The Use of the International Hydrographic Organisation's 'Standards for Hydrographic Surveys' As a Measure of Depth Accuracy in Continental Shelf Determinations

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Article 76 of UNCLOS requires the determination of depths of 2,500m to establish the position of one of the two alternative components of the Outer Constraint to the Continental Shelf. Recognising the water depth's possible role, the Guidelines produced by the Commission on the Limits of the Continental Shelf (CLCS) specify the types of depth-measuring instrumentation that can be used, the types of analysis to transform bathymetry data into a bathymetric model, and the type of database and supporting information to be provided. Included in the latter is the requirement to provide 'A priori or a posteriori estimates of random and systematic errors', where a priori errors may be calculated using the International Hydrographic Organisation's (IHO's) S44 Standard for Hydrographic Surveys. Having the CLCS refer to this internationally accepted standard as the most appropriate for UNCLOS purposes imposes a responsibility on the IHO to ensure that S44 does provide an appropriate, up to date and achievable standard for 2,500m water depths. This paper shows how S44 could be revised to make it fully suitable for this new task, one that for which it was not originally designed . S44 defines total error as the Root Sum of Squares (RSS) of the constant and variable depth errors. Marine areas are divided into zones according to their use by surface shipping, and a table provides the values to be substituted in the RSS equation for each area. While this approach has proven useful for transportation purposes, it is not necessarily applicable to deep-water contours, in that it does not take into account the magnitude and impact of the many factors that influence the uncertainty of location of deep water contours. These differ greatly in their magnitude and influence as the sea floor deepens beyond navigation depths, and are explained in this paper.
We conclude with a firm suggestion to the IHO to undertake production of a new edition of S44 and include information on how it can be expanded to become more applicable to deep water.

Introduction

Article 76 of UNCLOS requires the determination of the 2,500m isobath to establish the position of one of the two alternative components of the Outer Constraint to the Continental Shelf. The other is a line 350M from the Baselines from which the breadth of the Territorial Sea is measured. The Commission on the Limits of the Continental Shelf (CLCS) in its 'Scientific And Technical Guidelines' (the Guidelines) (United Nations, 1999) requires *'A priori or a posteriori estimates of random and systematic errors'* for the bathymetric database used in the delineation of the 2,500 metre isobath. The Guidelines suggest that within submissions *' A priori depth error estimates may be computed by means of the following internationally accepted formulae'* and cite the formulae in the International Hydrographic Organisation's S44 (IHO, 1998). If the CLCS is acting appropriately by requiring error estimates, they are wise to refer to an already established standard produced by an international body that is cited in the Convention, but S44 was not, in our view, designed for this type of problem. Having the CLCS refer to this standard for navigational hydrography as the most appropriate for UNCLOS purposes imposes a responsibility on the IHO to ensure that S44 does provide an appropriate, up to date and achievable standard for 2,500m water depths. This paper argues for the IHO to examine the possibility of updating S44 to accommodate this requirement.

The Role of Depth in UNCLOS Article 76

Although Article 76 describes underwater terrain, the only specific depth it mentions is 2,500m. Paragraph 5 - 'The fixed points comprising the line of the outer limits of the continental shelf on the seabed, drawn in accordance with paragraph 4 (a)(i) and (ii), either shall not exceed 350 nautical miles from the baselines from which the breadth of the territorial sea is measured or shall not exceed 100 nautical miles from the 2,500 metre isobath, which is a line connecting the depth of 2,500 metres.' Bathymetry, the determination of the shape of the seafloor, without any specific depth value, is also important in determining the location of the Foot of the Slope, and may figure in establishing natural prolongation through what the CLCS calls a 'test of appurtenance'.

Comparative Uncertainty between All Components of a Continental Shelf Claim

Article 76 says nothing directly about how accurately the 2500m isobath, or indeed any of the other elements that it includes, needs to be located. However, an indirect indication may be embedded in Paragraph 7 which states *'The coastal State shall delineate the outer limits of its continental shelf, by straight lines not exceeding 60 nautical miles in length, connecting fixed points, defined by co-ordinates of latitude and longitude'.* Clearly those who drafted of the Convention, who were defining the locus of the outer limit, were prepared to live with a boundary that could be delineated by straight line segments, joining points that could be up to 60M apart. They offer no guidance on how well the *co-ordinates of latitude and longitude* are to be delineated: traditional rule of thumb says that co-ordinates recorded to the nearest second are positioned to within ±30m, but co-ordinates could be reported to the nearest minute, for instance, and still comply with the letter of the treaty. Was the treaty crafted this way in order to make it less expensive for a country to prepare a claim, perhaps? Perhaps flexibility was wanted, since Coastal States may delineate their outer limit by points very closely spaced if desired. In practice, a Coastal State

