EFFECT OF SONAR BEAMWIDTH AND SLOPING SEA BED ON THE ACCURACY OF BATHYMETRIC SURVEY.

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SUMMARY

In the S-44 publication, the IHO has specified the accuracy criteria for different categories of bathymetric survey. To achieve the expected standard, the necessary required instrumentation must be considered with respect to the environment. This paper investigates the effect of sonar beam width and sea bed slope on the accuracy of the bathymetric survey. Simulations were carried out to compare obtained values with IHO standards. The paper shows that sea bed's Total Vertical Uncertainty (TVU) and Total Horizontal Uncertainty (THU) can be obtained under specific combination of sea bed slope angle and beam width. It further concludes that the IHO standards can be achieved if beam widths of sonar systems that are employed in bathymetric surveys within the special order and Order 1(a, b) criterion are not more than 6 degrees and 12 degrees respectively

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1. INTRODUCTION

1.1. Statement of problem

Sonar systems are used everywhere in the world for bathymetric survey purposes. Most hydrographers employ a particular sonar system for all kinds of bathymetric activities. This may be as a result of the availability of the very sonar system or their ignorant of the need for the consideration of the efficacy of the instrument with regards to the area of the water body where the project is to be executed. The determination of which sonar system to be used in a specific area is dependent on the beamwidth of the instrument. Most of the challenges experienced in navigation are as a result of poor delineation of sea in the course of bathymetric operations. Employment of an inadequate sonar system in an environment gives birth to poor coverage of the features beneath the sea surface. The beamwidth of the sonar system determines its footprint on the sea bed. In sounding operation generally, the acoustic pulse is expected to be transmitted truly vertical towards the sea bed. This is not always the case because of errors due to the motion of the vessel carrying the sonar instrument and the effect of the sea bed slopes.

The International Hydrographic Organization (IHO) has developed a means of determining the accuracy standards of bathymetric surveys based on the section of the water body where the activity is taking place. To accommodate in a systematic manner, the different accuracy requirements for areas to be surveyed, four orders of survey are defined by IHO in her publication of S-44 5th Edition 2008. The classifications are special order, Order1a, Order1b and Order 2. **Special Order** surveys are meant for berthing areas, harbours and critical areas of shipping channels where the depth of water is not more than 40 metres. In **Order 1a,** under-keel clearance becomes less critical than in special order above as depth increases, so the size of the feature to be detected by the full sea floor search is increased also and the range of water depth is greater than 40 metres. Order 1a surveys may be limited to water shallower than 100 metres. **Order 1b** is intended for areas shallower than 100 metres where a general depiction of the seabed is considered adequate for the type of surface shipping expected to transit the area. A full sea floor search is not required which means some features may be missed although the maximum permissible line spacing will limit the size of the features that are likely to remain undetected. This order of survey is only recommended where under-keel clearance is not considered to be an issue. **Order 2** surveys are limited to areas deeper than 100 metres. It is the least stringent order and is intended for those areas where the depth of water is such that a general depiction of the seabed is considered adequate. A full sea floor search is not required.

For these different classifications of Survey, it therefore, becomes a very big challenge to determine which sonar instrument will be adequate for use in these areas to meet their respective accuracy standards.

2. AIM AND OBJECTIVES

2.1. Aim

The aim of this work is to investigate and recommend the ranges of sonar beam widths that are suitable for the accuracy standards of bathymetric surveys as specified by International Hydrographic Organization

2.2. Objectives

1. Evaluation of the accuracy standard provided by IHO
2. Determination of the effect of ranges of beam widths in single beam echo-sounders, on different sea bed slopes
3. Extraction of different values of beamwidths and sea bed slope angles that fall within the acceptable ranges of the accuracy standards for analysis.
4. Recommendation of the range of sonar beam width to be employed in bathymetric survey of a specified range of sea bed slopes that will conform to the IHO standard at 95% confidence level.

