Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 11 (7): 1136-1142, 2011
ISSN 1812-5654 / DOI: 10.3923/jas.2011.1136.1142

1D EM Modeling for Onshore Hydrocarbon Detection using MATLAB

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Abstract: Controlled Source Electromagnetic (CSEM) is a new technique used for hydrocarbons detection. This study focuses on One dimension (1D) modeling of hydrocarbon detection for onshore application using the principles of electromagnetic (EM) waves propagation. The transmitted frequency which is 0.25 Hz was used to characterize the hydrocarbon at 500 m, 1000 m and 1500 m. Electric fields detected by the receivers at 500, 1000 and 1500 m were 22.85, 20.4 and 17.1 V m^{-1}, respectively which was determined by using 1D simulation. This non-seismic 1D modeling may provide alternative solution for hydrocarbon (HC) detection for oil and gas industry.

Key words: Electromagnetic, 1-D modeling, hydrocarbons, electric field strength

INTRODUCTION

Acoustic waves in seismic sounding have importance due to mapping of different layers with distinct acoustic properties. Seismic data can provide detailed information about layering structure but is not compatible for direct detection of pore fluid reservoir. Detection of subsurface hydrocarbons by an active source electromagnetic (EM) application, termed as Seabed Logging (SBL), has been fully demonstrated (Kong *et al*., 2002). Sea bed logging which is the application of CSEM (Controlled Source electromagnetic) has many advantages over other techniques for the detection of hydrocarbons. Most of the authors used MCSEM (Marine Controlled Source electromagnetic) surveys in sea bed logging for the detection of hydrocarbons (Ellingsrud *et al*., 2002; Hesthammer and Boulaenko, 2005; Eidesmo *et al*., 2002; Carazzone *et al*., 2005). Electromagnetic methods detect hydrocarbons due to contrast between higher resistivity structures of hydrocarbons and higher conductivity of salt around the hydrocarbon. It has been reported by Cox *et al.* (1986) that conductivities of hydrocarbons are 0.01 and 0.1 S m^{-1} or higher in depth of 50 to 150 km, where as transverse resistance of hydrocarbon detected by Transverse Magnetic (TM) mode in Controlled Source electromagnet (CSEM) is -109 ohm-m reported by Mackie *et al.* (1988) and Ulaby (2005). In EM methods, increase in the strength of electromagnetic return signals are caused by the reflection and refraction of EM energy from high resistivity hydrocarbons which is situated approximately 1000 m below the seabed. Onshore hydrocarbons detection by using EM methods was discussed by authors (Sheard *et al*., 2005; Ziolkowski *et al*., 2002). They reported that hydrocarbons can be detected by using 1-D, 2-D and 3-D simulations, also by mapping different layers. EM methods were also used in base metal industry (Sheard *et al*., 2005).

The aim of this paper is to simulate the EM wave propagation for hydrocarbon detection of onshore applications in one dimension (1D) using MATLAB software. Some electromagnetic principles were used to attain the expected results on hydrocarbon detection. The schematic diagram of hydrocarbon detection is shown in Fig. 1.

Theoretical background: The electromagnetic waves have many characteristics such as attenuation, propagation, refraction and reflection etc. The EM wave parameters have importance in order to simulate the propagation phenomenon. The electromagnetic waves in free space can be derived from Maxwell's relations, which are:

$$\nabla^2 \overline{E} = -\omega^2 \mu_o \varepsilon_o \overline{E} \tag{1}$$

$$\nabla^2 \overline{E} = \gamma^2 \overline{E} \tag{2}$$

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Where:
γ = Propagation constant, β = Phase shift constant,
α = Attenuation constant, v = Velocity of propagations
λ = Wavelength, η = Intrinsic impedance and
σ = Conductivity

