Improving Sea Bed Logging with Magnetic Field Measurements*

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Abstract

The primary CSEM data are in-line electric field from end-fire electric dipole source and broadside electric field from broadside electric dipole source. There are other electric field responses that may be sensitive to a deep resistivity anomaly. The magnetic field is also induced from the electric dipole source and may be sensitive to an anomaly as much as the electric field. The magnetic field data are generally not considered as primary data. In the borehole logging, it has been known that the cross-component measurement, i.e. the transverse field from an axial transmitter, is useful for a detection of an adjacent bed. Is there similar advantage of using the cross-component electric field measurement in CSEM? It has been recently recognized that the transverse magnetic field from the axial electric dipole source is more sensitive to the adjacent bed around the borehole than the coaxial electric field at very low frequency. Isn't the magnetic field measurement similarly sensitive to a deep anomaly in CSEM and helpful to detect the anomaly?

To examine such possibilities, I calculated all the electric and magnetic field responses using a simple 3D CSEM model and compared how sensitive these responses are to a resistivity anomaly. I found that one cross-component measurement of the vertical electric field is as sensitive to the anomaly as the in-line electric field. I also found that the transverse magnetic field from the end-fire electric dipole source is more sensitive than the in-line electric field. The transverse magnetic field measurement has deeper depth of detection than the in-line electric field. Analyzing the data with the constant transmitter-receiver offsets, like in the streamer-CSEM survey, I will show that sensitivity of the transverse magnetic field exceeds that of the in-line electric field. Adding the transverse magnetic field data will help CSEM interpretation and inversion. Likewise, in-line magnetic field from a broadside electric dipole source is more sensitive than the broadside electric field. It is not surprising that joint inversion of both magnetic and electric field data is more robust than inversion using the electric field data alone. The result also suggests that adding the magnetic field data may be helpful in some other geophysical surveys using the electric dipole source.

Introduction

The CSEM has been used as a direct hydrocarbon indicator (Cox et al., 1971; Constable and Cox, 1996; Constable, 2010). In CSEM, the source is electric dipole and the receivers are electric field sensors. Magnetic field sensors are also available for CSEM measurements as CSEM is often deployed with Magnetotelluric measurements (Constable et al., 1998). The advantage of magnetotelluric TM data (transverse magnetic field data) was noted for salt dome profiling (Hoversten et al., 1998). In some applications, the use of vertical magnetic field measurement was suggested (Goldman et al., 2011). However, the magnetic field responses have not generally been regarded as primary CSEM data.

I examined the CSEM magnetic field responses from an electric dipole source to see if there is any merit of using the magnetic field data in addition to the electric field data. I found that the magnetic field is more sensitive to a deep resistivity anomaly, such as a high resistivity bed, than the electric field. The magnetic field measurement has deeper depth of detection than the routine electric field measurement. It is not surprising that joint inversion of both magnetic and electric field data is more robust than inversion using the electric field data alone (Kapuchenko et al., 2007).

Previously I showed that the resistivity anomaly may be identified more intuitively from the CSEM data with multiple depths of investigations. Namely, in analogy to the wireline logging, the CSEM data were grouped into data sets with the constant transmitter-receiver offsets that are indicative of the depths of investigation. It was shown that the data set with a constant offset clearly indicates a resistivity anomaly at the lateral extent of the deep anomaly. The data sets with different offsets responded differently to the anomaly, depending on the depth and the resistivity of the anomaly. (Hagiwara, 2013)

In the following, I present the case for the endfire electric dipole source and examine all the electric and magnetic field responses using model calculations. Using conventional data display, I will show that the transverse magnetic field response from an end-fire electric dipole source is more sensitive to a deep resistivity anomaly than the in-line electric field response. Analyzing the data with the constant transmitter-receiver offsets I will show that sensitivity of the transverse magnetic field data exceeds that of the in-line electric field data.

I will also present the case for the broadside electric dipole source. Only the summary will be presented: the in-line magnetic field data is more sensitive to the resistivity anomaly than the broadside electric field data.

I suggest that adding the magnetic field data should be helpful for CSEM interpretation. Joint inversion of both magnetic and electric field data should be more robust than inversion using the electric field data alone. The magnetic field data may be helpful in some other geophysical surveys using electric dipole sources.

Model

Consider the CSEM data acquisition for a 2D Earth model of Figure 1. The array of receivers are placed on the sea floor at (x_R=x_i) at a regular interval $\delta = x_i - x_{i-1}$ between two adjacent receivers along the x-direction. The transmitter is towed over the receiver array. Its lateral location is noted at (x_T). The in-line receiver response along the x-axis direction of the receiver at x_i from the transmitter at x_T is noted as $E_x(x_T\ x_i)$.

The resistivity anomaly target is 200 m thick, located at 1500 m deep from the sea floor. It is 6,000 m long in the x-direction. It is much longer, 21,000 m long, in y-direction; hence, this is practically a 2D model. The center of the rectangular anomaly is noted as an origin (x=0, y=0).

In the model calculation, the sea water is 3,000 m deep, and the transmitter is towed at 100 m above the sea floor. The resistivity of sea water is 0.3 Ohm-m. The resistivity of the target anomaly is 100 Ohm-m, while the background resistivity is 1 Ohm-m. The frequency is at 0.1, 0.25, 0.5, and 1.0Hz.

In-Line Electric Field Amplitude

Figure 2a shows the in-line electric field amplitudes $E_x(x_T, x_R)$ along the receiver array from x_R = -8,000 m to x_R =8,000 m, for three different transmitter locations, respectively, at x_T= –3,000 m, 0 m, and 5,000 m at 0.5 Hz. The dashed lines indicate the response for each transmitter position when there is no resistivity anomaly. The difference from the dashed line suggests a resistivity anomaly.

The difference is, however, very small, as shown in Figure 2b, where the transmitter is located at x_T =0 m. For comparison, the in-line E_x amplitude without anomaly is plotted as Back Ground. The relative difference, that is the ratio of the difference to the in-line E_x amplitude without anomaly at x_R =0, is shown in Figure 2c. The difference caused by the anomaly is only 10-5 of the E_x amplitude at x_R =0 without anomaly. In order to detect the anomaly, this relative difference must be measured. Namely, the precision of the measurement must be finer than this relative difference. In the following the term, detection sensitivity, is used for the relative difference.

Transverse Magnetic Field Amplitude

It is known that the end-fire electric dipole (x-axis polarization) transmitter generates stronger transverse (y-axis) magnetic response when there is a resistivity anomaly nearby. Figure 3a shows the transverse magnetic field amplitudes $H_y(x_T, x_R)$ along the receiver array from x_R = -8,000 m to x_R =8,000 m, for three different transmitter locations, respectively, at x_T=- 3,000 m, 0 m, and 5,000 m. The dashed lines indicate the response for each transmitter position when there is no resistivity anomaly.

Figure 3b shows the difference when the transmitter is located at x_T =0 m. The transverse H_y amplitude without anomaly is plotted (as BG) for comparison. The relative difference to the transverse H_y amplitude at x_R=0 without anomaly is shown in Figure 3c. The relative difference caused by the anomaly is nearly one order of magnitude larger for the transverse H_y amplitude than that for the in-line E_x amplitude. The relative difference increases for lower frequency. This example clearly shows that the transverse magnetic field (H_y) measurement is more sensitive to a deep resistivity anomaly.

Case for Broadside Electric Dipole Source

When the broadside electric dipole source is used, the broadside electric field and the in-line magnetic field respond to the deep resistivity anomaly. The same earth model of Figure 1 is considered. The relative differences of the in-line H_x amplitude and broadside E_y are compared in Figure 4. The relative difference caused by the anomaly is nearly one order of magnitude larger for the in-line H_x amplitude than that for the broadside E_y amplitude. The relative difference increases for lower frequency. This example clearly shows that the magnetic field measurement is more sensitive to a deep resistivity anomaly than the electric field measurement when the electric dipole source is used.

