Visualization of Sediment Thickness Variation for Sea Bed Logging using Spline Interpolation

Hanita Daud , Noorhana Yahya , Vijanth Sagayan , and Muizuddin Talib .

Abstract—This paper discusses on the use of Spline Interpolation and Mean Square Error (MSE) as tools to process data acquired from the developed simulator that shall replicate sea bed logging environment. Sea bed logging (SBL) is a new technique that uses marine controlled source electromagnetic (CSEM) sounding technique and is proven to be very successful in detecting and characterizing hydrocarbon reservoirs in deep water area by using resistivity contrasts. It uses very low frequency of 0.1Hz to 10 Hz to obtain greater wavelength. In this work the in house built simulator was used and was provided with predefined parameters and the transmitted frequency was varied for sediment thickness of 1000m to 4000m for environment with and without hydrocarbon. From series of simulations, synthetics data were generated. These data were interpolated using Spline interpolation technique (degree of three) and mean square error (MSE) were calculated between original data and interpolated data. Comparisons were made by studying the trends and relationship between frequency and sediment thickness based on the MSE calculated. It was found that the MSE was on increasing trends in the set up that has the presence of hydrocarbon in the setting than the one without. The MSE was also on decreasing trends as sediment thickness was increased and with higher transmitted frequency.

Keywords—Spline Interpolation, Mean Square Error, Sea Bed Logging, Controlled Source Electromagnetic

I. Introduction

THE use of controlled source electromagnetic (CSEM) method in hydrocarbon exploration has gained tremendous interest to oil and gas exploration companies and is called sea bed logging (SBL). This technique is based on resistivity contrasts due to the fact that hydrocarbon reservoir is known to have high resistivity while saline water formations are very conductive. This technique was introduced by [1-2] and since then the concept has been embraced with enthusiasm by the exploration industry, mainly as a tool for assessing the resistivity of targets identified by seismic surveys prior to drilling [3]. SBL technique is as depicted in Figure 1 [4]. It uses horizontal electric dipole (HED) which is towed about 30m above the sea floor by the vessel. The transmitter emits a low frequency electromagnetic (EM) signal that couples with the surrounding water and then into the underlying seabed and downwards. Array of magnetic and electric receivers are placed at the predetermined locations.

This work was funded by the Malaysian Ministry of Higher Education (MOHE) under the Fundamental Research Grant Scheme (FGRS).

Hanita Daud is a senior lecturer in Fundamental and Applied Sciences Department with Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, MALAYSIA (*phone* : 605 − 3687844; *fax* : 605 − 3655905; *e − mail* : *hanita_daud@petronas.com.my*).

Noorhana Yahya is with Fundamental and Applied Sciences Department Universiti Teknologi PETRONAS.

V Sagayan and A M Talib are with Electrical and Electronics Engineering Department, Universiti Teknologi PETRONAS.

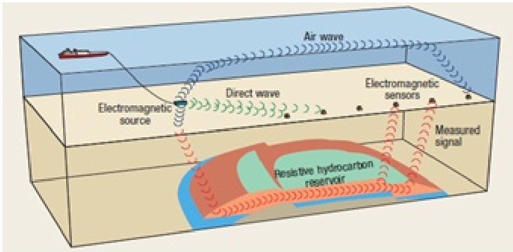

Fig. 1. Sea Bed Logging Environment [4]

The overburden sediments are effectively partial conductors, the penetration of EM field is limited by skin depth particularly with high frequency fields. In practice, this means that a low frequency EM signal must be generated typically between 0.25 to 10Hz to allow penetration to 2,500 to 3,000 m into the subsurface [4]. If position of hydrocarbon is deeper than 3000m, frequency of lower than 0.25Hz is required. The transmitter is towed 10km before the first receiver and ends about 10km after the last receiver. This ensures that all receivers have active source data with source-receiver offsets of 10km [5]. When the source-receiver distance is larger than reservoir depth, energy from the resistive layer will dominate the directly transmitted energy. Therefore, the direct energy transmitted through seawater dominates the recordings only at short source-receiver offsets. The air-wave (down going field) dominance depends on the source frequency, seawater depth, seawater and subsurface resistivity distribution, and source-receiver distances. In high-resistivity subsurface layers (20 to 1000 Ωm), EM energy propagates at a higher velocity as guided waves with less attenuation and is transmitted back (up going field) to the receivers at the seafloor. The up going field from a high resistivity subsurface layer will dominate over directly transmitted energy, when the source-receiver offset is comparable to or greater than approximately twice the depth to this layer from the seafloor [6]. Detection of this anomalous dispersion energy is the basis of SBL as depicted in Figure1.