3. BACKGROUND OF STUDY

3.1. Acoustic Beam Width of Transducers

Beam width is the angle between the line perpendicular to the center of the transducer face and the line through the half power point. Other energies beyond the beam width are not actually utilized in sonar operation (O.C Ojinnaka, 2007). The transducer can be characterized by its beam width b_w which is commonly defined by the angle at the -3 dB level, that is to say, that angular aperture corresponding to half power referred to the beam axis $b_w = 2\theta_{-3dB}$ (IHO Manual on Hydrography, 2005)

The choice of beam width depends on several considerations that can affect data collection or quality. A narrow beam requires a greater active area of transducer elements than does a wider beam at the same frequency. Wider beams allow for a greater sample volume. Transducers with wider beam widths are given consideration for portable acoustic systems. The data from wider beam transducers are also less affected by vessel motion as the greater ping- to- ping overlap in the ensonified volume will result during pitch/roll. (Lars R and Patrick S (last accessed 22/1/2018))

3.2. Bathymetric Survey Accuracy Standards

The process of obtaining an accurate bathymetric survey is substantially more difficult than that associated with land-based surveying. Measurement error is defined as the difference between a measured value and the true value, and it can be categorized as a blatant error, systematic error, or random error. Blatant errors (human blunders) can usually be eliminated with adequate quality control procedures. Systematic errors, if identified, are those that can be measured or modeled (estimated) through calibration and removed from the survey data (e.g., tide corrections, instrument calibration). Random errors typically are small errors resulting from the limitation of measuring devices and the inability to perfectly model systematic errors; they can be negative or positive and are governed by the laws of probability. The accuracy of observed bottom elevations for historical and recent surveys is dependent on many random and systematic errors present in the measurement process. Unlike land-based surveying, bathymetric and hydrographic surveying has few quality control indicators to check resultant accuracy. Because the bottom elevation being measured is not visible, sometimes even blatant errors are difficult to detect. As such, maintaining prescribed accuracy criteria requires precision, care and quality control in the measurement process (Mark R. Byrnes, Jessica L. Baker, and Feng Li, 2002)

3.3. Error in Depth measurement due to Sonar Beam Width and Sloping Sea bed

Sonar beam width is the angle between the line perpendicular to the centre of the transducer face and the line through the half-power point (that is where the energy contained in the beam is reduced to half that of the perpendicular). Other energies beyond the beam width are not actually utilized in sonar operation. Wide beam width sonar can introduce the following uncertainties:

1. They can smoothen the shape of large features and simultaneously introduce errors in their horizontal position.
2. They can obscure features whose wave lengths are less than twice the ensonified area.
3. Also they can introduce horizontal displacement in the presence of a sloping sea floor.

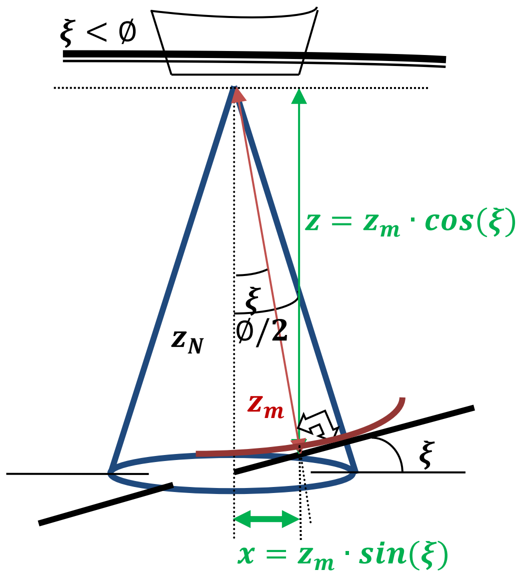

FIGURE 2: Slope angle less than one half the beam width

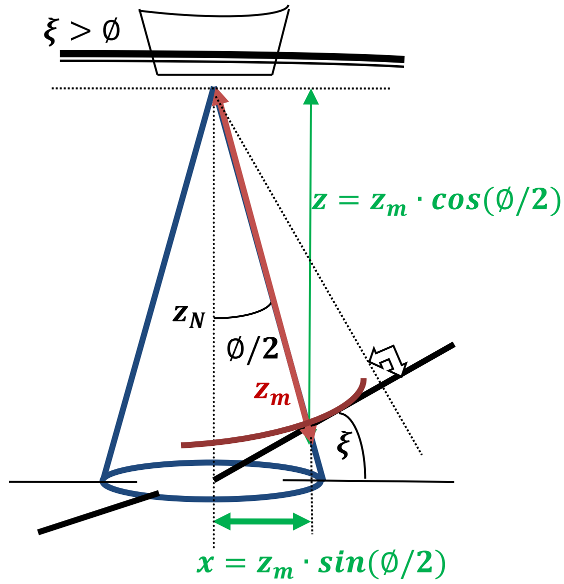

FIGURE 3: Slope angle greater than one half the beam widths

Figures 2 & 3 demonstrate the uncertainties in vertical and horizontal positions due to the beam width and sloping sea bed respectively