In the following section I assess the advantage of transverse magnetic field measurements for deeper depth of detection. I present only the case for the in-line electric dipole source where I examine both in-line electric field and transverse magnetic field responses for the constant transmitter-receiver offsets at different frequencies.

The Response of Constant Transmitter-Receiver Offset to a Resistivity Anomaly

The streamer EM data are collected by towing an array of transmitters and receivers. The streamer data are collected with the constant transmitter-receiver offsets. The data with different offset responds to the resistivity anomaly with different depth of investigation. The location and the resistivity of the anomaly are routinely determined using inversion. However, the location and the resistivity of the anomaly may be estimated more intuitively, using the data from several different offsets.

We introduced below the method of using the response of constant offset and differential amplitude data. The method is readily applicable to the streamer EM data.

We define the data with the constant transmitter-receiver offset L by,

$E_x(x_T;L)=E_x(x_T,x_R=x_T+L)$ or $E_x(x_T, x_R=x_T-L)$; $H_y(x_T;L)=H_y(x_T, x_R=x_T+L)$ or $H_y(x_T, x_R=x_T-L)$

For ease of data interpretation, the data set may be symmetrized with respect to the transmitter location or the receiver location. The symmetrized data with the offset L is defined by,

$E_x(x_T;L)=0.5*\{E_x(x_T,x_R=x_T+L)+Ex(x_T,x_R=x_T-L)\}$; $H_y(x_T;L)=0.5*\{H_y(x_T,x_R=x_T+L)+Hy(x_T,x_R=x_T-L)\}$

We may define the data with respect to the receiver location as,

$E_x(x_R;L)=0.5*\{E_x(x_T=x_R+L,x_R)+E_x(x_T=x_R-L,x_R)\}$; $H_y(x_R;L)=0.5*\{H_y(x_T=x_R+L,x_R)+H_y(x_T=x_R-L,x_R)\}$

We discuss only the case for the endfire electric dipole source with in-line electric field data and transverse magnetic field data below. Figure 5a and Figure 5b are the symmetrized in-line Ex data with the offset L=300 m and L=1,000 m, respectively, at 0.1 Hz in the model of Figure 1. Figure 6a and Figure 6b are the symmetrized transverse H_y data with the offset L=300 m and L=1,000 m, respectively, at 0.1 Hz in the same model. It is interesting to note that the both electric field and magnetic field response decrease in amplitude when there is a resistive anomaly in this model at this frequency.

These plots clearly show the resistivity anomaly, from -3,000 m to +3,000 m in the x-direction. The true location of the resistivity anomaly is indicated by a bar from -3,000 m to +3,000 m in the plot. In Figure 5a for the transmitter-receiver offset of L=300 m, the BG signal level of the in-line electric field amplitude is about 4.27*10-8 V/m when the transmitter is laterally far from the anomaly, and the anomaly is detected by the decrease of signal by about 4*10-11 V/m, that is 0.1% of the BG signal, when the anomaly is D=1000 m deep. Conversely, the D=1000 m deep anomaly can be detected if the electric field is measured to the 0.1% precision of the BG signal level.

In Figure 5b for L=1000 m offset, the BG signal level is 1.30*10-9 V/m and the anomaly can be detected by the signal decrease of about 1.6*10-11 V/m for the D=1000 m deep anomaly. The relative difference, that is the ratio of the signal difference to the BG signal, is 0.013. The data clearly show the resistivity anomaly, from -3,000 m to +3,000 m in the x-direction. The signal level is about 10-9 V/m when the transmitter is laterally far from the anomaly, and the response to the anomaly is detected by the decrease of signal by about 10-11 V/m, that is 1%. The true location of the resistivity anomaly is indicated by a bar from -3,000 m to +3,000 m in the plot.

In Figure 6a for L=300 m offset, the BG transverse magnetic field amplitude is about 8.06*10-6 A/m when the transmitter is laterally far from the anomaly, and the anomaly is detected by the decrease of signal by about 6*10-8 A/m when the anomaly is D=1000 m deep. The relative difference is 0.75% of the BG amplitude. Conversely, the D=1000 m deep anomaly can be detected if the magnetic field is measured to the 0.75% precision of the BG amplitude. This suggests that the transverse magnetic field measurement is more sensitive, by a factor of 7.5, than the in-line electric field measurement to the deep resistive anomaly in this model.

In Figure 6b for L=1000 m offset, the BG signal level is 6.9*10-7 A/m and the anomaly can be detected by the signal decrease of about 3.2*10-8 A/m for the D=1000 m deep anomaly. The relative difference is 0.047. The transverse magnetic field is more sensitive, by a factor of 3.7, to the anomaly.

It is advantageous to use the transverse magnetic field measurement also for detection of D=1500 m deep anomaly. These findings are compared in Table 1. It is interesting to note, however, that the transverse magnetic field and the in-line electric field measurements show similar relative difference for detection of D=2000 m deep anomaly with these offsets at 0.1 Hz.

Discussion and Conclusion

The CSEM data are collected by an array of receivers placed on the sea floor while the transmitter is towed above in the sea. The electric dipole is used as the source and the electric field responses are measured. The magnetic field responses are generally not considered as primary CSEM data.

I examined all the electric and magnetic field responses from the electric dipole source using model calculations. Using conventional data display, I found that the transverse magnetic field response from an end-fire electric dipole source is more sensitive to a deep resistivity anomaly than the in-line electric field response.

Analyzing the data with the constant transmitter-receiver offsets, I showed that sensitivity of the transverse magnetic field data exceeds that of the in-line electric field data. Though not presented here, the in-line magnetic field is also more sensitive than the broadside electric field from broadside electric dipole source.

The result suggests that adding the magnetic field data should be helpful for CSEM interpretation. Joint inversion of both magnetic and electric field data should be more robust than inversion using the electric field data alone. The result also suggests that adding the magnetic field data may be helpful in some other geophysical surveys using the electric dipole source.

