Article

UNDERWATER ACOUSTICS AND DEPTH UNCERTAINTIES IN THE TOPICS

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Abstract

Acoustic velocity is known to vary with temperature, depth and salinity (TDS). Calibration of acoustic systems is required at the beginning and end (and sometimes midway) of each hydrographic operation, in order to correct for these velocity variations. Estuarine waters in the tropics were investigated employing wide combinations of temperature, depth and salinity to verify the relationships between these parameters and the acoustic velocity. A maximum error in depth of 0.2m was obtained. Consequently, in the absence of other sources of errors, acoustic systems may need to be calibrated only once in the cause of a full day bathymetric survey operation in the tropics.

Résumé

L'on sait que la vitesse des ondes acoustiques varie en fonction de la température, de la profondeur et de la salinité (TDS). L'étalonnage de systèmes acoustiques est requise au début et à la fin (et parfois au milieu) de chaque opération hydrographique, afin de corriger ces variations de la vitesse. Les eaux d'estuaires dans les zones tropicales ont été ont fait l'objet d'investigations à l'aide d'une large combinaison de températures, de profondeurs et de salinité afin de vérifier la relation entre ces paramètres et la vitesse des ondes acoustiques. Une erreur maximum de profondeur de 0,2m a été obtenue. Par conséquent, en l'absence d'autres sources d'erreurs, les systèmes acoustiques peuvent devoir être étalonnés une fois seulement pour la cause d'une opération de levés bathymétriques d'une journée entière dans les zones tropicales.

Resumen

Se sabe que la velocidad acústica varía con la temperatura, la profundidad y la salinidad (TDS). Se requiere la calibración de los sistemas acústicos al principio y al final (y a veces a mitad de camino) de cada operación hidrográfica, para corregir estas variaciones de velocidad. Se estudiaron las aguas de las zonas de estuarios de los trópicos, empleando amplias combinaciones de temperatura, profundidad y salinidad para comprobar las relaciones entre estos parámetros y la velocidad acústica. Se obtuvo un error máximo de 0,2 m en la profundidad. Por consiguiente, en ausencia de otras fuentes de errores, los sistemas acústicos pueden necesitar ser calibrados sólo una vez a causa de una operación hidrográfica de un día entero de duración en los trópicos

Introduction

Estuaries represent one of the most ecologically important habitats on earth. An estuary is a semi-enclosed coastal body of water with one or more rivers or streams flowing into it, and with a free connection to the open sea, where freshwater from inland is mixed with saltwater from the sea (US Environmental Protection Agency, 2007a, 2007b; Pritchard, 1967; Stewart, 2005).

It has generally been established that the speed of propagation of sound in water varies with salinity, temperature, and pressure of the water body through which the sound propagates (Mackenzie, 1982; US Naval Academy, 2007). In order to compensate for the effect of the error in acoustic velocity introduced by this variation, acoustic systems are usually calibrated at the beginning, and end of bathymetric operations, and at times in between operations (US Army Corps of Engineers, 1998). The use of sound velocity profilers is also recommended for the determination of the speed of sound, at regular intervals, throughout the duration of survey (Canadian Hydrographic Service, 2005, 2008). These recommendations have been universally practiced for several years in both temperate and tropical regions. This practise has been found necessary for operations in temperate regions where variation in the speed of sound can cause an error as high as 0.7m in measured depth (Osada et al., 2003). However, the need for this practice in tropical regions, with relatively low variation in basic underwater acoustic parameters appears not to have been properly investigated.

The research is intended to determine the degree of variation of acoustic velocity in tropical estuaries, ascertain how it might affect bathymetric operations, and based on deduced facts, suggest appropriate instructions for bathymetric operations in similar environments.

Study Area

The rivers and creeks investigated in this study are all located in the Niger Delta region of Nigeria. This represents a densely populated region in Nigeria, and constitutes the hub of oil and gas industry in the country.

The Niger Delta, as officially defined presently by the Nigerian Government, extends over about 70,000 km² and makes up 7.5% of Nigeria's land mass, and includes Bayelsa, Delta, Rivers, Edo, Akwa Ibom, Imo, Abia, Cross River, and Ondo States *(see Figure 1)*.

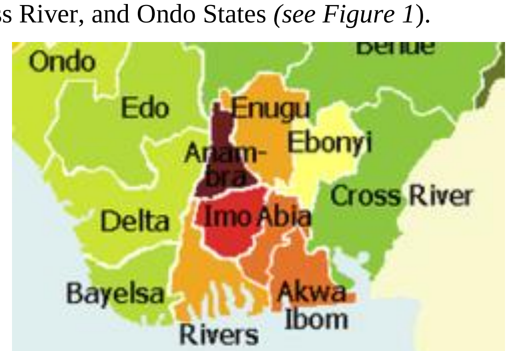

Figure 1. *Map of Niger Delta region MSN Encarta,*

The Niger Delta region is characterised by wetlands, and water bodies made up of creeks and rivers traversing the entire region and endowed with enormous natural resources. Apart from being the main source of large deposits of hydrocarbons in the country (Tuttle et al, 1999), it is home to the third largest mangrove forest, with the most extensive freshwater swamp forests, tropical rain forests, and rich biological diversity, in the world (Niger Delta Awareness, 2007).