Taking into consideration the different seabed slopes, in Figures 2 and 3 the error on the depth measurement, **dz**, depends on both beam width and slope. If no correction is applied, the error in depth will be given by

$$dz = z_m(\sec(\xi) - 1) \text{ if } \xi < \frac{\emptyset}{2} \qquad \ldots(1)$$

$$dz = z_m\left(\sec\left({}^{\emptyset}/_{2}\right) - 1\right) \text{ if } \xi > \frac{\emptyset}{2} \qquad \ldots(2)$$

Where $\frac{\emptyset}{2}$ is half beam width and ξ is the slope of the sea bed

(IHO Manual on Hydrography, 2005)

3.4. Uncertainties in Vertical and Horizontal positions due to Sloping Sea bed.

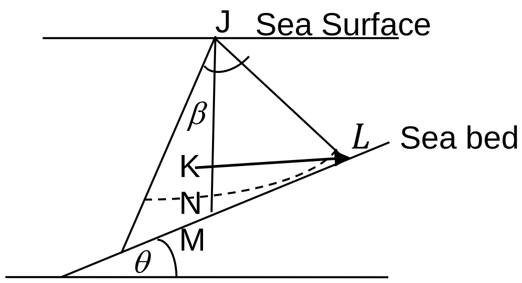

FIGURE 4: Uncertainties in vertical and horizontal positions due to sea bed slope angle (θ) and beam width (β).

The vertical and horizontal displacements NM and KL are respectively given in (Ojinnaka,2007)

Where KL = horizontal displacement

NM = vertical displacement

$$NM = JL\left(\tan{}^{\beta}/_{2}\, sin\theta - 1 + \cos{}^{\beta}/_{2}\right) \qquad \ldots(3)$$

$$KL = JL \tan{}^{B}/_{2}\ cos\theta \qquad \ldots(4)$$

Where β = Beam width, θ =sea bed slope angle, JL = Measured depth.

Figure 4 shows that increase in the slope of the sea bed results in increase in the depth uncertainty and decrease in the horizontal uncertainty. Sonar systems with beam width as small as 2^{o} are suitable and conforms to IHO S44 standards under special and first order surveys. (O.C. Ojinnaka, 2007)

Table 1: IHO minimum standard for Hydrographic Surveys(IHO S-44 5th editon, 2008)

Order	**Special**	**1a**	**1b**	**2**
Description of areas.	Areas where under-keel clearance is critical	Areas shallower than 100 metres where under-keel clearance is less critical but features of concern to	Areas shallower than 100 metres where under-keel clearance is not considered to be an issue for the type of	Areas generally deeper than 100 metres where a general description of

		surface shipping may exist	surface shipping expected to transit the area.	the sea floor is considered adequate.
Maximum allowable THU 95% Confidence level	2 meters	5 metres + 5% of depth	5 metres + 5% of depth	20 metres + 10% of depth
Maximum allowable TVU 95% Confidence level	a = 0.25 metre b = 0.0075	a = 0.5 metre b = 0.013	a = 0.5 metre b = 0.0013	a = 1.0 metre b = 0.023
Full sea floor Search	Required	Required	Not required	Not required
Feature Detection	Cubic features > 1 metre	Cubic features > 2 metres, in depths up to 40 metres; 10% of depth beyond 40 metres	Not Applicable	Not Applicalbe
Recommended maximum Line Spacing	Not defined as full sea floor search is required	Not defined as full sea floor search is required	3 x average depth or 25 metres, whichever is greater For bathymetric lidar a spot spacing of 5 x 5 metres	4 x average depth
Positioning of fixed aids to navigation and topography significant to navigation. (95% Confidence level)	2 metres	2 metres	2 metres	5 metres
Positioning of the Coastline	10 metres	20 metres	20 metres	20 metres

and Topography less significant to navigation (95% Confidence level)				
Mean position of floating aids to navigation (95% Confidence level)	10 metres	10 metred	10 metres	20 metres

The IHO equation for minimum standards with respect to different Orders of specification is

$S = \pm \sqrt{[a^2 + (b*d)^2]}$ …(5)

Where:

S = Uncertainty in bathymetric Survey

a = that portion of the uncertainty that does not vary with depth

b= a coefficient which represents the uncertainty that varies with depth

d = the depth

b *d= that portion of the uncertainty that varies with depth

4. ANALYSIS

In this work, we understood NM and KL (Vertical and Horizontal displacements in O.C. Ojinnaka, 2007) in equation three (3) and (4) above to mean TVU and THU (Total Vertical and Total Horizontal Uncertainties in IHO S-44, 2008) respectively.