In dealing with the EM signal collected, numerical techniques are often used to investigate initial information on the quantity and location of hydrocarbon reservoir. The most common ones are Finite element method (FEM), Finite difference method (FDM), Transmission line matrix (TLM) method, Method of moment (MOM), Boundary element method (BEM) and etc [7]. These techniques involve complicated mathematical procedures therefore require good computing facility. In this paper, authors are discussing on the use of numerical technique called Spline Interpolation with mean square error to distinguish signals that contain hydrocarbon information than the one that has none. Spline interpolation does not require high end computing facility and having simple mathematical procedures. Synthetics data are generated from simulator by varying sediments thickness and at frequency of 1Hz, 0.25Hz and 0.125Hz.

II. Theoretical Background

A. Sea Bed Logging

Seabed logging is using an active electromagnetic (EM) sounding technique in detecting subsurface hydrocarbon by transmitting low frequency EM waves (typically 0.01 to 10Hz). From [8], the receivers record the EM responses as a combination of energy pathways including signal transmitted directly through seawater, reflection and refraction via the sea-water interface, refraction and reflection along the sea bed and reflection and refraction via possible high resistivity subsurface layers.

B. Low Frequency EM Waves

From [6] the propagation (α) and attenuation (β) constants in conductive medium for frequencies below 10^5 Hz are defined as

$$\alpha = \beta = \sqrt{\frac{\omega\mu\sigma}{2}} \tag{1}$$

where ω, μ and σ represent angular frequency, magnetic permeability and conductivity, respectively. Due to non magnetic rocks in sedimentary basins then $\mu = \mu_0$ (magnetic permeability in free-space). Due to this, in the case of fixed geometry, EM energy attenuation depends only on frequency, conductivity and source-receiver distance. The rate of attenuation of a diffusing EM wave in a conductive medium is often described in terms of plane-wave skin depth given as in (2).

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

Where ω is the angular frequency, σ is the conductivity of the medium in which EM waves propagate and μ_0 the permeability of free space of value 4π x $10^{-7} H/m$ [9]. Skin depth is defined as the distance at which an EM plane wave will be attenuated to 1/e of its original value. In conductive media at low frequency, the skin depth is related to the wavelength via (3).

$$\lambda = 2\pi\delta \tag{3}$$

Skin depth shows how far the EM wave penetrates into the medium. It is large for high resistive medium and has less attenuation compared to low resistive medium. Similarly if the skin depth is shorter the response of electric or magnetic field is decreased. In SBL the low frequency is used to get less attenuation and more skin depth to get the response of electric or magnetic field from high resistive medium [10].

Reflection is when waves, whether physical or electromagnetic, bounce from a surface back toward the source. A mirror reflects the image of the observer. Whereas Refraction is when waves, whether physical or electromagnetic, are deflected when the waves go through a substance. The wave generally changes the angle of its general direction [11].

C. Simulator

In the last fifty years computer modeling and simulation has dominated the study of hydrocarbon reservoirs behavior especially in SBL application in deep water environment. The common one is a simulator which requires some foundation knowledge on mathematics and programming and good knowledge on electromagnetic behavior on the reservoir. The developed simulator shall be used as a platform to conduct simulation work based on determined physical aspects and behavior of the reservoir to achieve certain objectives. Synthetics data shall be generated from this simulator. A good simulator should produce results that match earlier production and other reservoir parameters called history matching. The developed physical models shall also be used to study certain phenomenon such as effect of airwave, sediment thickness, sea water levels and etc. [8],[12]. In this paper simulator developed by [13] is used to generate the synthetics data developed using MATLAB GUI and programming. The environment is assumed to be free from external disturbances, no bathymetry effect, no various shapes of hydrocarbon reservoirs as well as other aspects which we may find in real sea bed.