Propagation characteristics: The Propagation constant, γ (m^{-1}) is

$$\gamma = \sqrt{-\omega^2 \mu_o \varepsilon_o \overline{E}} \tag{3}$$

$$= j\beta \; j\omega\sqrt{\varepsilon_o \mu_o} \tag{4}$$

Where:

$$\beta = \omega\sqrt{\mu_o \varepsilon_o} \tag{5}$$

Similarly, propagations characteristics of electromagnetic waves equations in conducting medium are

$$\nabla^2 E - \gamma^2 E = 0 \tag{6}$$

And propagation constant γ (m^{-1}) for wave equations in conducting media is

$$\begin{aligned} \gamma &= \sqrt{j\omega\mu\sigma + (-\omega^2\mu\varepsilon)} \\ &= \sqrt{-\omega^2\mu\varepsilon + j\omega\mu\sigma} \\ &= \alpha + j\beta \end{aligned} \tag{7}$$

Skin depth: Skin Depth is a measure of the distance an alternating current can penetrate beneath the surface of a conductor. This principle can be used to calculate the frequency of EM waves using the Eq. 8:

$$\delta = \sqrt{\frac{2}{\sigma\mu\omega}} \tag{8}$$

δ is skin depth (meter), σ is the conductivity of the propagation medium, μ is the permeability of the propagation medium and ω is the angular frequency of the wave. Since $\omega = 2\pi f$ we can calculate the required frequency f by using equation:

$$f = \frac{1}{\pi\sigma\mu\delta^2} \tag{9}$$

Snell's law: Snell's law gives the relationship between angles of incidence and refraction for a wave impinging on an interface between two media with different indices of refraction. For a wave going from a medium with index

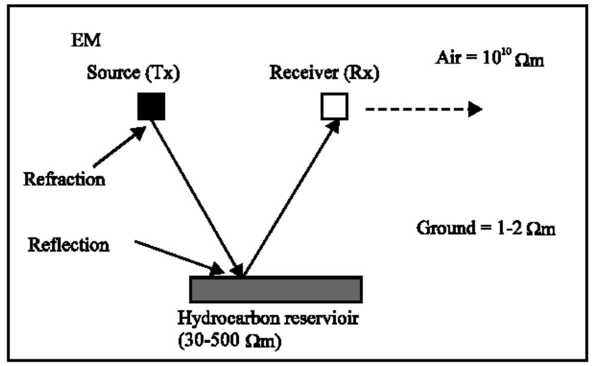

Fig. 1: Schematic diagram of hydrocarbon detection

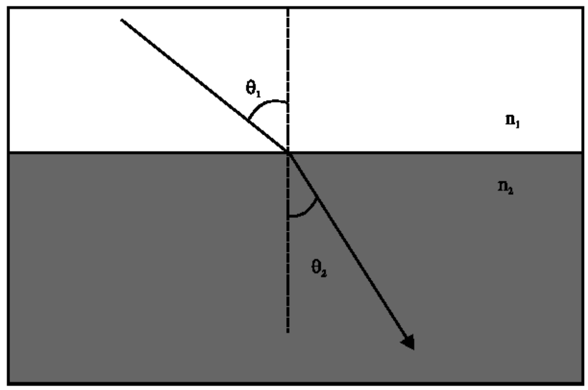

Fig. 2: Snell's Law

of refraction, n_1 to another with index of refraction, n_2 and angles of incidence and refractions, θ_1 and θ_2 respectively, as shown in Fig. 2, Snell's law states that

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{10}$$

Fresnel reflection and transmission coefficient: Fresnel's equations describe the reflection and transmission of electromagnetic waves at an interface, which gives the reflection and transmission coefficients for waves parallel and perpendicular to the plane of incidence. For a dielectric medium where Snell's Law can be used to relate the incident and transmitted angles, Fresnel's Equations can be stated in terms of the angles of incidence and transmission. Figure 3 shows the transmission of EM waves from Medium 1 to 2 of indices of refractions, n_1 and n_2 with angles of incident, reflection and transmission, θ_i θ_r and θ_t respectively.