All the subsequent analysis and derivations on this work are based on these understanding.

4.1. Computation of Horizontal and Vertical Uncertainties inherent in Bathymetric Survey

The computations were performed using equation (5) and the parameters given in table 1 for the computation of Total Vertical Uncertainties (TVU) and Total Horizontal Uncertainties (THU) at 95% confidence level.

The computation produced the following results:

At Special Order with depth 40.00m the THU and TVU were computed to be **2.00m**, and **0.391m** respectively whereas at Order 1(a,b) where the allowable depth is 100.00m, THU and TVU are **10.00m** and **1.393m** respectively.

4.2. Test of Suitable Sonar Beam Width on specified Slope Angle at Special Order and Order 1 criterion

The procedure used in this test can be explained in seven stages;

1. Compute the values of THU and TVU as explained in section 4.1
2. Set the values of THU and TVU as limits to check the range of acceptable values. This is necessary because any value(s) of the beam width and slope angle gotten when the limit is exceeded is not within the 95% confidence level and therefore, not considered acceptable by IHO standard.
3. Model equations 3 and 4 separately in excel worksheet. Equation 3 computes vertical displacement while 4 computes horizontal displacement caused by sonar beam width(β) and sea bed slope(θ)
4. Insert estimated values of (β) and (θ) into the modeled excel work sheet.
5. Vary the estimated value of one parameter, say, (β) while (θ) is kept constant. That is when the maximum value of (β) suitable for a constant value of (θ) is being determined.
6. Stop the variation at the point when either THU or TVU reaches maximum value.(which ever that occurs first)
7. The value of the parameter investigated, say, (β) at the time either THU or TVU reaches its maximum value is then extracted and recorded as the maximum sonar beam width that can be employed on that fixed value of slope angle to obtain a bathymetric result acceptable by IHO standard.

Samples of results of these tests are displayed in the tables below.

Table 2: Sample test of variation of Beam width at constant Slope angle for depths = 40.00m (Special Order)

S/N	Slope Angle (deg)	Beam Width (deg)	Measured Depth (m)	Vertical Uncertainty (m)	Horz. Uncertainty (m)

1	**2**	**1**	**40**	**0.011**	**0.349**
2	2	2	40	0.018	0.698
3	2	3	40	0.023	1.047
4	2	4	40	0.024	1.396
5	***2***	***5.73***	***40***	***0.019***	***2.001***

The maximum allowable horizontal uncertainty is attained at beam width equal to 5.73 degrees and slope angle 2 degrees

Table 3, displays the summary of respective simulation performed on series of varying possible beamwidths on slope angles. It is a collection of different sample tests such as table 2 above.

Table 3: **Summary of the variations of beamwidth at constant slope angle for depth =40.00m**

SLOPE ANGLE(deg)	**BEAMWIDTH**(deg)	**DEPTH**(m)	**TVU**(m)	**THU**(m)
1	**5.73**	**40**	**-0.020**	**2.00**
2	**5.73**	**40**	**0.019**	**2.00**
3	**5.74**	**40**	**0.055**	**2.00**
4	**5.74**	**40**	**0.089**	**2.00**
5	**5.75**	**40**	**0.125**	**2.00**
6	**5.76**	**40**	**0.159**	**2.00**
7	**5.77**	**40**	**0.195**	**2.00**
8	**5.79**	**40**	**0.230**	**2.00**
9	**5.80**	**40**	**0.266**	**2.00**
10	**5.82**	**40**	**0.302**	**2.00**
11	**5.84**	**40**	**0.337**	**2.00**

12	**5.86**	**40**	**0.373**	**2.00**

In table 3 above, the maximum allowable horizontal uncertainty(2.00m) were respectively attained for different levels of tests and at the end, we have that the final maximum allowable beam width is 5.86 degrees at slope angle not more than12 degrees.