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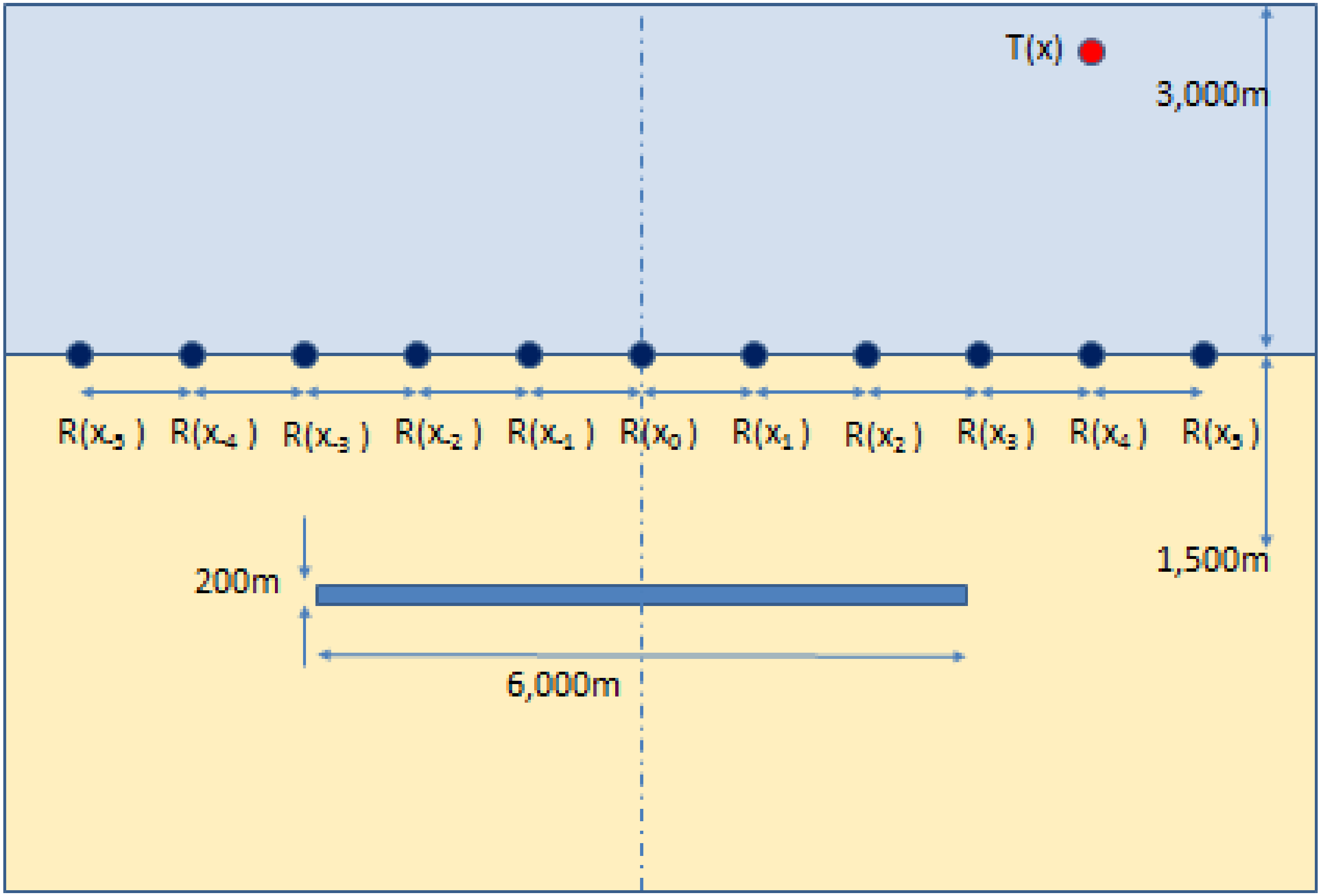

Figure 1. Earth model and CSEM data acquisition.

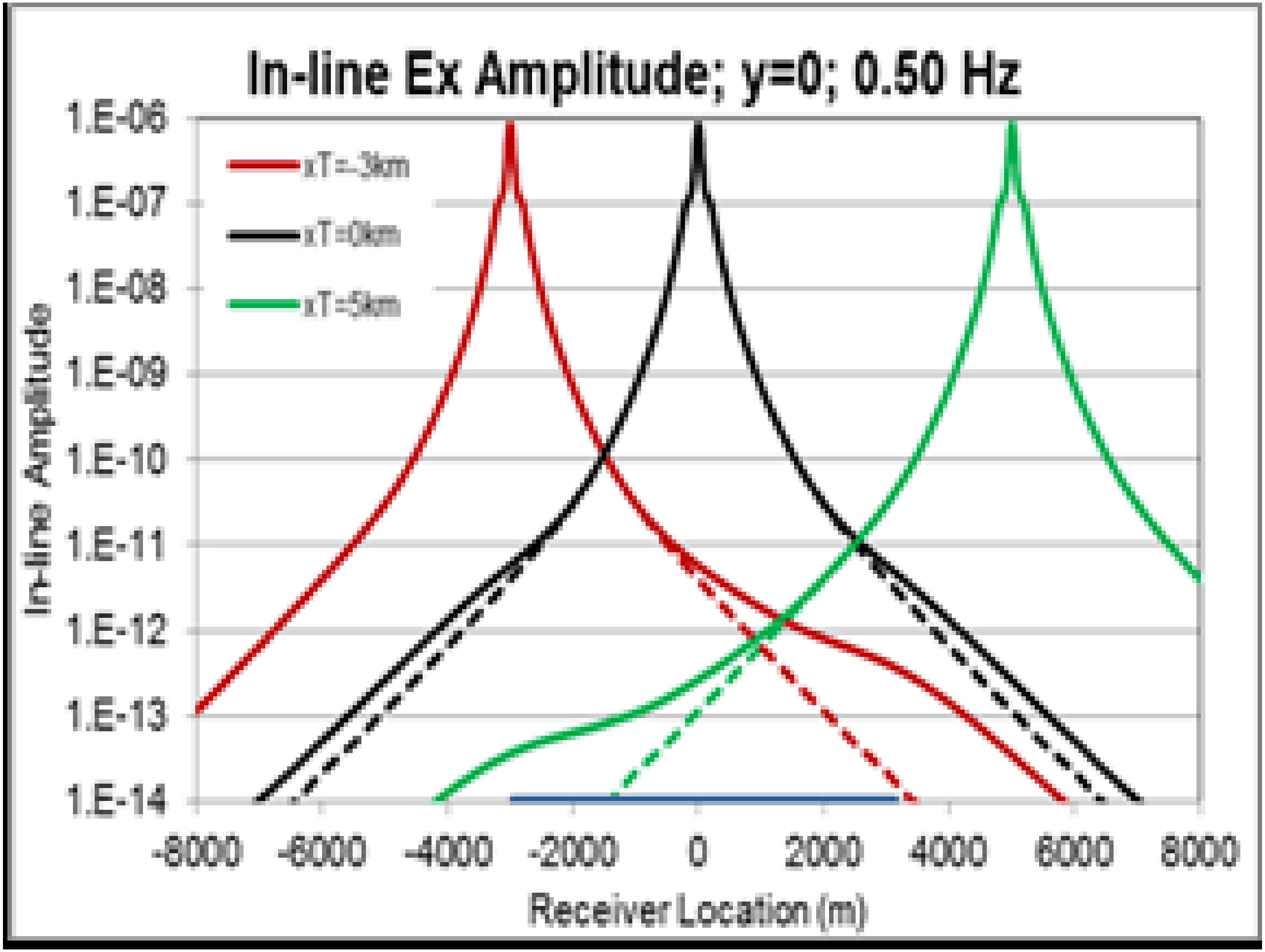

Figure 2a. In-line electric field CSEM data.