The reflection coefficient (Γ):

$$\Gamma_{\parallel} = \frac{E^r}{E^i} = \frac{\eta_2\cos\theta_t - \eta_1\cos\theta_i}{\eta_2\cos\theta_t + \eta_1\cos\theta_i} \tag{11}$$

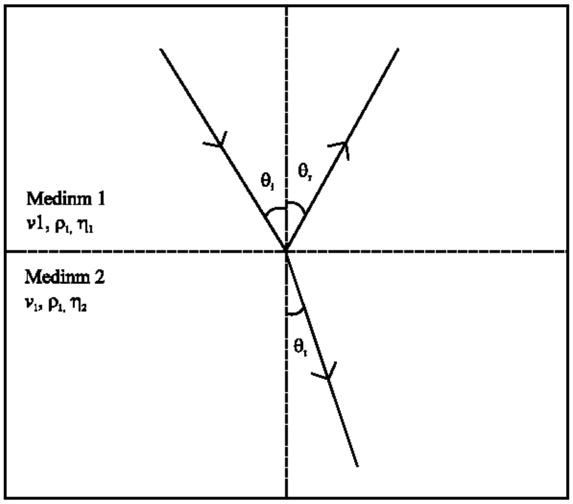

Fig. 3: Fresnel reflection and transmission diagram

And the transmission Coefficient, τ:

$$\tau_{\parallel} = \frac{E^t}{E^i} = \frac{2\eta_2 \cos\theta_i}{\eta_2 \cos\theta_t + \eta_1 \cos\theta_i} \qquad (12)$$

Electromagnetic (EM) wave equation: The Electric field vector along the x-direction is:

$$E_x = \hat{x}E_0^+ e^{-\alpha z} e^{-j\beta z} \qquad (13)$$

$$\alpha = \omega\sqrt{\mu\varepsilon}\left[\frac{1}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)\right]^{1/2} \qquad (14)$$

$$\beta = \omega\sqrt{\mu\varepsilon}\left[\frac{1}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1\right)\right]^{1/2} \qquad (15)$$

where, α is the attenuation constant and, β is the phase constant.

Intrinsic impedance:

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} \qquad (16)$$

Where:

μ = Permeability (H/m) [$\mu = \mu_r\mu_o$],
ϵ = Permittivity (F/m)
[$\epsilon = \epsilon_r\epsilon_o$], σ = Conductivity (S m^{-1}), ω = Angular freq. (rad see^{-1})

METHODOLOGY

1D simulation for electromagnetic waves for the detection of hydrocarbons was done by using MATLAB software. Transmitter with 0.25 Hz frequency and transmitting power of 100 V m^{-1} was used for the transmission of electromagnetic waves. The medium of electromagnetic waves propagation is isotropic and width of the hydrocarbon reservoir is 1000 m. The constant values used during the simulation modeling are given in Table 1. The vertical distance, h from ground surface to subsurface HC were varies with 500, 1000 and 1500 m, where as thickness of the subsurface hydrocarbon was 200 m as shown in Fig. 4.

RESULTS AND DISCUSSION

A set of EM wave equations in the form of incident, reflection and transmission are given as follows:

$$E_1(z) = \hat{x}E_0^+ e^{-\alpha z1} e^{-j\beta z1} \qquad (17)$$

$$E_2(z) = \Gamma_1 E_1 \qquad (18)$$

$$E_3(z) = \hat{x}E_0^+ e^{-\alpha z2} e^{-j\beta z2} \qquad (19)$$

$$E_4(z) = \tau_1 E_3 \qquad (20)$$

$$E_5(z) = \Gamma_2 E_4 \qquad (21)$$

$$E_6(z) = \tau_2 E_1 \qquad (22)$$

$$E_7(z) = \hat{x}E_0^+ e^{-\alpha z4} e^{-j\beta z4} \qquad (23)$$

$$E_8(z) = \tau_3 E_7 \qquad (24)$$

$$E_9(z) = \tau_4 E_8 \qquad (25)$$

$$E_{10}(z) = \Gamma_3 E_9 \qquad (26)$$

$$E_{11}(z) = \tau_5 E_{10} \qquad (27)$$

$$E_{12}(z) = \tau_6 E_{11} \qquad (28)$$

The total electric field reaching the receiver can be calculated by following equations