D. Spline Interpolation

A spline function consists of polynomial pieces on subintervals joined together with certain continuity conditions. Suppose points, $x_1, x_2, x_3, ..., x_n$ have been specified and satisfy $x_1 < x_2 < x_3........ < x_n$. These points are called knots and suppose also that an integer $k > 0$ has been prescribed. A spline function of degree k having knots $x_1, x_2, x_3, ..., x_n$ is a function S such that

a. On each interval $[x_{i-1}, x_i]$ is a polynomial of degree $\leq k$

b. S has a continuous k st derivative on $[x_i, x_n]$.

A spline of degree 0 is piecewise constants, a spline of degree 1 is a linear function, a spline of degree 2 is quadratic and a cubic spline is of degree 3. The essential idea of a spline is to provide a cubic equation connecting any two adjacent data points or to fit piecewise function of the form

$$S(x) = \begin{cases} S_o(x) & x \in [x_0, x_1] \\ S_1(x) & x \in [x_1, x_2] \\ .... & .... \\ S_{n-1}(x) & x \in [x_{n-1}, x_n] \end{cases} \tag{4}$$

where S_i is a third degree polynomial defined by

$$S_i(x) = a_i(x - x_i)^3 + b_i(x - x_i)^2 + c_i(x - x_i) + d_i \tag{5}$$

and the first and second derivatives of these equations are the fundamental to this process and as shown in (6) and (7) below.

$$S_i^{'}(x) = 3a_i(x - x_i)^2 + 2b_i(x - x_i) + c_i \tag{6}$$

$$S_i(x) = 6a_i(x - x_i) + 2b_i \tag{7}$$

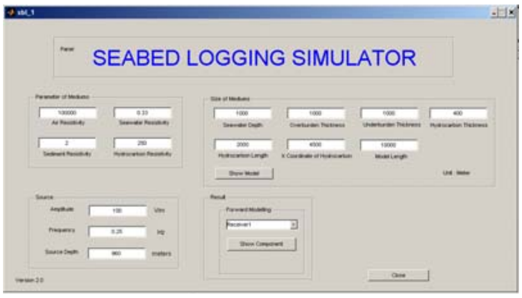

Fig. 2. Developed SBL Simulator

for $i = 1, 2, ..., n - 1$. Spline interpolation is not a new technique in signal/image processing and data visualization techniques. It provides a unifying framework for linking the continuous and discrete domains. It is well understood theoretically and is ideally suited for performing numerical computations [15]. This makes it a perfect tool for solving a whole variety of signal and image processing (or pattern recognition) problems that are best formulated in the continuous domain but call for a discrete solution [16-19].

E. Mean Square Error

In statistics, the mean square error or MSE of an estimator is one of many ways to quantify the difference between an estimator and the true value of the quantity being estimated or the difference between the forecasts and observations. MSE is a risk function, corresponding to the expected value of the squared error loss or quadratic loss. MSE measures the average of the square of the "error." The error is the amount by which the estimator differs from the quantity to be estimated. The difference occurs because of randomness or because the estimator doesn't account for information that could produce a more accurate estimate [20]. The MSE of an estimator $\hat{\theta}$ with respect to the estimated parameter θ is defined as

$$MSE(\hat{\theta}) = E[(\hat{\theta} - \theta)^2]. \qquad (8)$$

III. Methodology

Simulator from [13] is depicted as in Figure 2 is used to generate synthetics data for this work. Many assumptions are being made while conducting this simulation as mentioned in the previous section. This simulator shall be used for hydrocarbon mapping and to generate electromagnetic waves components. Hydrocarbon reservoir can be positioned at any desired location with any length, thickness and suitable x coordinate position. Sea water depth, sediments and hydrocarbon thickness as well as model length can be set in this simulator. Source is where the transmitter is placed above the sea bed. There are 11 receivers with first receiver is placed at origin (position 0m) and they are separated by 1km apart. These receivers shall receive combination of EM waves or energy. Table 1 tabulated all the parameters used and supplied to the simulator for this work.