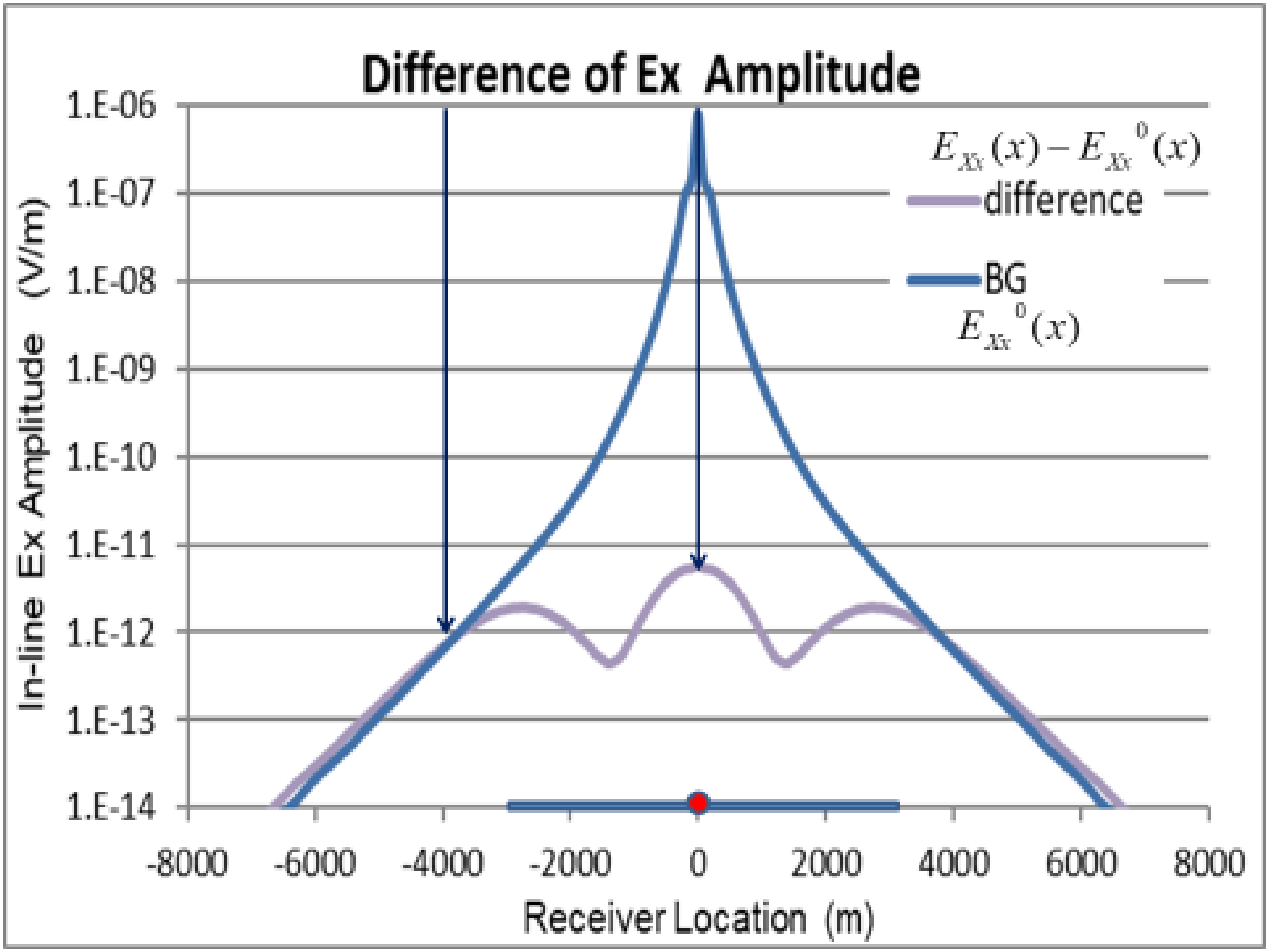

Figure 2b. Difference of in-line electric field amplitude.

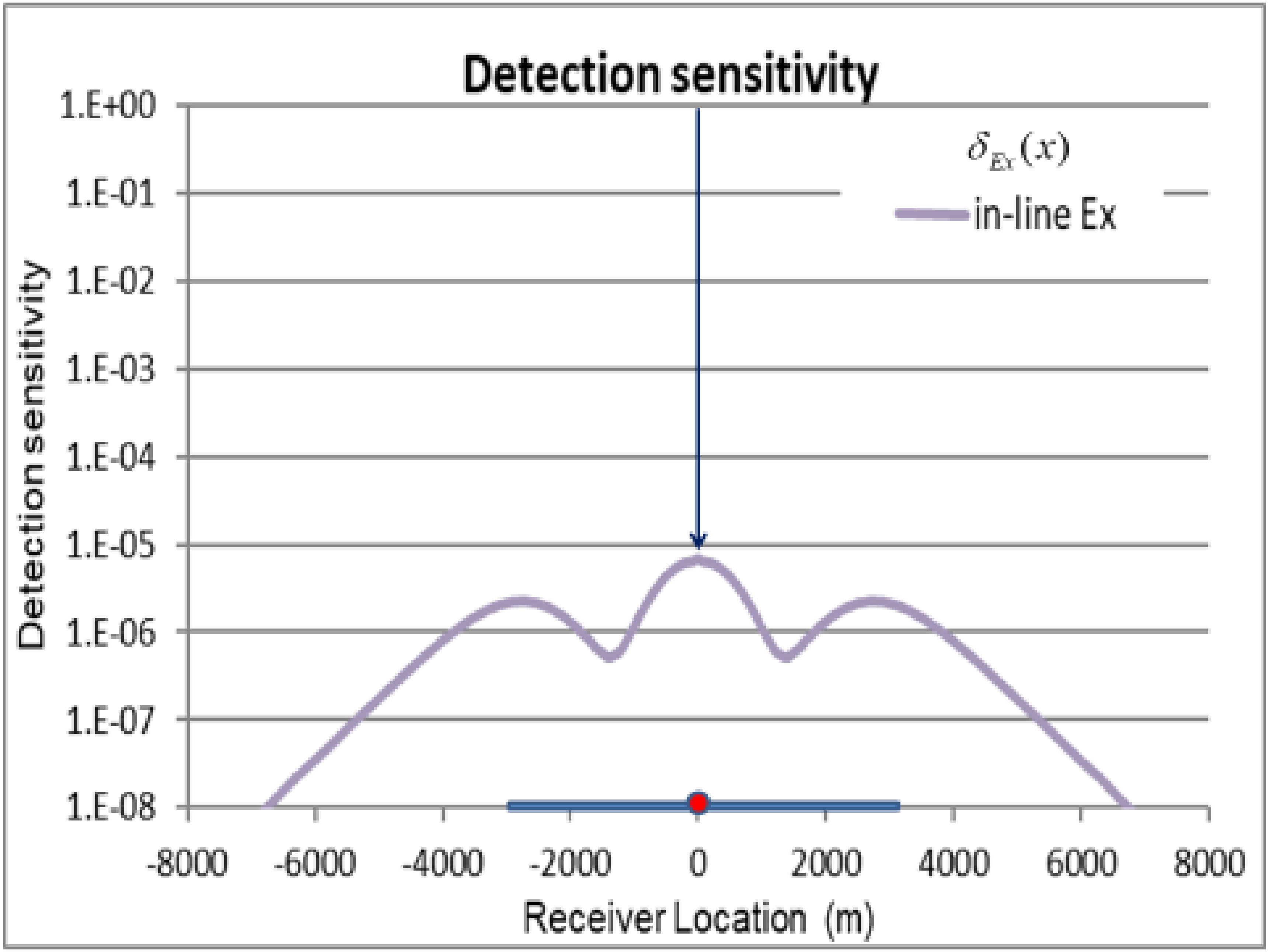

Figure 2c. Difference relative to BG amplitude at x_T=0m.