Acoustic Velocity

Underwater acoustics is of great interest to mariners involved in underwater communication, mapping of the ocean floor and seabed topography. In saltwater, sound travels at speed of between 1,420 m/s and 1,560 m/s or above. As shown in *Figure 2*, the principal factor influencing the speed of sound in seawater is temperature, with salinity and depth having lower effects. A change of 1°C will result in approximately 4 m/s, while a change of 1 parts per thousand (ppt) in salinity will result in about 1.3 m/s, and a depth of 100m will result in 1.7m/s variation in sound velocity (Dushaw et al. 1993, Hall, 2000). The average value of underwater acoustic velocity has been found to be approximately 1500m/s in seawater (US Naval Academy, 2007; Pike, 1998).

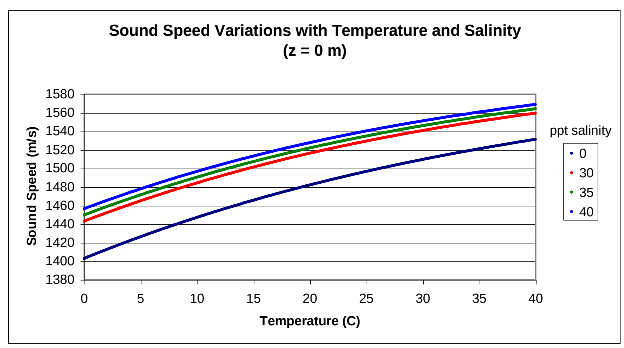

Figure 2. *Effects of temperature and salinity variations on sound velocity (After Lurton, 2002).*

There are numerous empirical relationships that have been developed for the computation of acoustic velocity from the three basic parameters (temperature, salinity, and pressure). Some of the prominent ones include Woods equation, Wilson equation, Del Grosso expression, Medwin formula, Chen and Millero formula, and Mackenzie formula (Pike, J.M. and Beiboer, 1993)

The various equations have different accuracy specifications, and are employed at different acoustic conditions. Consequently, depending on the expected accuracy, care is usually taken, in the choice of an appropriate model for the computation of acoustic velocities of different water bodies.

Estuaries

This project was developed from evaluation of series of hydrological and acoustic data captured in the course of field work in estuaries.

Estuaries are specialized environments and are usually calm, sheltered and shallow, and may vary greatly in temperature, salinity, and turbidity (murkiness). Thus, average acoustic velocities in estuaries are different from those of the oceans.

Estuaries are defined by tides, as they are washed either daily or twice daily with seawater. At high tide the salinity of the estuary will rise as seawater (20 – 35 ppt of salt dissolved in the water) enters the estuary mixing with freshwater (0 - 0.5 ppt) flowing downstream. The reverse takes place during low tide. Estuarine salinity can thus vary from 0 - 35 ppt depending on the tide and amount of freshwater input. The meeting of seawater and freshwater implies that a range of different temperatures, water levels, currents, and levels of oxygen are also possible.

Estuaries in the Study Area

The estuaries considered in this study are characterised by significant spatial and temporal variations of salinity. This is as a result of the mixing of the fresh waters and the sea waters, and the effect of rainfall in the area. At any given time of the year, a longitudinal salinity gradient exists from the upper reaches to the lower reaches of the estuaries (Dublin-Green, 1990).

The lower reaches (close to the seas) have higher salinity values than the upper reaches. Seasonal (temporal) variations in salinity of the river system are related to the rainfall regime. Maximum salinity values were normally recorded during the late dry season while minimum salinity values are recorded in the late wet season. There also exists slight vertical variation in salinity in the estuaries. Bottom water salinities were observed to be higher than those of the surface. There is also salinity variation over tidal cycles. The estuary waters were more saline during the high waters than the low water periods, due to the influx of sea water during high water (Dublin-Green, 1990).

Temperatures in most of the rivers of the estuaries were almost uniform (Dublin-Green, 1990). But despite the uniformity, water temperature varies seasonally, with maximum values during the late dry season and early wet seasons; and minimum values during the late wet seasons. There is also slight variation of temperature with depth. The temperatures tend to decrease with increasing depth.

The rivers and creeks considered in this study include: Bonny River in the eastern flank of the Niger Delta *(see Figure 3)*, Forcados River, Escravos River, Ramos River, Ethiope River, Benin River, Jones Creek, Odidi Creek, Staurt Creek, Odimodi Creek, Ahigbo Creek, Keremo Creek, and Iyeye Creek, all in the western flank *(see Figure 4)*.