It was deemed necessary to also investigate the possible behaviour of the slope angle when the beamwidth is kept constant. This was to ensure proper coverage of the possible range of acceptable beamwidth

Table 4: Summary of the Variations of Slope angles at Constant Beam width for depth = 40.00m

Slope Angle (deg.)	Beam width (deg.)	Measured Depth (m)	Vertical Uncertainty (m)	Horizontal Uncertainty (m)
34.67	**2.00**	**40**	**0.391**	**0.574**
22.73	**3.00**	**40**	**0.391**	**0.966**
17.30	**4.00**	**40**	**0.391**	**1.334**
14.22	**5.00**	**40**	**0.391**	**1.693**
12.28	**6.00**	**40**	**0.391**	**2.048**

The maximum allowable horizontal uncertainty is attained at beam width equal to 6 degrees and slope angle 12.28 degrees

A graphical representation of the behavior of slope angle and beam width is shown below in figure 5 using the data in table 4

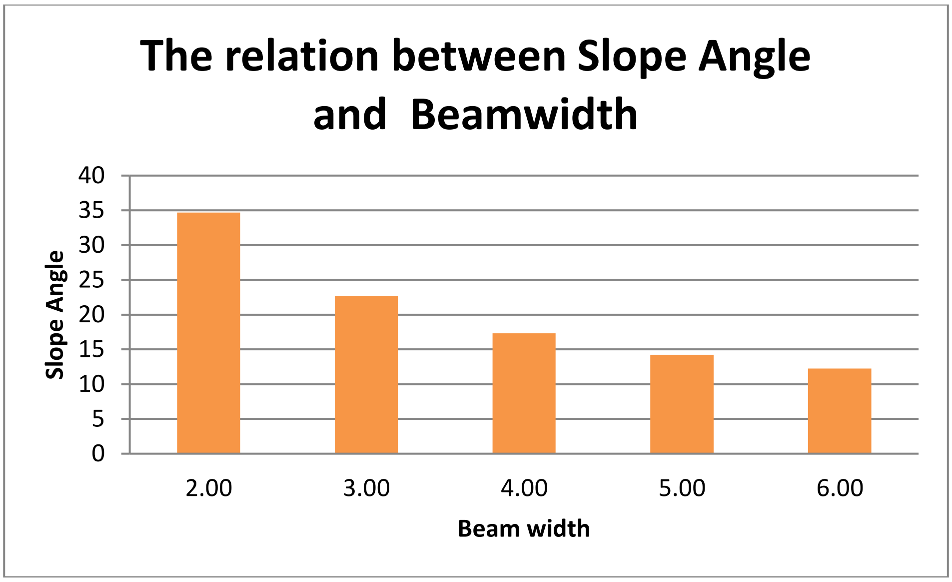

Figure 5: The relationship between Slope angle and beamwidth

Considering the result of the sample test table 2, and the summary tables 3 and 4, it can be concluded that for special order surveys, sonar instruments of beamwidth greater than 6.0 degrees should not be used so that the IHO accuracy requirement would be maintained.

With consideration to Order 1 regions of the water bodies (Areas of water body whose depths are greater than 40.00m but not more than 100.00m), table 5 presents a sample of the simulation test.

Table 5: Sample test of Variations of Slope angles at Constant Beam width for depth = 100m (Order 1)

S/N	Slope Angle (deg)	Beam Width (deg)	Measured Depth (m)	Vertical Uncertainty (m)	Horz. Uncertainty (m)
1	1	5	100	-0.019	4.365
2	2	5	100	0.057	4.363
3	3	5	100	0.133	4.360
4	4	5	100	0.209	4.355
5	5	5	100	0.285	4.349
6	6	5	100	0.361	4.342

7	7	5	100	0.437	4.334
8	8	5	100	0.512	4.324
9	9	5	100	0.588	4.312
10	10	5	100	0.663	4.300
11	11	5	100	0.738	4.286
12	12	5	100	0.813	4.271
13	13	5	100	0.887	4.254
14	14	5	100	0.961	4.236
15	15	5	100	1.035	4.217
16	16	5	100	1.108	4.197
17	17	5	100	1.181	4.175
18	18	5	100	1.254	4.152
19	***19.93***	***5***	***100***	***1.393***	***4.105***
20	20	5	100	1.398	4.103