$$E_T = E_2 + E_6 + E_{12} \ (V\ m^{-1}) \qquad (29)$$

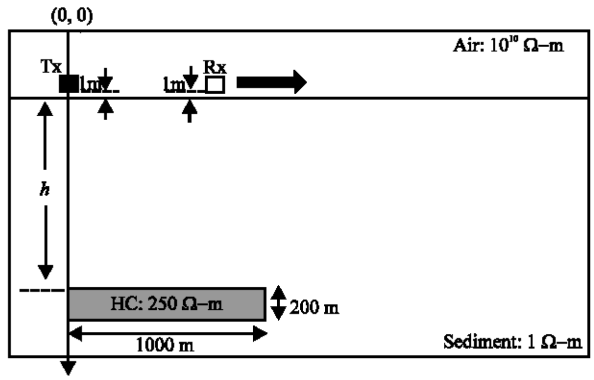

Fig. 4: Schematic diagram of hydrocarbon detection

Table 1: Constant values

	ε_r	μ_r	δ	ρ
Air	1	1	10^{-10}	10^{10}
Ground	3	1	1	1
HC	1	1	0.01	250

ε_r = Relative permittivity (F/m), μ_r = Relative permeability (H/m), δ = Conductivity (S m^{-1}), ρ = Resistivity (Om)

By applying fixed point iteration method on roots of equations, the solution of the electric field EM waves equations are given here in terms of ' f ' and 'j' with relative error of 0.05%.

$$f = b\tan\left[\sin^{-1}\left(\frac{\beta_1}{\beta_2}\sin\left[\tan^{-1}\left(\frac{e-f}{d-b}\right)\right]\right)\right]+a \quad (30)$$

$$j=\left\{\left[\tan\left[\sin^{-1}\left(\frac{\beta_1}{\beta_2}\left[\sin\left[\tan^{-1}\left(\frac{h-a}{b}\right)\right]\right]\right)\right]\right](d-b)\right\}+h \quad (31)$$

The simulated results were compared by detecting EM waves at the receiver. The results were obtained by the separation distance between the transmitter and receiver and electric field detected by the receiver. Figure 5, 6, 7 and 8 show the reflected, refracted and guided EM waves respectively and Fig. 9 shows the combination of the EM waves behavior for onshore hydrocarbon detection depth of 500, 1000 and 1500 m, the waves reflected from the target, hydrocarbon and guided from the hydrocarbon and then reflected back towards receiver are shown in Fig. 10, 12 and 14, respectively. From these figures, it can also be seen that as the depth increases, values of electric field detected by receiver decreases and very small values of electric field were detected for the waves reflected after being guided from the hydrocarbon. Resultant electric field response detected by the receiver at depth of 500, 1000 and 1500 m are shown in Fig. 11, 13 and 15, respectively. Table 2 shows the magnitude of electric field response by the receiver for reflected wave from ground, hydrocarbon