Figure 3: *Study Locations on Eastern Niger Delta, A = Bonny; B=New Calabar River, C=Sambreiro River;D=Buguma Creek; E=Krakrama Creek, F=Cawthorne Channel; and G=Andoni River*

Figure 4. *Study Locations on Western Niger Delta: A = Forcados River, B = Escravos Rivers, C= Odidi Creek, D= Egwa Creek, E = Jones Creek, Benin Creek, G = Ethiope River, H= Warri River, I = Staurt Creek, J= Odimodi Creek, and K= Iyeye Creek.*

Data Acquisition

The data used in this project were temperature, salinity, and depth values, obtained at 30 minutes interval, from the rivers and creeks in the Niger Delta region of Nigeria. *Table 1* shows sample data from the Forcados River while *Figures 5* and *6* show the plots of the deferent parameters. Almost all the data considered in the study were observed over a 25 hour period for the various rivers and creeks.
The data were mostly acquired by Geosite Surveys Nig. Ltd, who was commissioned by the Shell Petroleum Development Company of Nigeria (SPDC) to undertake site surveys of all pipelines within the Western Division, on the site of the then proposed Liquefied Natural Gas Loading Jetty (Osuagwu, 1989), in Bonny River. Some data were equally obtained from Zenith Niger Group, who carried out a hydrographic survey of a section of the Forcados River and around a rig site in the Benin Estuary for SPDC.

Location : Forcados River			Water Depth : 10 metres			
Position : 153000mN 327000mE			Date : 12/05/93			
05 23' 2.33" N 05 22' 4.89"E						
TIME	SURFACE SECTION		MDDLE SECTION		BOTTOM SECTION	
	Temp. (^{0}C)	Salinity ($^0/_{00}$)	Temp. (^{0}C)	Salinity ($^0/_{00}$)	Temp. (^{0}C)	Salinity ($^0/_{00}$)
13:30	27.29	16.54	26.66	22.45	26.62	25.1
14:00	27.47	16.8	26.74	24.4	26.63	25.45
14:30	27.26	18.33	26.67	25.65	26.61	25.4
15:00	27.06	18.9	26.69	24.6	26.58	25.16
15:30	26.88	17.81	26.63	24.3	26.55	25.13
16:00	26.82	18.06	26.6	24.26	26.54	24.92
16:30	26.74	18.02	26.69	23.82	26.52	24.27
17:00	26.45	16.98	26.65	22.5	26.52	23.96
17:30	26.3	16.12	26.63	22	26.53	23.5
18:00	26.12	15.95	26.57	21.16	26.52	23.06
18:30	26.3	15.03	26.5	19.5	26.45	23.02
19:00	26.69	14.64	26.57	19.4	26.5	23.1
19:30	26.4	17.55	26.48	19.22	26.4	21.32
20:00	26.48	16.42	26.45	18.9	26.45	22
20:30	26.55	16.14	26.45	18.5	26.38	20.6
21:00	26.57	15.9	26.5	18.4	26.45	22.4
21:30	26.58	16.81	26.48	18.8	26.45	23.4
22:00	26.59	16.91	26.49	19.3	26.46	23.3
22:30	26.6	16.72	26.48	19.38	26.45	23.55
23:00	26.62	16.7	26.5	20.3	26.48	24.04
23:30	26.7	16.45	26.51	21.5	26.5	24.5
00:00	26.8	16.66	26.62	21.7	26.58	24.9
00:30	27.18	16.97	26.65	23.08	26.56	25.13
01:00	27.29	16.5	26.66	23.4	26.62	25.1
01:30	27.44	16.8	26.75	24.4	26.6	25.45
02:00	27.26	17.3	26.67	24.75	26.61	25.4
02:30	27.1	17.8	26.7	24.6	26.58	25.2
03:00	26.88	17.8	26.63	24.1	26.55	25.13
03:30	26.85	17.7	26.58	23.55	26.5	24.92
04:00	26.74	15.9	26.69	21.23	26.52	24.2
04:30	26.7	15.5	26.64	20.2	26.52	23.65
05:00	26.69	15.1	26.66	19.8	26.5	23.45
05:30	26.64	15.95	26.58	19.2	26.52	23.3
06:00	26.57	15.05	26.53	19.07	26.49	23.02
06:30	26.21	14.32	26.4	20.51	26.42	22.8
07:00	26.32	14.57	26.43	20.76	26.48	22.83
08:00	26.43	17.55	26.46	19.22	26.45	21.32
08:30	26.48	16.45	26.45	19.9	26.45	22
09:00	26.52	16.14	26.47	19.85	26.45	21.9
09:30	26.57	15.94	26.5	18.77	26.45	22.4
10:00	26.57	16.81	26.5	18.8	26.48	23.45
10:30	26.59	16.7	26.49	19.26	26.46	23.3
11:00	26.61	16.72	26.49	19.38	26.48	23.55
11:30	26.62	16.72	26.5	20.22	26.48	24.04
12:00	26.69	16.45	26.54	21.9	26.55	24.54
12:30	26.8	16.64	26.62	21.72	26.58	24.92
13:00	27.14	16.97	26.66	23.08	26.6	25.13
13:30	27.2	17.1	26.78	23.1	26.7	25.2
14:00	27.35	17.23	26.95	23.23	26.67	25.12
14:30	27.1	17.2	26.87	23.13	26.8	25.2