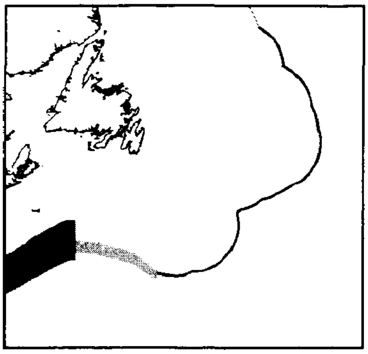

Figure 1: Diagram showing the horizontal uncertainty of the various components that could make up a hypothetical Outer Limit east of Canada. Thin pink line is 350M from the baselines, black line is 100M from 2,500 m isobath, blue is 60M from the Foot of the Slope, and red is a section based on sediment thickness from Foot of the Slope. While the uncertainty represented by the thickness of these lines is to scale, their location is arbitrary and is shown for illustrative purposes only

FEATURE	UNCERTAINTY (metres)	CLCS UNCERTAINTY REQUIREMENTS
PLUS 100 M	1	NOTHING
PLUS 60 M	1	NOTHING
350M	1	NOTHING
BASELINES	10	A PRIORI OR A POSTERIORI ESTIMATES
2500 m ISOBATH	100	A PRIORI OR A POSTERIORI ESTIMATES
Foot of the Slope - GEOMORPHOLOGY	1000	NOTHING
SEDIMENT THICKNESS	1000	EXPECTED RANGES OF ERROR
SEDIMENT THICKNESS	1000	ESTIMATE HORIZONTAL ERROR
F of S -EVIDENCE TO CONTRARY		
GEOLOGY	10 000	NOTHING
MAGNETICS	10 000	NOTHING
GRAVITY	10 000	A PRIORI OR A POSTERIORI ESTIMATES OF RANDOM AND SYSTEMATIC ERRORS

Table 1: Showing the elements that can comprise an outer limit under Article 76, an approximate magnitude of the uncertainty achievable for each element and the requirements to report uncertainty embedded in the CLCS Guidelines. Note that there is no uniform requirement for reporting uncertainty and no advice on what overall uncertainty should be

seeking to maximise its Continental Shelf will use 60M segments where the limit is concave (towards land) and very short segments where it is convex (away from land).

Do the 60M maximum line segments impact the uncertainty required of the 2,500m isobath and other components? Article 76 defines the final outer limit of the extended Continental Shelf of any Coastal State as a line that could be made up of a section that is 350M from the baselines, a section that is 100M from 2,500m contour and a section that is 60M from the Foot of the Slope, and a section based on sediment thickness from Foot of the Slope. The uncertainty associated with delineating this limit would vary from metres to tens of metres for the 350M section, tens of metres to hundreds of metres for the 2,500m contour, and hundreds of metres to tens of kilometres for the two criteria that begin with locating the Foot of the Slope. *See Table 1 and Figure 1.*

It could be argued that the required uncertainty of the outer limit is determined by the significant numbers in the co-ordinates of the points joining the straight lines. The uncertainty that the individual components must have in order to achieve this could be calculated. Alternatively, the uncertainty in the contributing components could be calculated and the outer points recorded to an equivalent uncertainty.

'Error Estimates' Required by the Commission

The CLCS Guidelines take a stance vis-à-vis uncertainty of the various components that make up the outer limit in which it is difficult to discern a central theme. For instance, they insist on error estimates for the bathymetry data used to establish the 2,500m contour, for the Baselines from which the breadth of the Territorial Sea is measured, for gravity data used to determine the location of the Foot of the Slope, and for sediment thickness. However, error estimates do not seem to be required for location of the Foot of the Slope determined on physiographic grounds, for geologic or magnetic data used in evidence to the contrary, or for any of the distance measurements. We thus have a situation where one of the components whose location is the best known, baselines, must have its errors reported, while Foot of the Slope with possible errors 100s or even 1,000s times greater need not be reported at all. Nor do the Guidelines make any effort to reconcile this range of uncertainty. They do not discuss how uncertainties in the different components combine to affect the outer limit. Nowhere do they say what they will do with the uncertainty values that are reported. For instance, is there any uncertainty value that is too great?