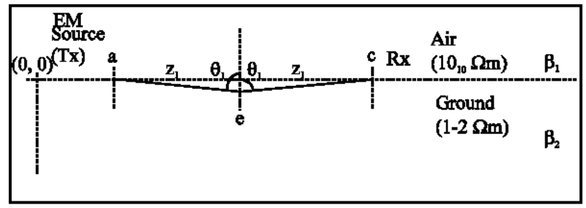

Fig. 5: Reflected wave from surface of earth

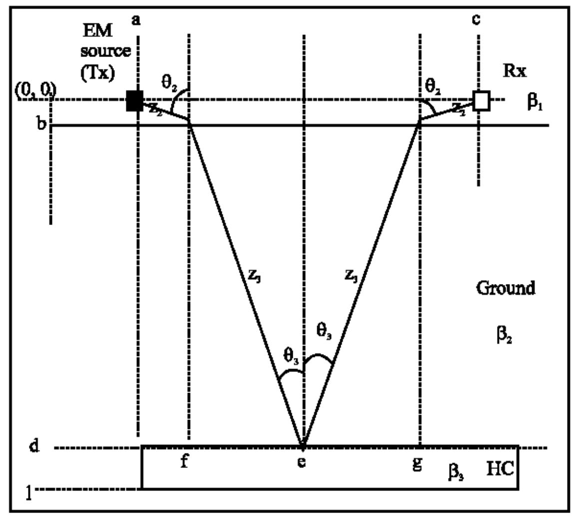

Fig. 6: Reflected wave from hydrocarbon

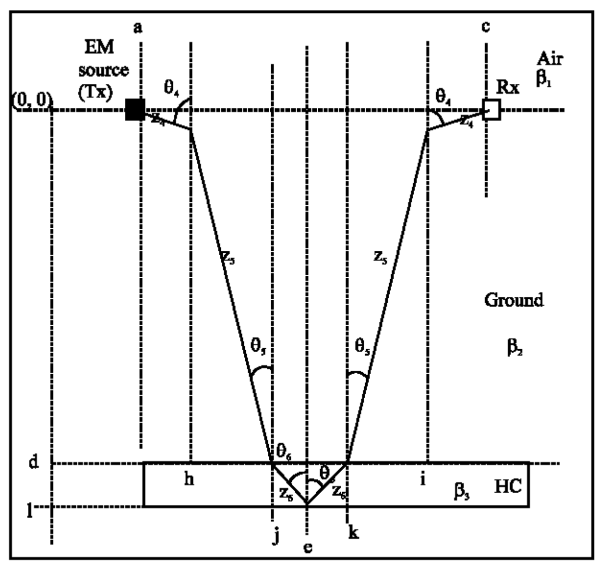

Fig. 7: Guided wave in hydrocarbon

and guided wave from hydrocarbon. It has also been observed that the resultant electric field decreases as the depth increases from the target. With no depth

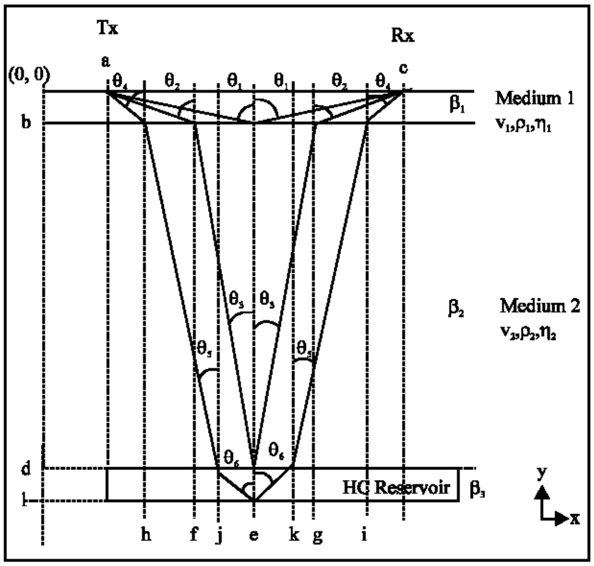

Fig. 8: Reflection and refraction diagram

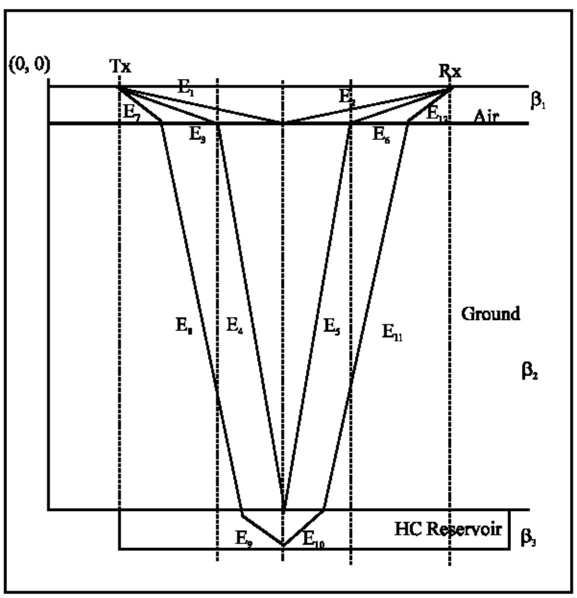

Fig. 9: Total electric field at receivers

Table 2: Magnitude of electric field for reflected wave from ground, hydrocarbon and guided wave from hydrocarbon