The simulation started with no hydrocarbon and continued with hydrocarbon positioned at 4500m from the first receiver

TABLE I
Parameters Used in Variation of Overburden/Sediment Thickness

Parameters	Value
Seawater Depth	1000 m
Sediment Thickness	Varied
Hydrocarbon Thickness	400 m
Sea Water Resistivity	$0.33\Omega m$
Sediment Resistivity	$2\Omega m$
Hydrocarbon Resistivity	$250\Omega m$
Hydrocarbon Length	2000 m
X Coordinate of HC	4500 m
Amplitude	100 V / m
Frequency	1Hz / 0.25Hz/ 0.125Hz
Focus Receiver	Receiver 7

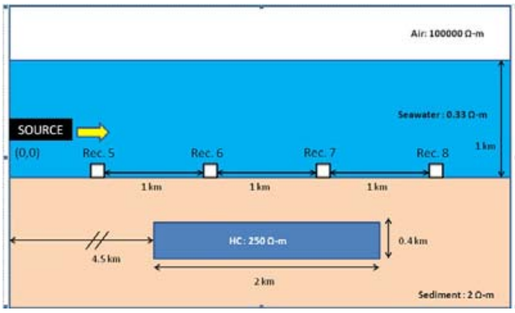

Fig. 3. Plane Layer Model of Sea Bed Logging

(the origin) with 2000m length. This means that the hydrocarbon is located directly underneath of receiver 6 and receiver 7. Sediment or overburden thickness is varied gradually from 1000m to 4000m, which indicates that hydrocarbon locations are also varied accordingly. Three frequencies are used in the simulations, 1Hz, 0.25Hz and 0.125Hz. Figure 3 shows the plane layer model of the sea bed logging environment used for this work.

These simulations and spline interpolation and MSE calculations are performed using minimum specification desk top computer that has low computing power.

IV. Results and Discusions

Simulations were carried out based on parameters and set up discussed in the previous section. Synthetics data were generated from the simulations with variation of sediment thickness at three different frequencies. These synthetics data were interpolated and mean square errors were calculated between original and interpolated data. Table 2, Table 3 and Table 4 show the MSE calculated for signals that have hydrocarbon and signals with no hydrocarbon at frequency of 1Hz, 0.25Hz and 0.125Hz respectively.

From the results obtained in Table 2, Table 3 and Table 4, the MSE calculated are on decreasing trends as the sediment thickness are increased for all the three frequencies. From eqn. (3) wavelength is inversely proportional to the transmitted frequency, therefore at 1kHz, the maximum distance the EM waves can penetrate is 1km, at 0.5Hz the maximum distance is 2km and at 0.125Hz the maximum distance is 8km. Due to this at frequency of 1Hz, as sediment thickness is increased to more

Table2: MSE for Variation of Overburden at 1.0Hz Frequency

Frequency Used	Overburden Thickness (m)	MSE of Spline Interpolated EM Waves		% MSE Difference
		No HC	With HC	
1.0Hz	1000	1.25E-03	1.73E-02	92.77
	1500	1.25E-03	2.43E-03	48.41
	2000	1.25E-03	1.44E-03	12.97
	2500	1.25E-03	1.28E-03	1.93
	3000	1.25E-03	1.25E-03	0.18
	3500	1.25E-03	1.25E-03	0.12
	4000	1.25E-03	1.25E-03	0