'A priori or a Posteriori Estimates of Random and Systematic Errors'

Generally, random and systematic errors can be estimated before taking the measurement, (*a priori*), or after the measurements have been collected, (*a posteriori*), and the Guidelines require a submission to include either. However, the third type of error, blunders or accidental errors, which are not mentioned in the Guidelines, cannot be estimated a priori although they can be detected and removed a posteriori. Before a survey is conducted, an application of the *a priori* approach tries to assess how well each piece of data might be collected, based on a theoretical appreciation of the equipment and methods used, the geometry of the survey lines in relation to the gross geomorphology of the area, the physical characteristics of the water mass, and other practical considerations. This can determine, for instance, whether the planned survey can possibly meet a particular required level of accuracy. In a way, *a priori* estimation is a one-sided test: it estimates how small the collective errors are most likely to be, but not how large the achieved errors can be. *A priori* estimation of uncertainty in bathymetry is often made more difficult since often the local slope and roughness of the seafloor are not known before the measurements are taken, yet these greatly influence the errors achieved.

Once data have been collected, the *a posteriori* approach to error estimation attempts to determine what accuracy really was achieved, and to classify the errors into random, systematic and accidental. It can be applied through successive iterations of the data cleaning process as errors are detected and removed. During each iteration, the data are examined and tested, resulting in an indication of how well they behave. During these iterations, if the data possess sufficient redundancy, blunders and systematic biases can be detected and eliminated or reduced. This approach can be applied to collections of data assembled from more than one source, collected by a variety of techniques over a number of years. This will be the type of data available for Continental Shelf determinations unless a new data set is collected specifically for Continental Shelf delineation.

All that can be determined from *a priori* estimates is the level of accuracy the survey was planned to meet. Whether it met this level of accuracy can only be determined by *a posteriori* testing. Given that the submissions to the Commission will be based on data that has already been collected, one wonders why the CLCS does not insist that only *a posteriori* estimates are permissible.

Method of Determining the *a Priori* Estimates of Depth Errors Required by the Guidelines

The stages in producing a bathymetric contour or isobath are the collection of water depths, the compilation of those depths into a database or model, and some manipulation of the data with output in the form of a contour. The Guidelines recognise these stages and specify the types of depth-measuring instruments that can be used while prohibiting the use of others, followed by a discussion of the uses of the database and types of analysis that can be performed. They demand that, paragraph 4.2.7. *'A full technical description of the bathymetric database will include. A priori or a posteriori estimates of random and systematic errors.'* They go on to specify that within submissions *' A priori depth error estimates may be computed by means of the following internationally accepted formulae'* and include the formulae from S44 with appropriate reference to the IHO (IHO, 1998). If the CLCS is acting appropriately by requiring these error estimates, they are wise to refer to an already established standard produced by an international body cited in the Convention, but S44 was not, to our knowledge, designed to be applied to this type of problem. The fact that it is being so used will hopefully be taken into consideration when the IHO commences work on a fifth edition.

S44 first addresses errors in the measurement of depth, in a section on hydrographic surveys, through a formula that basically combines the fixed (constant) and variable (i.e. varies with depth) errors as Root Sum of Squares, with no reference to whether the errors are random, systematic or accidental. For an existing data set, the magnitudes of each class of error within the data could be determined *a posteriori*, and the total error readily derived. [This is only possible if the data sources are well known. It would not be possible if the source was old charts or even old field documents.] However, since S44 is a standard for surveys to strive to achieve, it specifies, *a priori*, constant values for the fixed and variable errors that would be acceptable. These are grouped into four classes of surveys, with the class of survey to conduct being determined by the use an area will have by surface shipping. For example, a harbour used by deep draft vessels having more stringent permissible errors than an area that is occasionally used for a transit passage. Once hydrographers have decided the class of survey that an area requires, they simply use S44 to determine the error values they should achieve. Since the Guidelines do not propose any other values, it seems that the CLCS intends that submitting states use these same values. In that case, the literal interpretation of allowable error in measuring depths of 2,500m, according to the S44 Order 3 survey standard, is ±57.5m.