At depth	Reflected wave from ground (V m^{-1})	Reflected wave from hydrocarbon (V m^{-1})	Guided wave from hydrocarbon (V m^{-1})	Total electric field response (V m^{-1})
500 m	14.5	7.0	1.35	22.85
1000 m	14.5	4.9	1.00	20.40
1500 m	14.5	2.1	0.50	17.10

consideration, the graph shows the reflected wave from the surface of seabed is due to the distance between

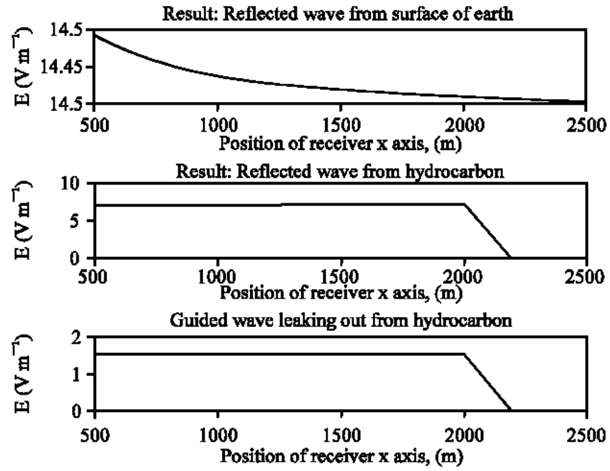

Fig. 10: Comparison results (h = 500 m)

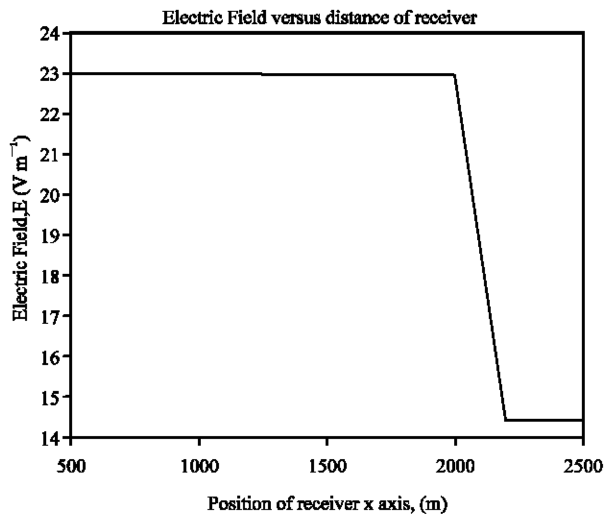

Fig. 11: Total electric field at receivers (h = 500 m)

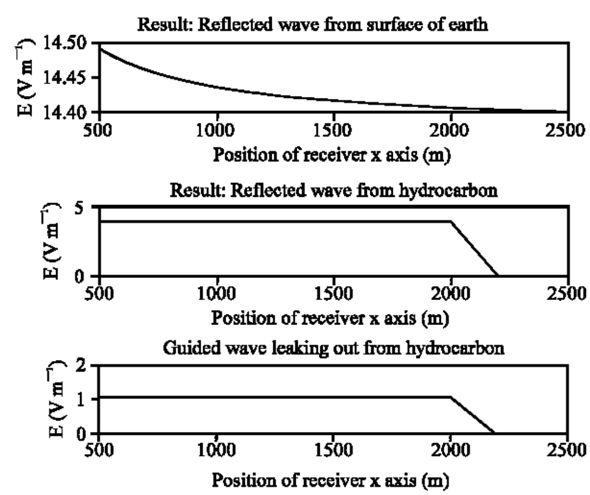

Fig. 12: Comparison results (h = 1000 m)

