and without the target and is illustrated by the magenta dashed-dotted line in Figure 2e.

[15] The examples show that the synthetic aperture technique dramatically increases the difference in electrical field response between the models with and without the reservoir by a factor of 30. Note that this is achieved without altering the data acquisition. If noise is added in the above example, the main observation still holds, but in that case we can not steer the field as effective as for noise free data and therefore the anomaly ratio is not as big as the factor of 30.

3.2. Real Data Example

[16] Next, we apply field steering to the real data. In the real data, the field ‘without’ the target is defined as the measured field at a reference site under which there is no reservoir. For a standard single dipole measurement, the inline electrical fields with and without the reservoir are shown by the red dashed and black solid curves, respectively, in Figure 3a. The corresponding ratio of the two fields is shown by the solid curve in Figure 3d. Note that only the area between $x = 4$ km to $x = 15$ km, where the reservoir imprint locates, is shown in Figure 3d. The reservoir is known to be located between $x = 3$ km and $x = 6$ km. A slight difference in the electrical field, caused by the reservoir, can be observed between the offset of 6 km and 10 km. Beyond the offset of 10 km, the ratio oscillates because the field reaches the noise level.

[17] Next, we construct a 4 km synthetic aperture source with no field steering (zero phase shift). The fields with and without the reservoir are shown by the red dashed and black solid curves in Figure 3b, respectively, and the corresponding ratio is the red dashed curve in Figure 3d. Because the longer dipole source has a better signal to noise ratio (the...
signal is stronger), both the $E_x$ field and the ratio are smoother than the field generated by an individual source. The overall difference between the responses, however, does not change too much.

[18] We next construct a 4 km synthetic aperture source with field steering toward the reservoir using a phase shift ($c_1 = 0.8$) and amplitude weighting ($c_2 = 0.6$). Figure 3c shows that the difference in the field between with and without the reservoir has significantly increased after we apply the field steering. The corresponding ratio is shown by green dashed-dotted line in Figure 3d. The imprint of the reservoir is much more pronounced in Figure 3c than those in Figures 3a and 3b. Note that the response at negative offsets does not show any difference in the field both before and after the field steering. This is because there is no reservoir for negative offsets.

4. Discussion and Conclusion

[19] The synthetic aperture technique opens a new line of research in CSEM data processing. Hidden information in CSEM data can be retrieved by using the synthetic aperture technique with no extra cost because there is no need to change the acquisition. The ability to detect reservoirs is dramatically increased after forming appropriate synthetic aperture sources. The depth of the reservoir that CSEM detects can potentially increase with the use of synthetic aperture methods. Additionally, synthetic aperture has potential for towing the source at shallower depth in the water, which would simplify CSEM acquisition and reduces the acquisition cost. In this paper, we only show examples of constructing synthetic aperture source in a line. In principle, one can construct 2D synthetic aperture surface source to better detect the 3D structure of the subsurface. For example, when data are collected with antennas along parallel lines, one not only can steer the field in the inline direction, but also in the crossline direction. The synthetic aperture technique is not limited to the source side, but can also be applied to the receiver side.

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References


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