Errors in the production of isosbaths from the depth measurements are dealt with in S44 as the 'Bathymetric Model'. Errors are calculated using the same formula as used to determine depth measurement errors, with larger values of the fixed and variable errors. Since with old style Single Beam Echosounders (SBES) surveys, the contours were often drawn in non-sounded spaces, larger values are intuitively correct, (Monahan and Casey, 1983) although the magnitudes they should have is not obvious. From the S44 tabled values, the allowable error in deriving a 2,500m isobath from the bathymetry model is ±125m.

Impact on the Location of the 2,500 m Contour of Current Error Values in S44

The translation of permissible errors in (vertical) depth measurement into horizontal uncertainty of the location of the 2,500m contour is (Horizontal uncertainty of contour = ± uncertainty in depth measurement / cosine of bottom slope) (Monahan and Wells, 1999). Bottom slopes in areas where the 2,500m contour will be used generally have very low gradients. Conventionally, the Continental Slope averages 1-3 degrees, the Continental Rise less than 1 degree. Pratson and Haxby,(Pratson and Haxby,1996), measured Continental Slope gradients when they compared both regional and local slopes as measured by Multibeam Echosounder (MBES) over five portions of the US Continental Slope. The steepest area they examined was off New Jersey where they measured a regional slope of 2.5 degrees and a local slope of 7.6 degrees. These observations seem to confirm the 2 to 4 degrees average gradient expected. The impact of these slope values is demonstrated in Table 2.

We believe the uncertainty values in Table 2 are too pessimistic, and can be reduced considerably. Doing so requires revising S44. The Introduction to S44 states that the intent is to update S44 every five years. However, a rewrite should not only reflect the improvements in technology that allow smaller error values, it should increase the scope of the standard to encompass all users and producers of depth data. In the following sections we discuss estimates of depth error at 2,500m that can be achieved at present.

S44 Element	**Water Depth**	**Vertical Accuracy**	**Horizontal Uncertainty (m) over Bottom Slopes of**			
			1 deg	**2.5 deg**	**7.6 deg**	**10 deg**
Surveys Depths	2500	±57.5	±3295	±1317	±431	±326
Bathymetric Model Contour	2500	±125.1	±7167	±2865	±938	±709

Table 2: Uncertainty in the location of the 2,500m contour, based on expected seabed slopes and the error values in S44

Uncertainty in Components of Depth Measurements and Isobaths Derived from Them

Edition 4 of S44, the current edition, is written so that the variable errors quickly become dominant as depth increases, to the point where the constant errors are negligible at 2,500m. The principal contributors to uncertainty in deep water sounding come from the geometry of the acoustic beam and its intersection with the bottom and from uncertainty in determining sound speed. In this section we discuss their contributions and how they can be reduced.

The Effect of Beam Width

Sound propagates away from the face of the transducer in a pattern that resembles a cone or beam, and the concept of 'beam width' is used to rate sounding systems. Beam width is twice the angle between a line perpendicular to the centre of the transducer face and the point where the energy contained in the beam is reduced to half that at the perpendicular (i.e. 3dB. below the maximum source level). The intersection between the beam and the seafloor is called the area insonified or footprint, and the size of this area greatly affects the uncertainty of the soundings obtained. Design and construction of the echosounder transducer dictates the beam width it propagates at a given frequency, while distance to the seafloor regulates the size of the area insonified. Area insonified produces three different uncertainties. It can smooth the shape of large seafloor features, it can obscure features whose wavelengths are less than twice the diameter of the insonified area (assuming a circular footprint), and it can introduce horizontal uncertainty of the location of a sounding when the seafloor is sloping.

The size of the area insonified has been reduced greatly in the last few years. In part this is due to the reduction in beam width from 30 degrees for older single beam sounders to 2 degrees or less with multibeam sounders, in part because of the growth in deploying the transducer close to the seafloor. When S44 was drafted, wide beam sounders were still in common use, but the trends discussed above mean that wide beam sounders are being phased out. Consequently, the portion that beam width contributed to overall uncertainty can be greatly reduced. [While wide angle SBES are quickly being eliminated for shallow water surveys, data being reviewed for the 2,500m isobath will be for the most part from old poorly calibrated sounders at least for the next five years.]