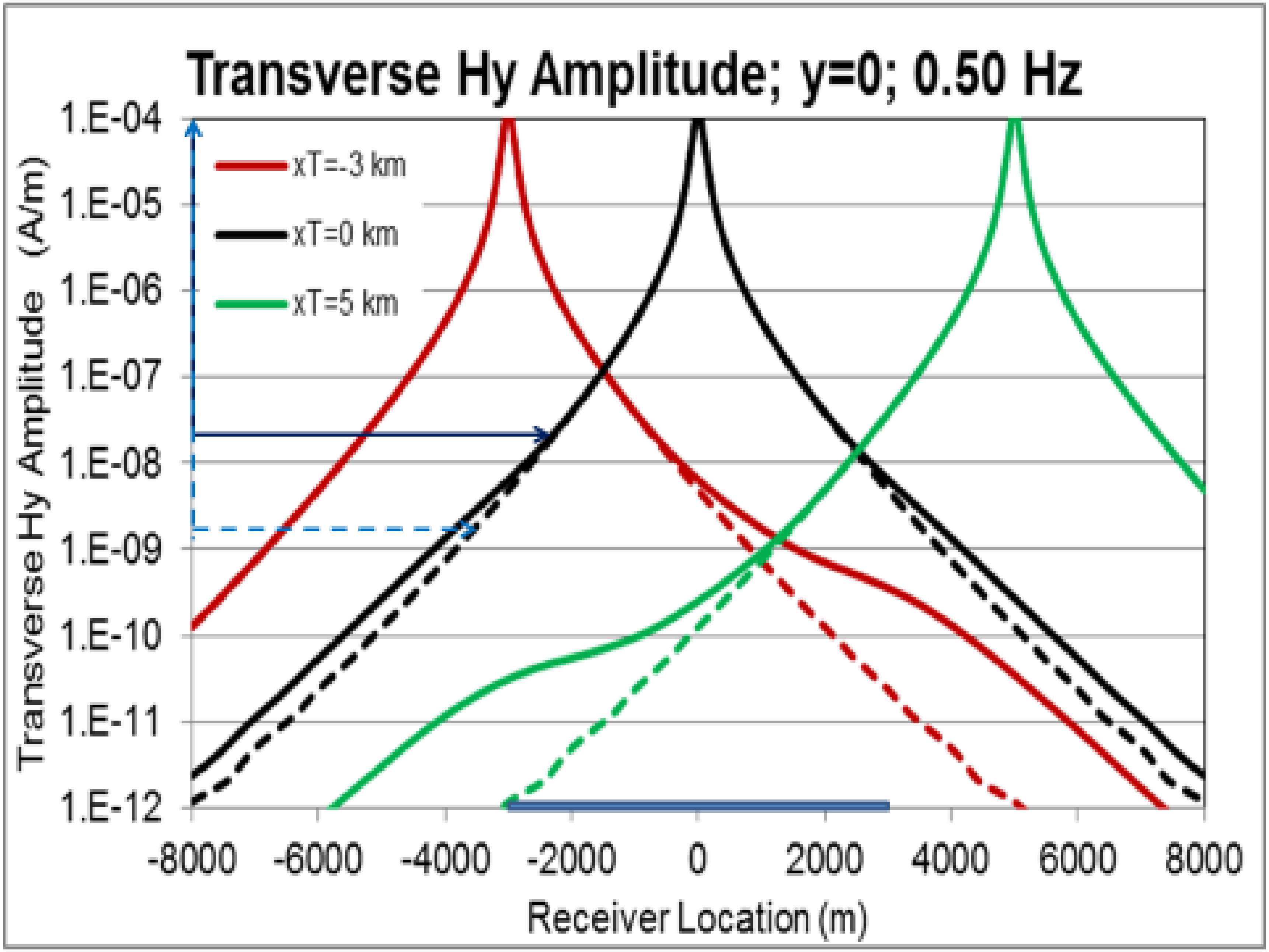

Figure 3a. Transverse magnetic field CSEM data.

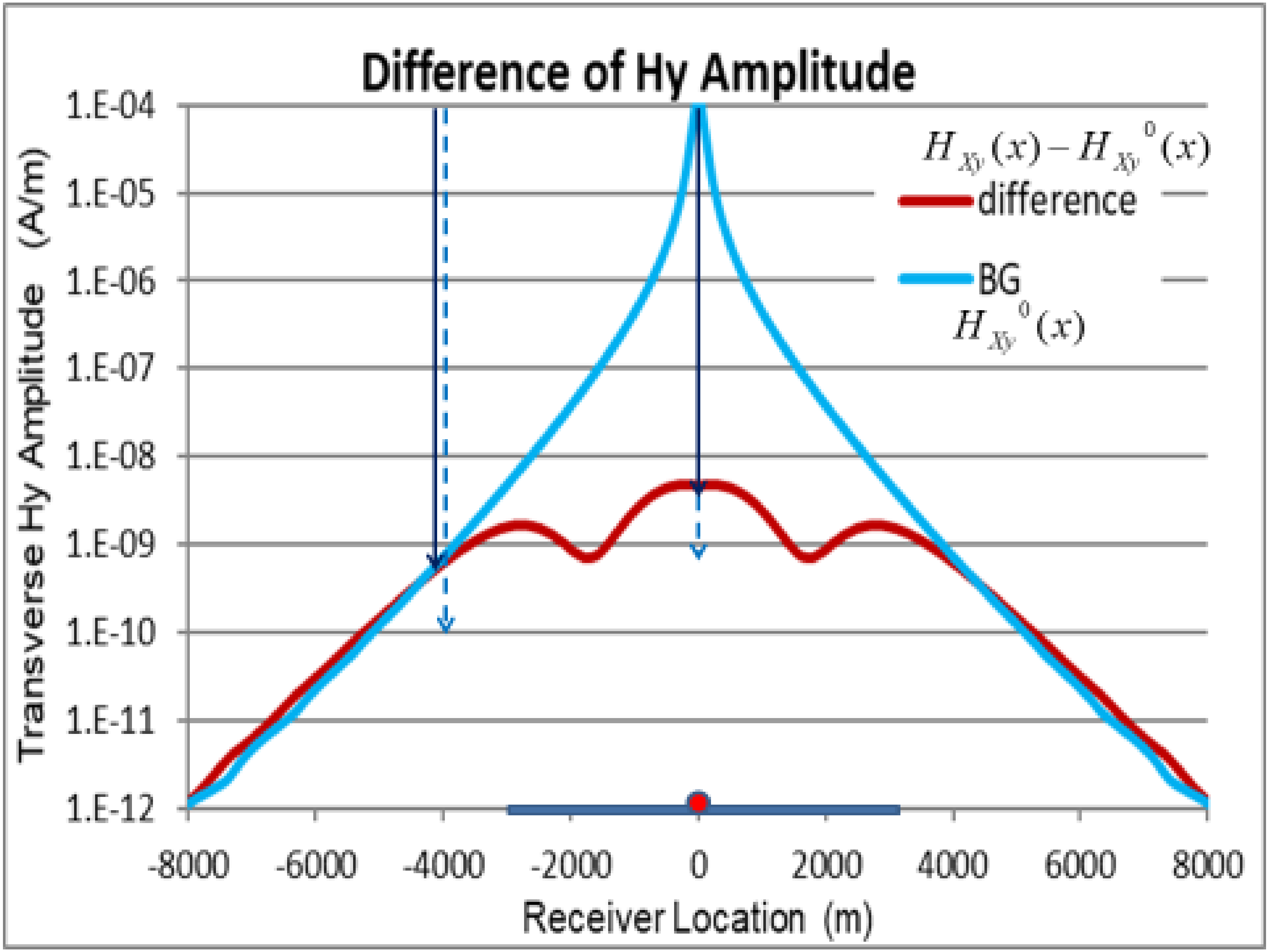

Figure 3b. Difference of transverse magnetic field amplitude.