The maximum allowable vertical uncertainty is attained at beam width equal to 5 degrees and slope angle 19.93 degrees

The summary of series of such tests is also shown in table 6

Table 6: Summary of the allowable limits of Beam widths computed when beam widths are varied at respective constant slope angles at depth equal to 100.00m

S/N	Slope Angle (deg)	Beam Width (deg)	Measured Depth (m)	Vertical Uncertainty (m)	Horz. Uncertainty (m)
1	1	11.43	100	-0.322	10.006
2	2	11.43	100	-0.148	10.002
3	3	11.44	100	0.026	10.003

4	4	11.45	100	0.201	10.001
5	5	11.47	100	0.375	10.005
6	6	11.49	100	0.549	10.006
7	7	11.51	100	0.724	10.003
8	8	11.54	100	0.900	10.006
9	9	11.57	100	1.076	10.006
10	10	11.60	100	1.252	10.003
11	***11***	***11.64***	***100***	***1.429***	***10.01***

It can also be seen from table 6 that the maximum size of sonar beam width considerable for use on areas within IHO order 1a and 1b is 11.64 degrees

Table 7: Summary of the limits of allowable beam widths with respect to varying slope angles computed from series of variations of Slope angles at respective constant Beam widths and water depth not more than 100.00m

S/N	Slope Angle (deg)	Beam Width (deg)	Measured Depth (m)	Vertical Uncertainty (m)	Horz. Uncertainty (m)
1	53.8	2	100	1.393	1.031
2	33.03	3	100	1.393	2.195
3	24.6	4	100	1.393	3.175
4	19.93	5	100	1.393	4.105
5	16.97	6	100	1.393	5.013
6	14.96	7	100	1.392	5.909
7	13.53	8	100	1.392	6.799
8	12.48	9	100	1.392	7.684
9	11.69	10	100	1.392	8.567

10	***11.1***	***11***	***100***	***1.393***	***9.449***
11	10.64	12	100	1.393	10.330

Sample test table 5 and the summary tables 6 and 7 reveals that maximum size of sonar beamwidth angle that can be acceptable by IHO standard for bathymetric surveys within order 1a and 1b regions is 12 degrees.

It can also be noticed from all the summary tables 3,4, 6 and 7 that in the cause of the simulation, that if beamwidth is varied with constant slope angle, the vertical uncertainty varies in direct proportion with the beam width whereas at constant beamwidth, and varying slope angle, the horizontal uncertainty varies indirectly to the slope angle .This relationships can be graphically expressed as depicted in figures 6 and 7