***Table 1**. Forcados River Salinity, Temperature, Depth Values*

Figure 5. *Plot of sectional temperature values against time, for the Forcados River.*

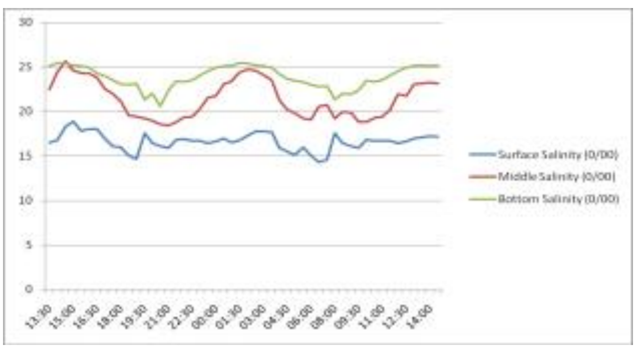

Figure 6. *Plot of sectional salinity values against time, for the Forcado River.*

Data Processing

To compute the maximum variation in acoustic velocities of the rivers and creeks, the velocities of the water bodies for a particular period were initially computed from the temperature, salinity, and depth (pressure) values, obtained from the rivers. The acoustic velocities were computed using the Chen and Millero formula. The prevalent conditions in the estuaries of the tropics fall within the ranges of the parameters contained in the Chen and Millero algorithm.
The Chen and Millero expression is based on the comprehensive observation of sea waters in the ranges of :

$0 < T < 40°$; $0 < S < 40$; $0 < Pb < 1000$.

where:

Pb = Hydrostatic Pressure in bars

From the validity matrix of Del Grosso formula, it was observed that the Del Grosso formula, which compares with Chen and Millero in precision and accuracy, is only suitable for deeper waters (depth > 1000m). In addition to this, the valid temperature and salinity ranges are outside the temperature and salinity ranges of the rivers and creeks considered.

The same applies to the Medwin formula. Furthermore, the Mackenzie formula that could have approximated the Chen and Millero formula has a valid salinity range above those encountered in the estuary of study.

Chen and Millero Equation

This formula, developed in 1977 and adopted by UNESCO in 1983 is given by:

$$C = C_w(t,p) + A(t,p)*S + B(t,p)*S^{3/2} + D(t,p)*S^2$$

where :

$$C_w(t,p) = (C_{00} + C_{01}*T) + (C_{02} * T^2 + C_{03}*T^3 + C_{04}*T^4 + C_{05}*T^5) + (C_{10} + C_{11}*T + C_{12}*T^2 + C_{13} * T^2 + C_{14}*T^4)* P_b + (C_{20} + C_{21}*T + C_{22}*T^2 + C_{23} * T^2 + C_{24}*T^4) * P_b^2 + (C_{30} + C_{31}*T + C_{32}*T^2) * P_b^3$$

$$A(t,p) = (A_{00} + A_{01}*T) + (A_{02} * T^2 + A_{03}*T^3 + A_{04}*T^4 + A_{05}*T^5) + (A_{10} + A_{11}*T + A_{12}*T^2 + A_{13} * T^2 + A_{14}*T^4)* P_b + (A_{20} + A_{21}*T + A_{22}*T^2 + A_{23} * T^2 + A_{24}*T^4) * P_b^2 + (A_{30} + A_{31}*T + A_{32}*T^2) * P_b^3$$

$$B(t,p) = (B_{00} + B_{01}*T) + (B_{10} + B_{11}*T)*P_b$$

$$D(t,p) = D_{00} + D_{10}*P_b$$

Computation was however truncated at the 2nd term of the above expressions (i.e. for C_W, A(t, p), B(t,p) and D (t,p)) since this is adequate for the accuracy requirement in this investigation.

The coefficients in the above expressions to the 2nd term are defined in *Table 2.*

Table 2. *Definition of coefficients in Chen and Millero Equation*

SUBSCRIPT	A	B	C	D
00	+ 1.389	-1.922E-2	1402.388	1.727E-3
01	-1.262E-2	-4.42E-5	5.03711	*
02	+7.164 E-5	*	-5.80852E-2	*
03	2.006E-6	*	3.3420E-4	*
04	-3.21E-8	*	-1.4780E-6	*
05	*	*	3.1464E-9	*
10	9.4742E-5	7.3637E-5	0.153563	-7.9836E-6
11	-1.258 E-5	1.7945E-7	6.8982E-4	*

Computation of acoustic velocities of the rivers

A program was developed based on the Chen and Millero formula for the computation of the acoustic velocities. The depth values, where appropriate, were converted to pressure values using Medwin Depth/Pressure relationship given by:

$$D = 9.7153*Pk$$

where;

D = Depth

Pk = Hydrostatic Pressure ($kg.cm^{-2}$)

It should be noted that 1bar = 10^5 Pa = $10/g(\phi)$ $Kg.Cm^{-2}$) where:

g = Acceleration due to gravity at latitude ϕ

The acoustic velocities of the surface, middle, and bottom sections of each column of rivers were computed, and the mean of these sectional velocities were taken as the velocity of each column of water, for the particular time interval. The initial velocities computed were based on the original raw data captured directly from the field. To ascertain the effect of variation of any of the three basic parameters (temperature, salinity, depth) on the acoustic velocities; and to simulate all possible conditions in the entire estuary, the parameters were subsequently varied from the lowest to the highest expected range in tropical estuaries. *Table 3* shows the various combinations of the parameters employed in the computations for all the rivers. Salinity was varied between $0^0/_{00}$ – $35^0/_{00,}$ temperature was varied between 15°C – 35°C, and depth, from 3m – 15m.These values represent the extreme ranges that can be encountered in estuaries in Nigeria.