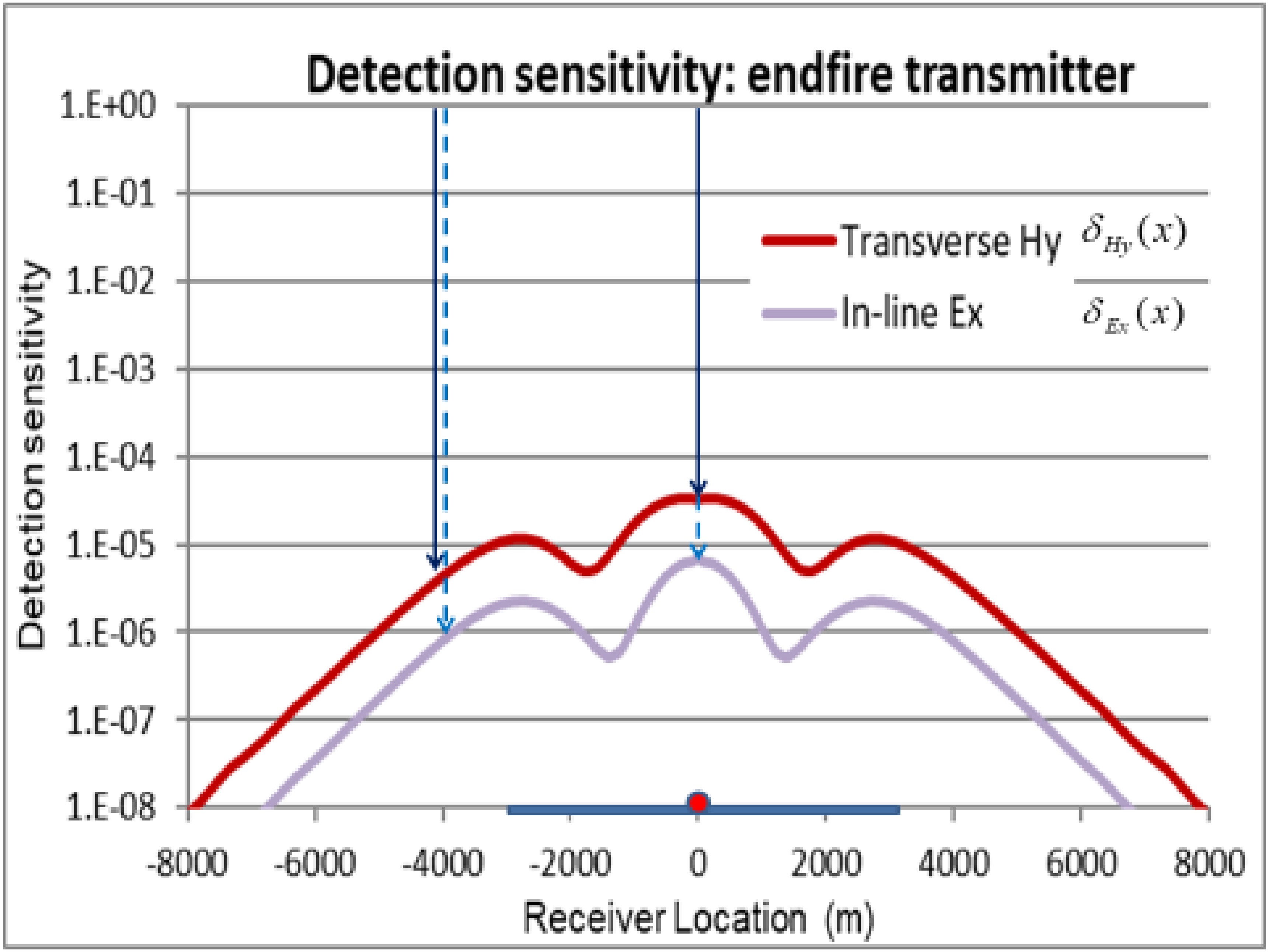

Figure 3c. Difference relative to BG amplitude at x_R=0m.

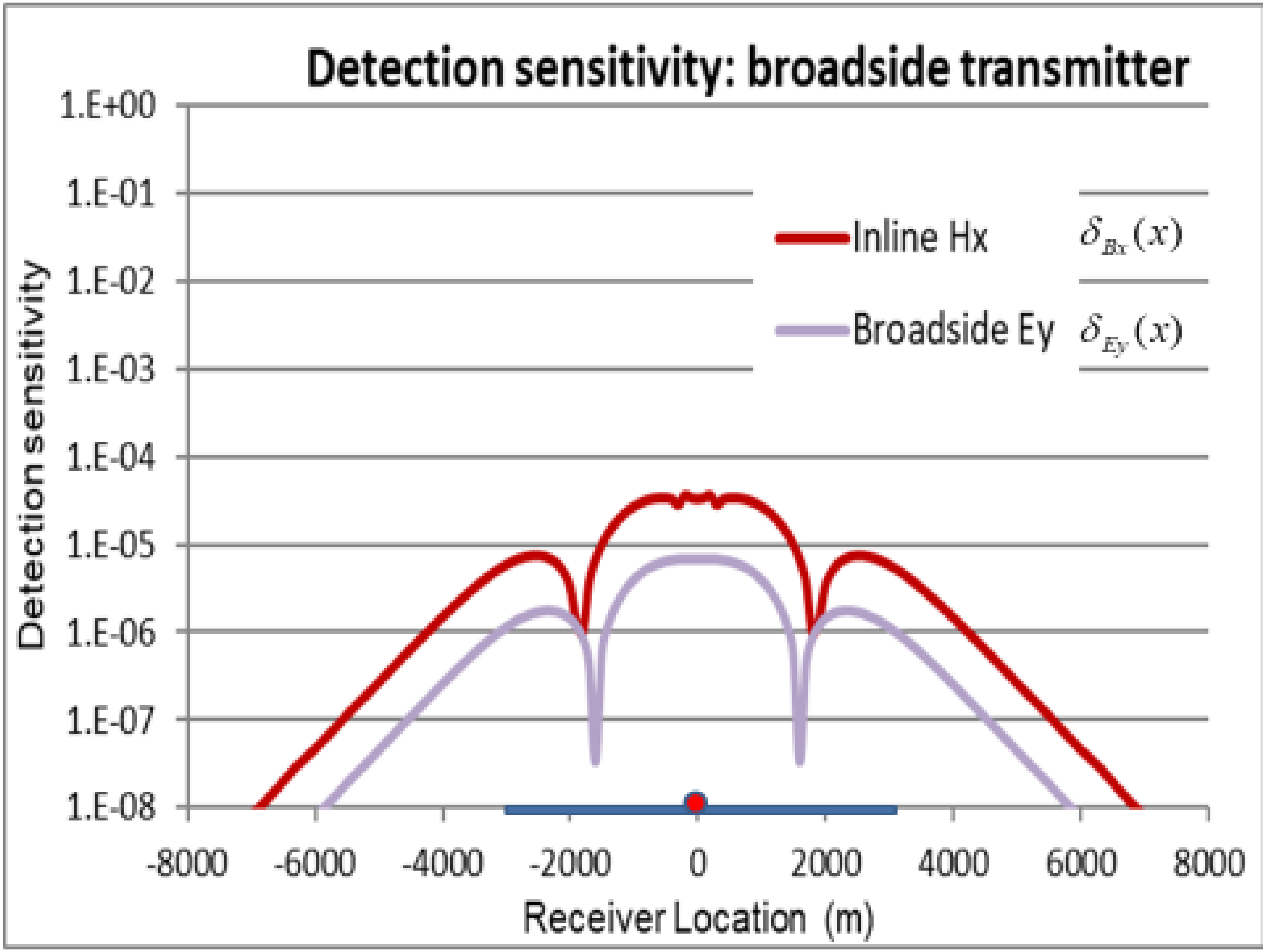

Figure 4. Relative difference for broadside transmitter.