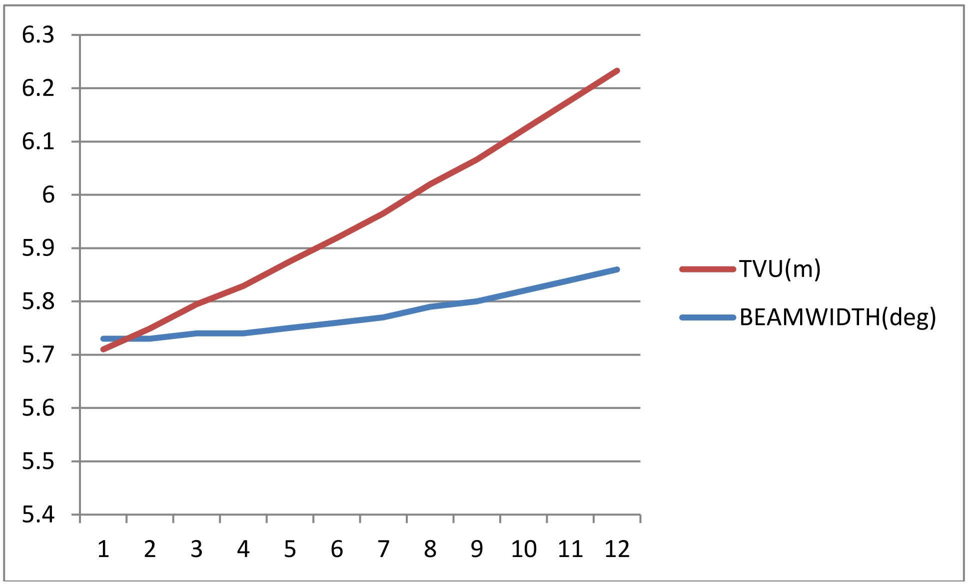

Figure 6: Direct relation exists between Vertical uncertainty and beamwidth

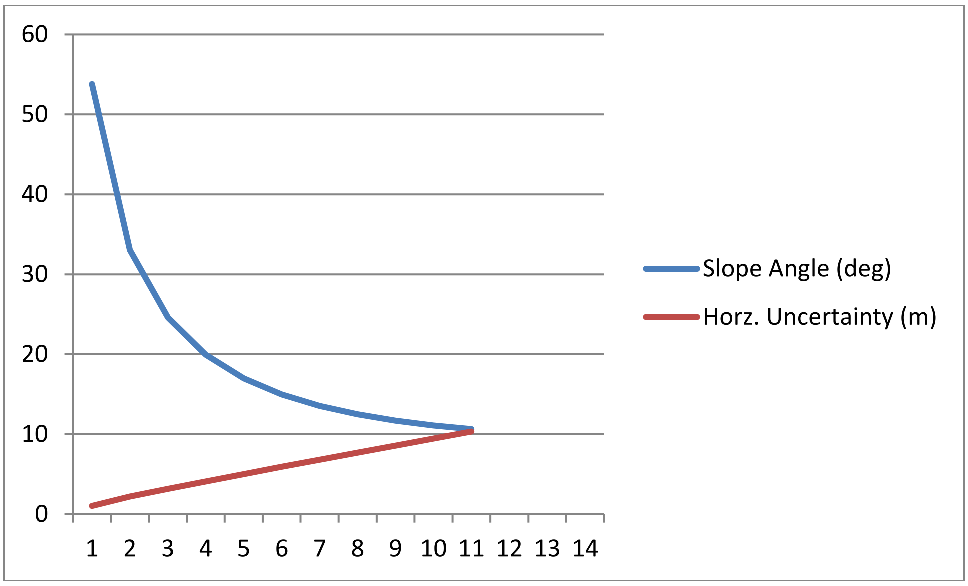

Figure 7: Inverse relation exists between horizontal uncertainty and slope angle

5. DISCUSSIONS

What has been supplied here is summarized version of the simulations as depicted in the tables. The simulation stops for a particular test when either the vertical uncertainty or the horizontal uncertainty exceeds its computed limit. It was also observed in the course of the analysis that inverse relation exists between horizontal uncertainty and slope angle whereas, a direct relation exists between vertical uncertainty and beamwidth. This calls for further research in this direction to ascertain a possible contribution to horizontal and vertical errors by sea bed slope angle and sonar beamwidth respectively.

6. CONCLUSION

From the foregoing calculations, simulations, results and analysis it follows that special interest should be attached to the sonar beamwidths employed in bathymetric survey operations. Certain sizes of sonar beamwidth are meant to be engaged in surveys of distinct parts of water bodies. To achieve bathymetric results within the limit of IHO specifications, the maximum beam widths of transducers that should be employed in bathymetric surveys within the special order and Order 1(a, b) criterion should not be more than 6 degrees and 12 degrees respectively. This range of beamwidths can accommodate all sea bed slope angles that are not hazardous to navigation in these areas.

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BIOGRAPHICAL NOTES

After my undergraduate studies in 2007, I joined an engineering firm; LEMNA Nig. Ltd a Nigerian based American company where I functioned as a site surveyor saddled with the setting out of an irrigation and flood control at Itu river bank and environ, Akwa Ibom State, Nigeria. I left the company in 2009 to join Enugu State Ministry of Works and infrastructure where I was engaged in high-way department to supervise and monitor road constructions with the province. In 2010, I got employed by the University of Nigeria as a graduate assistant. In 2012, I obtained an M.Sc. certificate in Hydrographic Surveying which fetched me a promotion to Assistant Lecturer. Currently I am a lecturer II in carder. Also an appraisal to lecturer I, has be sent to my employer. I am currently a Ph.D student of Hydrographic Surveying in the same institution,

I have presented so many conference papers in Nigeria and have published in International Journal of science and Engineering Volume 4, Journal of Environmental and Earth Science, volume 3 and tropical Environment; Journal of the faculty of Environment studies, University of Nigeria Nsukka, Volume 10 as co-other.

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