The mean velocities for the rivers were computed from the acoustic velocities already computed, using the moving averages.
That is:

$$\text{Mean Velocity} = \frac{((v_1 + (2.v_2) + v_3))}{4}$$

where v_1, v_2, v_3 represent velocities at the surface, middle and bottom respectively.

Computation of maximum variation of acoustic velocity

Proceeding from the previous section, the maximum and minimum variation in acoustic velocities of the rivers and creeks for all the considered conditions were determined. The maximum velocity variation was computed as the difference between the highest mean velocity value and the lowest mean velocity value of any particular river.

Modelling the effect of acoustic velocity variation

Having computed the maximum velocity variation from the different models, the effects of the variations on sounded depths were computed. The two-way travel time of the acoustic wave is given by:

$$t = \frac{2.d}{v}$$

where:

v and *d* represent the acoustic velocity and the sounded depth respectively.

The effect 'μ' of the variation of the acoustic velocity on depth '*d*' were computed from the computed velocity variations, and the mean time of travel in the river. This was done for all the combinations of the temp, depth and salinity for the rivers and creeks considered.

That is:

$$\partial = \frac{\mu.t}{2}$$

where:

μ = Variation of acoustic Velocity (Maximum Mean Velocity – Minimum Mean Velocity)
t = Mean time of travel
∂ = error in d due to μ

Results and discussion

Table 4 shows the velocity computations for the observed combination of parameters, whilst *Figures 7* to *9* show plots of velocities for the original data obtained from the Forcados River, Odidi Creek and the Bonny River. *Table 5* shows the maximum and minimum values of the velocities for the various models, while *Figure 10* shows the velocity variation plot for all the chosen combinations of temperature, salinity, and pressure.

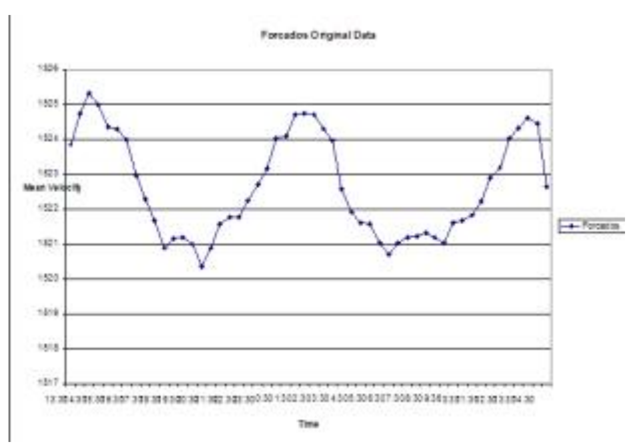

Figure 7. *Forcados River mean velocity vs time (original data)*

S/N	Model	Temperature (°C)	Salinity (‰)	Depth (m)
1	Original Data	Original value	Original value	Original value
2	0- Salinity model	Original value	0	Original value
3	0-Salinity-3m Depth	Original value	0	3
4	0-Salinity-15m Depth	Original value	0	15
5	3m Depth	Original value	Original value	3
6	15m Depth	Original value	Original value	15
7	15- Salinity	Original value	15	Original value
8	15- Salinity-3m Depth	Original value	15	3
9	15- Salinity-15m Depth	Original value	15	15
10	35- Salinity model	Original value	35	Original value
11	35-Salinity-3m Depth	Original value	35	3
12	35- Salinity-15m Depth	Original value	35	15
13	15 Degree Temp	15	Original value	Original value
14	15 Degree – 3m Depth	15	Original value	3
15	15 Degree – 15m Depth	15	Original value	15
16	15 Degree – 3m Depth-0 Sal	15	0	3
17	15 Degree – 15m Depth-0 Sal	15	0	15
18	15 Degree –0 Salinity	15	0	Original value
19	15 Degree –15 Salinity	15	15	Original value
20	15 Degree –35 Salinity	15	35	Original value
21	35 Degree Temp	35	Original value	Original value
22	15 Degree –0 Salinity	35	35	Original value
23	35 Degree –15 Salinity	35	15	Original value
24	35 Degree –0 Salinity	35	0	Original value
25	35 Degree – 3m Depth-35 Sal	35	35	3
26	35 Degree – 15m Depth-35 Sal	35	35	15