Table3: MSE for Variation of Overburden at 0.5 Hz Frequency

Frequency Used	Overburden Thickness (m)	MSE of Spline Interpolated EM Waves		% MSE Difference
		No HC	With HC	
0.5Hz	1000	5.64E-04	1.24E-01	99.55
	1500	5.64E-04	2.63E-02	97.85
	2000	5.64E-04	2.21E-03	74.42
	2500	5.64E-04	9.26E-04	39.08
	3000	5.64E-04	5.72E-04	1.3
	3500	5.64E-04	5.65E-04	0.16
	4000	5.64E-04	5.64E-04	0.03

than 1500m, the percentage of MSE difference is becoming smaller and at 2500m onwards they become insignificant. At frequency of 0.5Hz, percentage of MSE different becomes smaller at sediment thickness of 2500m and become insignificant as sediment thickness is 3000m and above. For frequency of 0.125Hz, percentage of MSE difference is still significant even at 4000m sediment thickness. Also observed here in Table 2, Table 3 and Table 4 are that when there is no hydrocarbon in the set up, the percentages of MSE are consistent for all sediment thickness. It means that the MSE readings remain the same as sediment thicknesses are increased gradually for all the three frequencies with no hydrocarbon in the set up.

These percentages of MSE difference can be well observed in graph as in Figure 4. At frequency of 0.125Hz the percentage of MSE different is decreasing minimally as sediment thickness is reaching 4000m. For frequency of 1.0Hz the reading or the percentage of MSE drops significantly at 2000m and becomes almost non existence for sediment thickness of above 2000m. For frequency of 0.5Hz the reading or the percentage of MSE decreasing minimally from 1000m to 2500m and becomes non existence for sediment thickness of 3000m and above.

MSE results obtained after Spline interpolations were applied to the data that have hydrocarbon and to the data that have no hydrocarbon have shown very high percentage different among them. These findings were very impressive and gave good indication on the suitability of Spline interpolation and MSE in processing the CSEM data. Other impressive findings were all the Spline interpolation and MSE calculations and simulations were conducted with very minimum time even though low computer specifications were used. Each simulation and computation was performed in few seconds only.

Table4: MSE for Variation of Overburden at 0.125Hz Frequency

Frequency Used	Overburden Thickness (m)	MSE of Spline Interpolated EM Waves		% MSE Difference
		No HC	With HC	
0.125 Hz	1000	6.08E-05	1.10E+00	99.99
	1500	6.08E-05	6.16E-01	99.99
	2000	6.08E-05	6.67E-02	99.91
	2500	6.08E-05	4.02E-02	99.85
	3000	6.08E-05	8.75E-03	99.31
	3500	6.08E-05	1.48E-03	95.88
	4000	6.08E-05	4.76E-04	87.22

Table4: MSE for Variation of Overburden at 0.125Hz Frequency

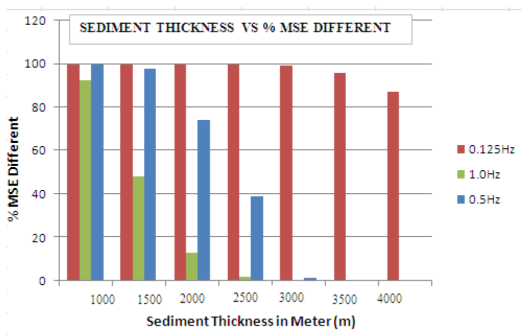

Figure 4: Percentage of MSE Difference for sediment thickness variation at frequency of 0.125Hz, 1.0Hz and 0.5Hz respectively

V. Conclusion

The significance of this work is demonstrating use of Spline interpolation technique with mean square error (MSE) in distinguishing data that have information on hydrocarbon to the data that no hydrocarbon. Combinations of these two techniques have produced impressive results/findings and have shown that at higher frequency the skin depth or wave penetration is lower than the lower frequency. The most important thing here was all the computations were conducted on lower specification computer facility and each computation was conducted in very short time. With these findings, geophysicists shall consider a suitable frequency that is suitable for the target depth that they are looking for and to minimize the resources and cost in conducting the survey and processing the acquired data.

ACKNOWLEDGMENT

The authors would like to acknowledge Malaysian Ministry of Higher Education Malaysia (MOHE) for funding this research work under Fundamental Research Grant Scheme (FRGS UTP Ref. no 15/8200/102).