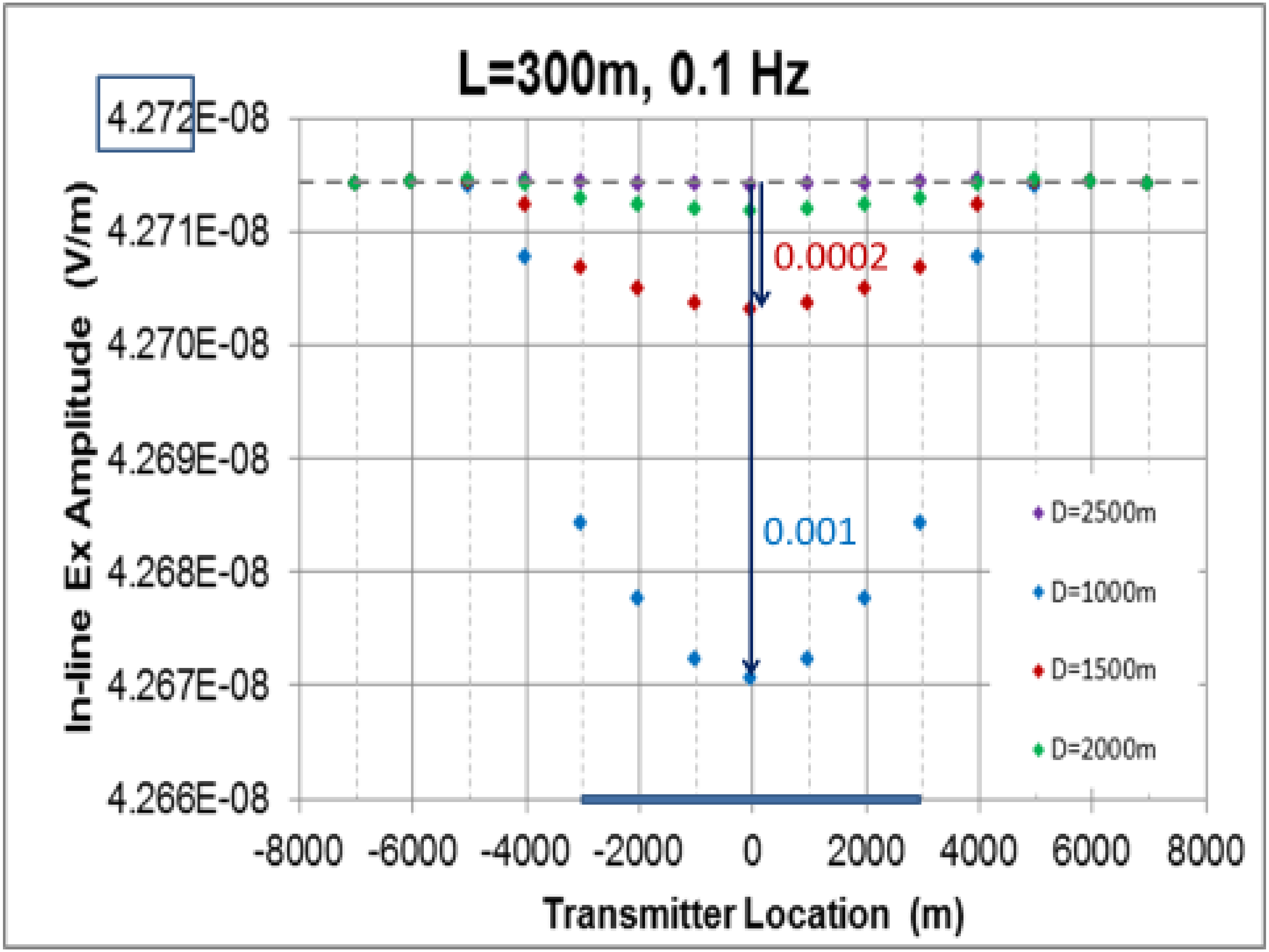

Figure 5a. In-line Ex amplitude for L=300 m offset at 0.1Hz.

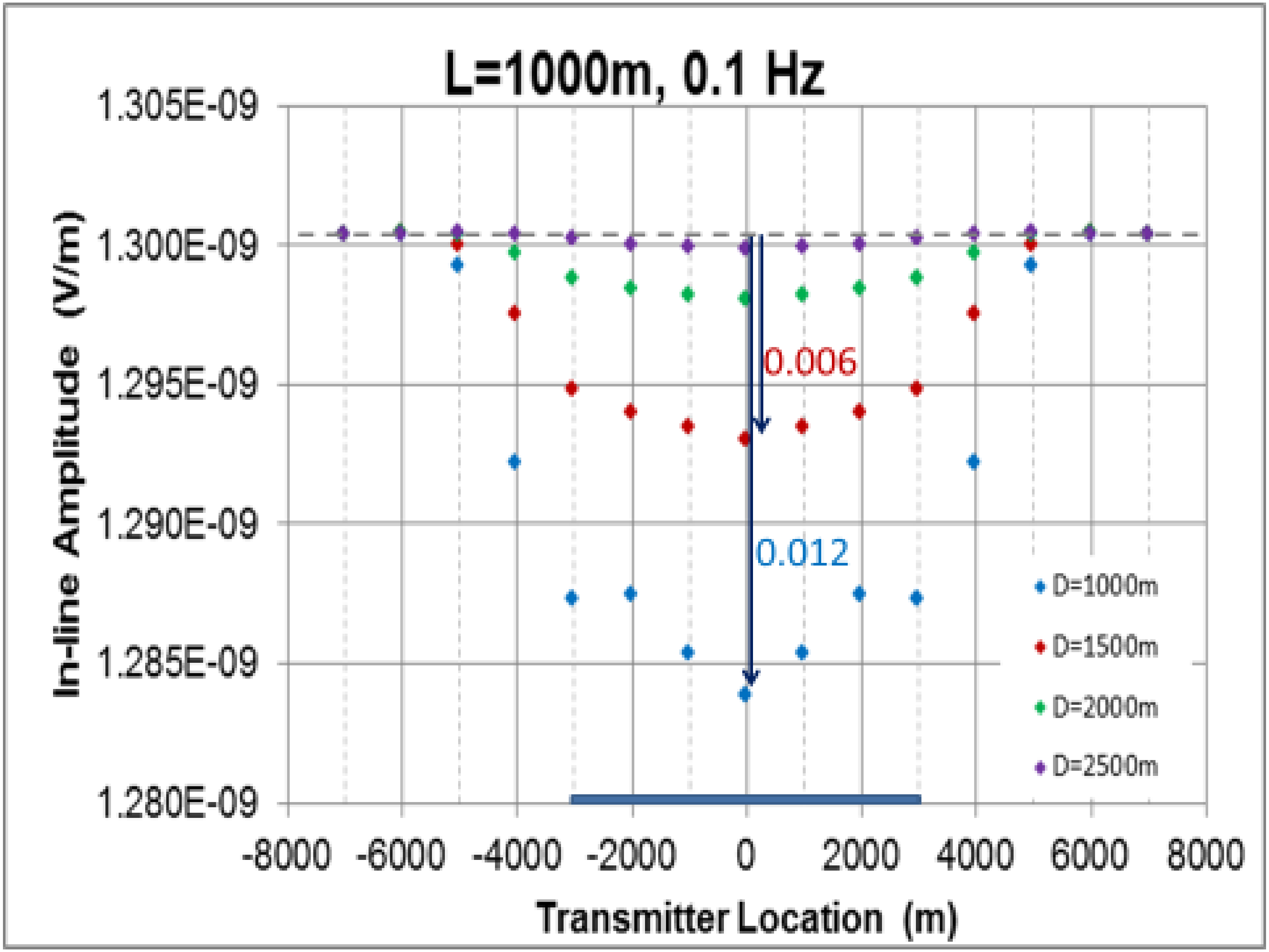

Figure 5b. In-line Ex amplitude for L=1000 m offset at 0.1Hz.