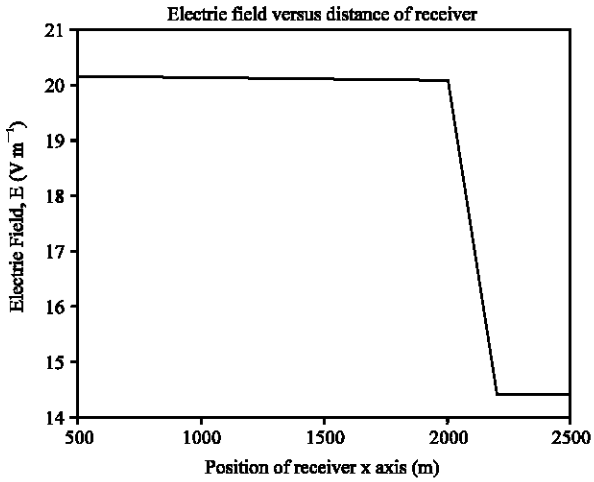

Fig. 13: Total electric field at receivers (h = 1000 m)

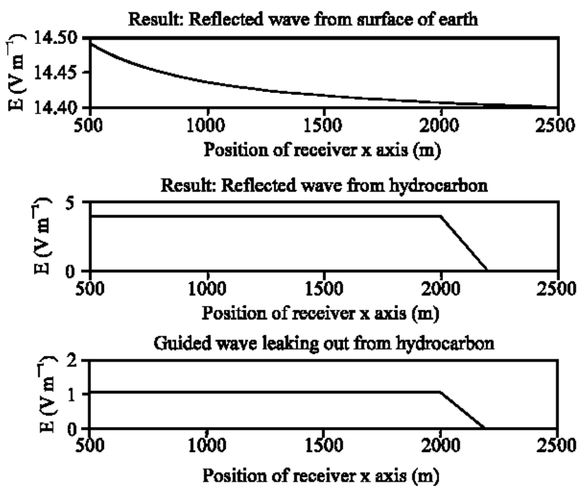

Fig. 14: Comparison results (h = 1500 m)

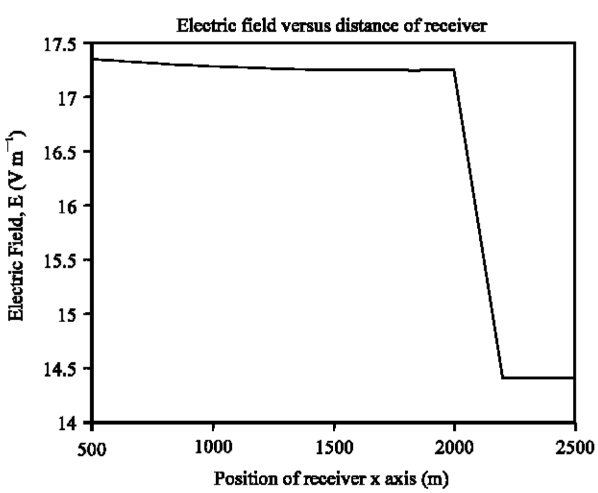

Fig. 15: Total electric field at receivers (h = 1500 m)

transmitter and receiver. This shows that the receiver has not received or detected signal that propagates and reflected from the hydrocarbon above 2000 m.

CONCLUSION

1-D modeling of onshore hydrocarbon detection by electromagnetic waves was done by using MATLAB software. The simulating results were obtained at very low transmitting frequency of 0.25 Hz and power of 100 V m^{-1}. It was concluded that the total electric field detected by the receiver decreases as the depth increases from the position of the EM transmitter. The increased return signal is due to reflection and refraction of electromagnetic energy by the high resistivity of hydrocarbon at 500, 1000 and 1500 m. It was also calculated that as the depth increases from 500 to 1000 and 1500 m, electric field value detected by the receiver decreases, 22.85, 20.4 and 17.1 V m^{-1}, respectively. This is reduction by 10.72 and 25.16% for the lower offset. These fundamental simulations give and indication of the depth of hydrocarbon for onshore application.

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