The Effect of Sound Speed

How accurately we know the speed of sound will affect the accuracy of the depth measurement. Speed of sound varies with the density of the medium through which it is travelling and the density of seawater is calculated by measuring its salinity and temperature. Although these can vary widely in shallow water, deep-water salinities and temperatures are much more predictable. The less variability there is in

Fixed errors	Nominal beam angle	Beam angle Uncertainty	Sound Speed Var'n	Sound Speed error	Vertical Error	Percent of Depth	Horizontal uncertainty on seafloors sloping			Radius ensonified
							1 deg	2.5 deg	7.6 deg	
m	degrees	m	m/s	m	m	%	m	m	m	m
0	1	0.10	0.0	0.00	0.10	0.00	5	2	1	22
0	2	0.38	0	0.00	0.38	0.02	22	9	3	44
0	24.6	57.39	0	0.00	57.39	2.30	3289	1304	431	545
0	30	85.19	0	0.00	85.19	3.41	4882	1936	640	670

Table 3: Showing the effect of typical SBES and modern MBES (in vertical mode) beam widths on uncertainty in location of the 2,500 m contour. Nominal beam angle of 1 and 2 degrees marks the extremes between which MBES beamwidths normally fall. Nominal beam angle of 24.6 degrees is the minimum required to achieve the S44 standard, in the absence of all other uncertainty. Nominal beam angle of 30 degrees represents the standard for SBES in deep water that will apply to most existing single beam soundings. Vertical error is the RSS of fixed errors, beam angle uncertainty and sound speed error. Seafloor slopes are a nominal 1 degree, and the regional and local maxima of Pratson and Haxby, 1996. Radius ensonified assumes that the seafloor is flat and horizontal as the sound beam intersects it

Fixed errors	Nominal beam angle	Beam angle Uncertainty	Sound Speed Var'n	Sound Speed error	Vertical Error	Percent of Depth	Horizontal uncertainty on seafloors sloping			Radius ensonified
							1 deg	2.5 deg	7.6 deg	
m	degrees	m	m/s	m	m	%	m	m	m	m
1	1	0.10	0.0	0.00	1.00	0.04	58	23	8	22
1	2	0.38	0	0.00	1.07	0.04	61	24	8	44
1	24.6	57.39	0	0.00	57.39	2.30	3289	1304	432	545
1	30	85.19	0	0.00	85.19	3.41	4882	1936	641	670

Table 4: Showing the same contents as Table 3 with the addition of fixed errors of 1m, the value in S44. Although the fixed errors make a negligible contribution at large beam angles, they are the major component at the small angles used in MBES

Fixed errors	Nominal beam angle	Beam angle Uncertainty	Sound Speed Var'n	Sound Speed error	Vertical Error	Percent of Depth	Horizontal uncertainty on seafloors sloping			Radius ensonified
							1 deg	2.5 deg	7.6 deg	
m	degrees	m	m/s	m	m	%	m	m	m	m
0	0	0.00	1.0	1.67	1.67	0.07	96	38	13	0
0	0	0.00	2.0	3.33	3.33	0.13	191	76	25	0
0	0	0.00	5.0	8.33	8.33	0.33	478	189	63	0
0	0	0.00	10.0	16.67	16.67	0.67	955	379	125	0

Table 5: Showing the predicted effect (at nadir) of sound speed uncertainty alone

the parameter being measured, the smaller the chance of error in measuring it.

For vertical incidence soundings (SBES and the nadir beams of MBES) it is the harmonic mean sound speed that matters. At 2,500m, to introduce a depth uncertainty of 1m requires the harmonic mean sound speed to have an uncertainty of 0.6 m/s. Modern Conductivity-Temperature-Depth (CTD) profile sampling instruments can predict absolute sound speed to better than 0.5 m/s (Hare, 2001).[Nevertheless, these modern devices were not available when the data were gathered and even now, vertical casts rather than profiling are more common at 2,500 m.]

For non-nadir MBES beams, the refraction or ray bending of the echosounding signal dominates the sound-speed-related depth uncertainty. Sound speed uncertainties at the transducer face and near the surface have a more dramatic effect than do sound speed uncertainties deeper in the water column. In simplified terms, to the nadir uncertainty must be added a term which increases with beam angle as $\tan^2$(beam angle) (Hare, 2001). Hence, at a beam angle of 45° away from nadir, a given uncertainty (bias) in sound-speed would produce a depth uncertainty three times as large as the nadir depth uncertainty, and at a beam angle of 60° it would be four times the nadir uncertainty.