Table 3: *Matrix of models*

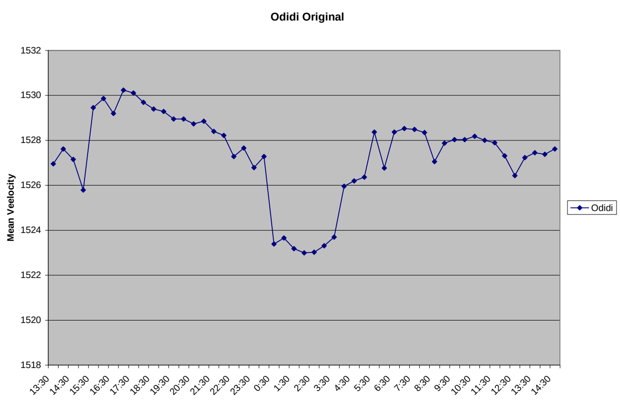

Figure 8. *Odidi Creek mean velocity per time (original data)*

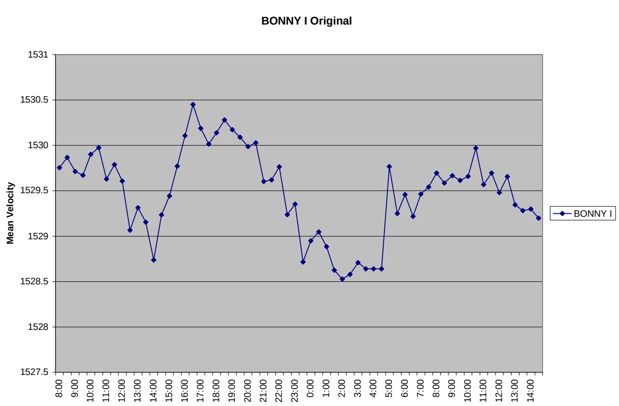

Figure 9*. Bonny River mean velocity per time (original data)*

The error in depth introduced by the maximum velocity variation in *Figure 10* was compared with the allowable errors for the various orders of bathymetric surveys.

The International Hydrographic Organisation (IHO) classified hydrographic operations into four different orders (special, first, second and third order) for the purpose of evaluating depth/bathymetric uncertainties. (IHO S44, 1998, Wells and Monahan, 2002).