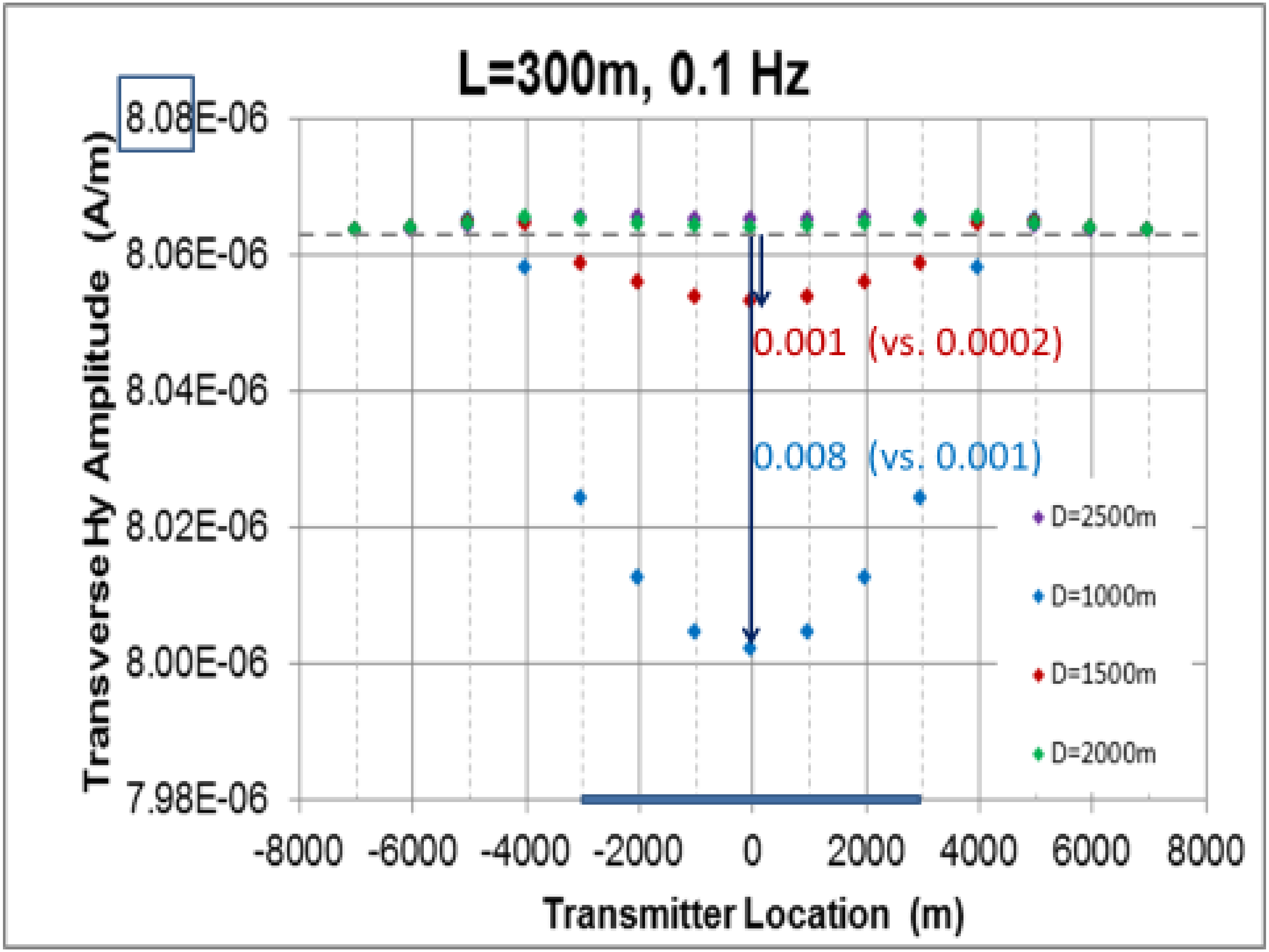

Figure 6a. Transverse H_y amplitude for L=300 m at 0.1Hz.

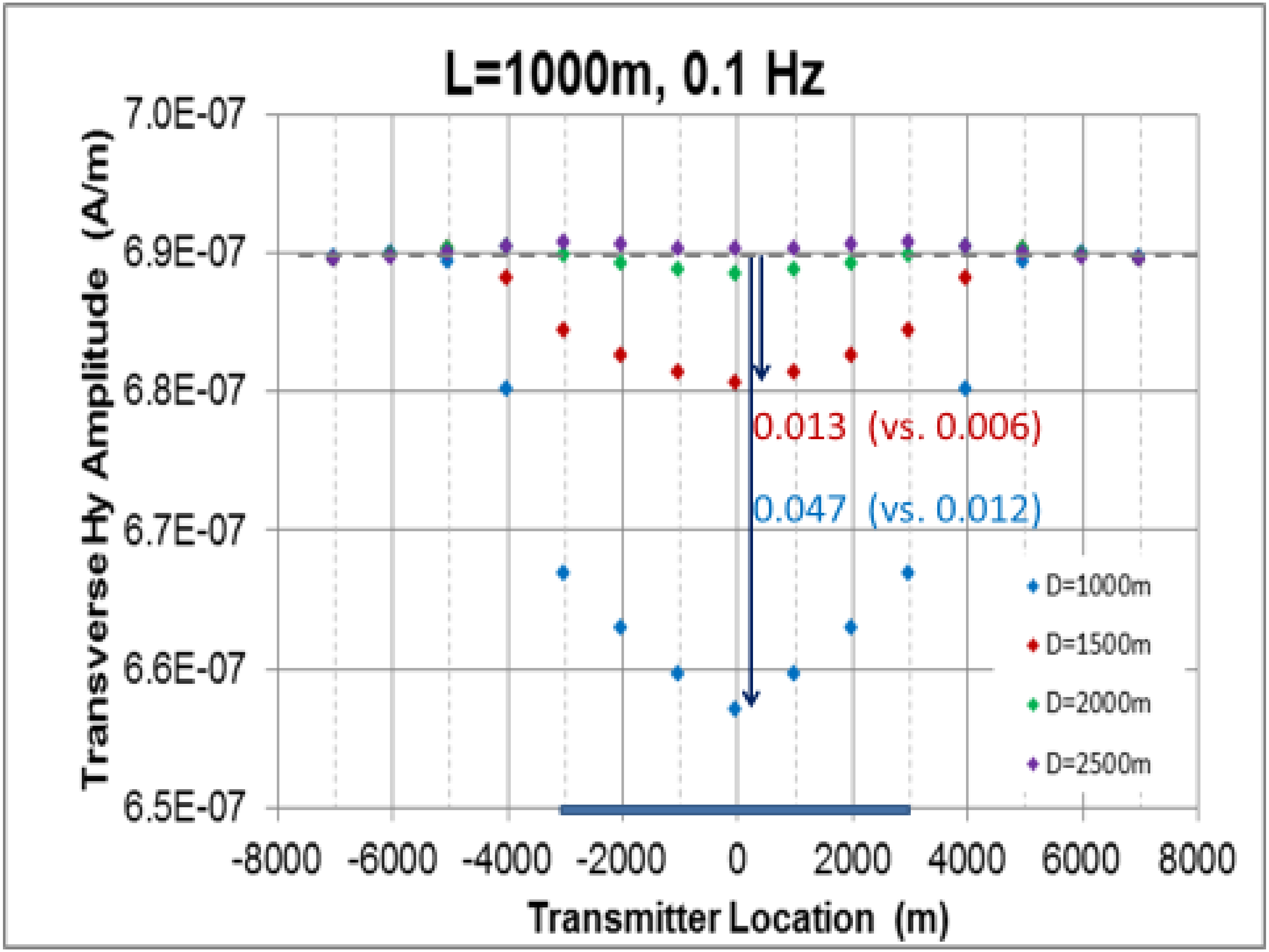

Figure 6b. Transverse H_y amplitude for L=1000 m at 0.1Hz.

	L=300m	0.1 Hz					
	Ex (1e-8 V/m)	difference	Sensitivity	Hy (1e-6 A/m)	difference	Sensitivity	Hy advantage
D=1000m	4.26707	-0.00436	0.00102	8.00192	-0.06178	0.00766	7.51
D=1500m	4.27032	-0.00111	0.00026	8.05317	-0.01053	0.00131	5.03
D=2000m	4.27119	-0.00024	0.00006	8.06392			

	L=1000m	0.1 Hz					
	Ex (1e-9 V/m)	difference	Sensitivity	Hy (1e-7 A/m)	difference	Sensitivity	Hy advantage
D=1000m	1.28391	-0.01646	0.01266	6.56993	-0.32566	0.04723	3.73
D=1500m	1.29301	-0.00736	0.00566	6.80622	-0.08937	0.01296	2.29
D=2000m	1.29805	-0.00232	0.00178	6.88551	-0.01008	0.00146	0.82

Table 1. Comparison of Transverse H_y amplitude and In-line Ex amplitude.