REFERENCES

[1] E. N. Kong, H. Westerdhal. Seabed Logging: A possible direct hydrocarbon for deepsea prospects using EM energy. Oslo :Oil Gas Journal, 2002. - May 13, 2002 edition.
[2] T. Eidesmo, et al. Sea Bed Logging (SBL), A New Method for Remote and Direct Identification of Hydrocarbon Filled Layers in Deepwater Areas using Controlled Source Electromagnetic Sounding, Technical Article, First Break Volume 20, 2002, p. 144-152.
[3] S. Constable,, L.J.Srnka,An Introduction to Marine Controlled Source Electromagnetic Methods for Hydrocarbon Exploration, Geophysics 72, no 2, 2007,WA3-WA12
[4] Dirk Smit, Pal R. Wood, Experience is crucial to expanding CSEM use, World Oil, September 2006, pg 37-43.
[5] S. Ellingsrud, T. Eidesmo, M. C. Sinha, L.M. MacGregor, S. C. Constable. Remote Sensing of Hydrocarbon Layers by Sea Bed Logging (SBL): Results from a Cruise Offshore Angola, Leading Edge 20(10), 2002, pp 972-982.
[6] Anwar Bhuiyan, Tor wicklund, Stale Johansen, High Resistivity Anomalies at Modgunn Arch in the Norwegian Sea, Technical Article, first break volume 24, January 2006
[7] N.O. Sadiku, "Numerical methods in Electromagnetics", second edition, Mathew, Boca Raton London New York Washington, D.C. (2001).
[8] Cox, C.S. Constable, S.C., Chave, A.D, Webb S.C.Controlled-source Electromagnetic Sounding of the oceanic Lithosphere, Nature Magazine, 1986, 320, pp 52-54.
[9] Evan S Um, David L Alumbaugh, Marine CSEM Methods on the Physics of the Marine CSEM Method, Geophys. Res. Vol.72, No. 2, pp. 13 - 18, 2007.
[10] N Nasir, A Shafie, H Daud, H M Zaid, N Yahya, M N Akhtar, M Khasif, Magnitude Versus Offset (MVO) Study with EM Transmitter in Different Resistive Medium, Journal of Applied Sciences 11 (7), pp. 1309-1314, 2011
[11] Ulaby Fawwaz T. Electromagnetics for Engineers. New Jersey : Pearson Education, 2005.
[12] L.M.MacGregor, M.Tompkins, Imaging Hyrocarbon Reservoirs using Marine Controlled-Source Electromagnetic Sounding, in Offshore Technology Conference, 2-5May 2005, paper OTC 17163.
[13] Daud, H., Yahya, N., Asirvadam, V. Development of EM simulator for sea bed logging applications using MATLAB Indian Journal of Marine Sciences 40 (2), pp. 267-274, 2011
[14] Sky McKinley, Megan Levine, Cubic Spline Interpolation, available online at http://online.redwoods.cc.ca.us/instruct/darnold/laproj/Fall98/SkyMeg/Proj.PDF (Accessed on 30/08/2010)
[15] C. de Boor, A Practical Guide to Splines, 1978, Springer-verlag, New York.
[16] JM. Unser, Splines: A Perfect Fit for Signal and Image Processing, 1999, IEEE Signal Processing Magazine, Vol 16, pp 22-38
[17] Panayiotis Foteinopoulos, Cubic spline interpolation to develop contours of large reservoirs and evaluate area and volume, 2009, Journal of Advances in Engineering Software 40, pp 23-29.
[18] M Sarfaz, Malik Zawwar Hussain, Data visualization using rational spline interpolation, Journal of Computational and Applied Mathematics 189 (2006) pgp 513-525.
[19] JM. Unser, Splines and Wavelets: New Perspectives for Pattern Recognition, 2003, pp 244-248, Springer-Verlag Berlin Heidelberg.
[20] E.L. Lehmann; Casella, George (1998). Theory of Point Estimation (2nd ed.). New York: Springer