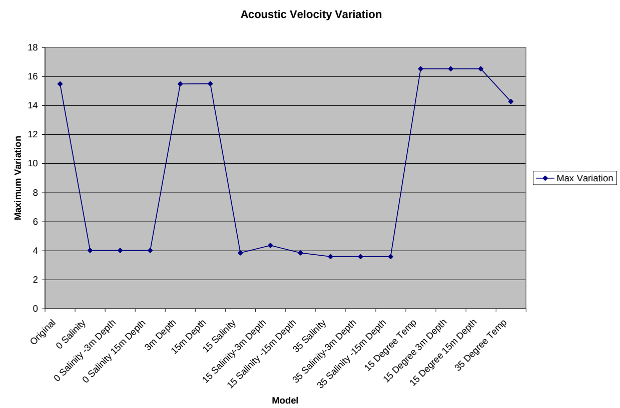

Figure 10*. Maximum Acoustic Velocity Variation Plot*

TIME	Jones Crk	TIME	Ethiope	TIME	Benin Lt	TIME	Escravos	TIME	Jones	TIME	BONNY I
10:30	1515.25	8:00	1520.21	11:00	1519.01	7:30	1521.35	8:00	1515.04	8:00	1529.78
11:00	1515.12	8:30	1520.79	11:30	1520.00	8:00	1520.78	8:30	1515.12	8:30	1529.80
11:30	1514.57	9:00	1520.98	12:00	1520.66	8:30	1520.61	9:00	1515.25	9:00	1529.71
12:00	1514.26	9:30	1520.21	12:30	1520.47	9:00	1520.66	9:30	1515.49	9:30	1529.65
12:30	1514.27	10:00	1519.91	13:00	1519.87	9:30	1520.77	10:00	1515.54	10:00	1529.9
13:00	1515.95	10:30	1519.43	13:30	1518.23	10:00	1520.8	10:30	1515.6	10:30	1530.02
13:30	1513.06	11:00	1519.15	14:00	1516.44	10:30	1520.97	11:00	1515.7	11:00	1529.63
14:00	1514.2	11:30	1518.89	14:30	1517.1	11:00	1520.79	11:30	1515.75	11:30	1529.1
14:30	1514.48	12:00	1518.77	15:00	1516.26	11:30	1521.23	12:00	1515.89	12:00	1529.41
15:00	1514.7	12:30	1518.6	15:30	1518.28	12:00	1521.68	12:30	1515.97	12:30	1529.02
15:30	1515.53	13:00	1518.51	16:00	1516.61	12:30	1523.01	13:00	1516.05	13:00	1529.29
16:00	1515.79	13:30	1518.49	16:30	1516.94	13:00	1523.41	13:30	1516.21	13:30	1529.18
16:30	1515.6	14:00	1518.81	17:00	1516.66	13:30	1523.88	14:00	1516.37	14:00	1528.72
17:00	1515.09	14:30	1517.86	17:30	1516.02	14:00	1524.38	14:30	1517.12	14:30	1529.23
17:30	1515.51	15:00	1515.66	18:00	1516.66	14:30	1525.21	15:00	1517.61	15:00	1529.43
18:00	1515.43	15:30	1515.68	18:30	1516.80	15:00	1525.1	15:30	1517.77	15:30	1529.77
18:30	1515.38	16:00	1515.42	19:00	1516.81	15:30	1526.32	16:00	1517.85	16:00	1530.09
19:00	1515.27	16:30	1515.66	19:30	1516.57	16:00	1526.17	16:30	1517.8	16:30	1530.40
19:30	1515.22	17:00	1512.73	20:00	1517.27	16:30	1526.32	17:00	1517.81	17:00	1530.18
20:00	1515.09	17:30	1512.77	20:30	1517.13	17:00	1526.6	17:30	1517.35	17:30	1530.02
20:30	1515.32	18:00	1515.29	21:00	1516.00	17:30	1526.79	18:00	1516.9	18:00	1530.15
21:00	1515.02	18:30	1515.17	21:30	1517.02	18:00	1526.09	18:30	1515.6	18:30	1530.27
21:30	1515.39	19:00	1512.6	22:00	1519.96	18:30	1525.15	19:00	1515.59	19:00	1530.17
22:00	1515.29	19:30	1512.48	22:30	1522.2	19:00	1524.36	19:30	1515.55	19:30	1530.00
22:30	1514.88	20:00	1512.44	23:00	1520.75	19:30	1524.07	20:00	1515.59	20:00	1529.98
23:00	1514.27	20:30	1512.55	23:30	1518.00	20:00	1523.61	20:30	1515.7	20:30	1530.02
23:30	1513.8	21:00	1512.22	0:00	1517.04	20:30	1522.77	21:00	1515.74	21:00	1529.61
0:00	1513.53	21:30	1512.74	0:30	1516.35	21:00	1522.42	21:30	1515.94	21:30	1529.62
0:30	1513.44	22:00	1512.84	1:00	1515.30	21:30	1521.76	22:00	1515.92	22:00	1529.77
1:00	1513.32	22:30	1512.4	1:30	1513.48	22:00	1521.53	22:30	1515.82	22:30	1529.27
1:30	1513.25	23:00	1512.42	2:00	1512.02	22:30	1521.39	23:00	1515.87	23:00	1529.35
2:00	1513.19	23:30	1512.44	2:30	1511.19	23:00	1521.04	23:30	1515.85	23:30	1528.60
2:30	1513.29	0:00	1512.35	3:00	1512.37	23:30	1520.92	0:00	1515.82	0:00	1528.35
3:00	1513.38	0:30	1512.31	3:30	1512.2	0:00	1520.81	0:30	1515.84	0:30	1529.02
3:30	1513.06	1:00	1512.33	4:00	1511.9	0:30	1521.1	1:00	1515.87	1:00	1528.79
4:00	1513.01	1:30	1512.32	4:30	1512.3	1:00	1520.85	1:30	1515.87	1:30	1528.61
4:30	1515	2:00	1512.4	5:00	1512.17	1:30	1521.15	2:00	1515.76	2:00	1528.55
5:00	1515.00	2:30	1512.48	5:30	1512.39	2:00	1522.11	2:30	1515.82	2:30	1528.57
5:30	1515.2	3:00	1512.41	6:00	1519.47	2:30	1522.7	3:00	1516.05	3:00	1528.67
6:00	1515.31	3:30	1512.22	6:30	1516.51	3:00	1522.9	3:30	1516.27	3:30	1528.62
6:30	1515.36	4:00	1512.61	7:00	1517.72	3:30	1523.8	4:00	1516.32	4:00	1528.62
7:00	1514.79	4:30	1513.03	7:30	1518.81	4:00	1523.78	4:30	1516.43	4:30	1528.62
7:30	1514.4	5:00	1512.94	8:00	1517.47	4:30	1524.36	5:00	1516.47	5:00	1528.65
8:00	1515.01	5:30	1514.39	8:30	1517.64	5:00	1523.85	5:30	1516.34	5:30	1529.25
8:30	1514.77	6:00	1512.28	9:00	1517.92	5:30	1524.48	6:00	1516.2	6:00	1528.51
9:00	1514.77	6:30	1515.17	9:30	1517.80	6:00	1524.59	6:30	1516.61	6:30	1529.23
9:30	1515.07	7:00	1518.97	10:00	1520.1	6:30	1525.38			7:00	1529.47
10:00	1515.29	7:30	1518.61	10:30	1520.13	7:00	1523.74			7:30	1529.53
10:30	1514.08	8:00	1519.8	11:00	1521.11	7:30	1523.01			8:00	1529.71
11:00	1514.27	8:30	1513.71	11:30	1520.2	8:00	1522.64			8:30	1529.55
11:30	1513.8			12:00	1520.02	8:30	1522.09			9:00	1529.00
mean	1514.68		1515.24		1517.29		1523.06		1516.15		1529.48