Combination of Sound Speed and Beam Width Uncertainty

Predicted sound speed and beam width uncertainties are combined in Table 6. Beam widths compatible with nadir beams from a MBES produce predicted vertical errors of between 0.08 per cent and 0.14 per cent of depth, conforming to accuracies of 0.2 per cent that have been reported for deep water swath bathymetric data at high aspect ratios (±45 degrees). This is an order of magnitude better than required by a literal interpretation of S44, and reduces the horizontal uncertainty to levels approaching those of the other Outer Constraint, the 350 M line.

More Appropriate Values for S44

Horizontal uncertainty in the 2,500m contour plus 100M constraint, based on data that meet the S44 standard is more pessimistic than necessary with present day technology. It is probably greater than most archived data, particularly after the data have been cleaned and adjusted. A much smaller uncertainty,

Fixed errors	Nominal beam angle	Beam angle Uncertainty	Sound Speed Var'n	Sound Speed error	Vertical Error	Percent of Depth	Horizontal uncertainty on seafloors sloping			Radius ensonified
							1 deg	2.5 deg	7.6 deg	
m	degrees	m	m/s	m	m	%	m	m	m	m
1	1	0.10	1.0	1.67	1.95	0.08	112	44	15	22
1	2	0.38	2.0	3.33	3.50	0.14	201	80	26	44
1	24.5	56.92	5.0	8.33	57.54	2.30	3297	1308	433	543
1	30	85.19	10.0	16.67	86.81	3.47	4975	1973	653	670

Table 6: Showing combination of predicted sound speed and beam width uncertainty. (Beam angle in row three is reduced to allow for the inclusion of fixed errors)

10s of meters rather than 100s, is readily achievable. A more appropriate value for 'b', the depth-dependent uncertainty component, would be 1 per cent of depth. This is the value associated with S44 4th Edition Special Order survey specifications, and with S44 3rd Edition.

The present S44 4th Edition claims on one hand to be minimum standards, but on the other hand is silent on the conditions under which it would be appropriate to deviate from the prescription that Order 3 standards (for which 'b' is 2.3 per cent of depth) be applied for all areas with depths exceeding 200m. The CLCS reference to S44 is also silent on whether S44 should be interpreted differently for Article 76 surveys, in contrast to shallow water surveys.

Technology permits, and reasonable Article 76 survey uncertainty management demands, that the S44 standards be interpreted as requiring Special Order, rather than Order 3, depth uncertainty for Article 76 surveys. What would be preferable is that the application of S44 to Article 76 surveys be carefully considered when the 2500m isobath is produced or used for UNCLOS purposes.

Conclusions

The CLCS has found it important to refer to the IHO internationally recognised standard for accuracy in water depth measurements. This imposes a responsibility on the IHO to ensure that the standard does produce useful results for Article 76 purposes. As currently written, S44 is a standard based on navigation requirements, and has largely ignored deep water. It does not embody current capability and is much too loose.

We propose three actions:

The IHO should issue a footnote / additional instruction / interpretation regarding S44 4th Edition, pointing out that, for Article 76 surveys, specifying a vertical uncertainty of 1 per cent of water depth is appropriate, achievable, reflects the capability of historic archived data sets, and does not impose an unrealistic burden on new data acquisition.

The CLCS should amend their guidelines, referring to this new IHO S44 instruction /interpretation.

The IHO should as soon as possible commence work on S44 5th Edition, with the specific goal of incorporating more thoroughly the demands of Law of the Sea and other users, with the addition of sections dealing with deep water, and other non-navigational applications of bathymetric surveys.

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Biographies

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Dave Wells retired from the University of New Brunswick in 1998, after two decades of teaching hydrographic surveying there. He now follows the seasons, and this year taught at four universities: University of Southern Mississippi from January to May; University of New Hampshire in May and June; Universiti Teknologi Malaysia during the summer; and from September to December back to the University of New Brunswick, where is now Professor Emeritus, and where this fall he introduced three new hydrography courses (on tides, kinematic positioning, and hydrographic data management). Dave and three colleagues teach a short course on multibeam sonar surveying four times each year at various locations around the world. Since 1990 Dave has been a member of the FIG/IHO International Advisory Board on Standards of Competence in Hydrographic Surveying, which meets for 10 days each year in exotic locations. Dave is exploring the possibility of doing some of his teaching via online (or CD) course delivery, perhaps reducing some of his hectic travel.

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