Table 4*. Mean Velocities (Moving Averaging) from Jones Creek, Ethiope, Benin, Escravos and Bonny Rivers (Original Data).*

Model	Maximum Variation Velocity (m/s)	River/Creek	Minimum Variation Velocity (m/s)	River/Creek
Original Data	15.4903	Benin	1.5056	Egwa
0- Salinity model	4.011	Odidi	0.7802	West Keremo
0-Salinity-3m Depth	4.011	Odidi	0.7802	West Keremo
0-Salinity-15m Depth	4.011	Odidi	0.7803	West keremo
3m Depth	15.489	Benin	1.5056	Egwa
15m Depth	15.495	Benin	0.5056	Egwa
15- Salinity	3.843	Odidi	0.748	West Keremo
15- Salinity-3m Depth	4.362	Odidi	0.7479	West Keremo
15- Salinity-15m Depth	3.844	Odidi	0.748	West Keremo
35- Salinity model	3.591	Odidi	0.6998	West Keremo
35-Salinity-3m Depth	3.591	Odidi	0.6997	West Keremo
35- Salinity-15m Depth	3.591	Odidi	0.6998	West Keremo
15 Degree Temp	16.530	Benin	0.4395	Odimodi
15 Degree – 3m Depth	16.529	Benin	0.4395	Odimodi
15 Degree – 15m Depth	16.529	Benin	0.4395	Odimodi
35 Degree Temp	14.277	Benin	0.0214	Egwa

***Table 5**. Results of maximum and minimum acoustic velocity variation*

The expression for the bathymetric uncertainty is given by:

$$S = \pm\sqrt{[a^2+(b*d)^2]}$$

where:

S = uncertainty
a = sum of depth independent errors, i.e. the sum of all constant errors
b = sum of depth dependent errors,
d = depth of water column in metres

The values of these factors are given in *Table 6* below.

ORDER	Special	First	Second	Third
Reduced depth Accuracy Factors (IHO, 1998)	a =0.25m b =0.0075	a = 0.5m b =0.013m	a = 1.0m b =0.023m	a = 1.0m b =0.023m
Depth	15m / 40m	100m	200m	250m
Allowable Error	0.274m/ 0.391m	1.393m	4.707m	5.836m

***Table 6** Depth Accuracy Factors (IHO, 1998) and Allowable Depth Error*

Using the above equation and the factors in *Table 6*, the following allowable depth errors were computed for each of the categories of hydrographic survey (see also Table 6).

Figure 11 shows the plot of the errors in sounded depth due to the different velocity variation in all the models and the plots the allowable error for a 15m and 40m depth estuary. It was found in this study that for the maximum velocity variation of 16.5296m/s in the study area, an error of 0.0819m in the sounded depth, will result. But as seen from the computation presented in *Table 6* and *Figure 11*, special order bathymetric surveys will have an allowable depth error of 0.274m for a 15m depth estuary, and 0.391m for a 40m depth estuary.

It can therefore be inferred that the effect of the variations in acoustic velocity on the sounded depth is insignificant for most practical purposes for bathymetric surveys in estuaries in the tropics. Consequently, for such surveys in the tropics, and in the absence of other sources of errors, the initial calibration (start of sounding calibration) will be sufficient for the whole duration of the survey.

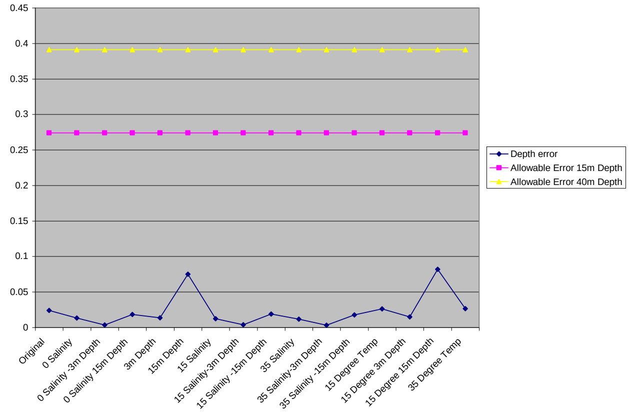

Figure 11. Maximum Depth Error Plot

Conclusion

The studies have shown that even under extreme combinations of temperature and salinity, the maximum velocity variation obtained in the tropics, and particularly in Nigeria, was 16.53m/s and this introduced a depth error of 0.082m for a depth 15 meters, which is greater than the maximum depth in the area. Computation of errors for bathymetric uncertainty for a depth of 15m is 0.274m while the error for the maximum depth of 40m in special order surveys is 0.391m.

It is therefore obvious that the error introduced by the variation of acoustic velocity in tropical estuaries is below the allowable error and can be regarded as having insignificant effect to the sounded depth.
It can therefore be inferred that whilst carrying out a bathymetric survey in these locations, the initial calibration (start of sounding calibration) will suffice for the duration of the survey and the variation in the acoustic velocity will be assumed to be negligible for all practical purposes. Consequently, when providing hydrographic survey instructions, it is recommended to make a distinction between tropical and temperate environments.

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