Vector Data Extraction from Forward-Looking Sonar Imagery for Hydrographic Survey and Hazard to Navigation Detection

R. Glenn Wright
GMATEK, Inc., Annapolis, MD USA
World Maritime University, Malmo, Sweden
glenn@gmatek.com / p1301@wmu.se

Cheryl M. Zimmerman
FarSounder, Inc.
Warwick, RI USA
cheryl.zimmerman@farsounder.com

***Abstract*— This paper describes research to determine the effectiveness of forward-looking sonar as a means to safely navigate vessels in frontiers such as the Arctic and other regions that may be lacking recent or comprehensive hydrographic survey. Key elements of this investigation include the range at which valid measurements may be taken, uncertainty in measurement, confidence level of the measured value and resolution available to detect underwater hazards affixed to the bottom and suspended within the water column to provide time sufficient to enable the crew to take action to alter course and/or speed to avoid casualty. An additional factor involves examining forward-looking sonar measurements as a means to survey shallow sea bottom where hydrography data does not exist or is not accurate, potentially offering a valuable resource to supplement scarce national hydrographic office assets to accomplish this task. An assessment of viability is also made regarding compliance with the International Hydrographic Organization (IHO) standards for hydrographic surveys that form the basis for soundings that appear on navigation charts.**

***Keywords*— forward-looking sonar; navigation; nautical charts; hazard to navigation; grounding; Arctic; reef**

I. INTRODUCTION

Research is presently underway investigating the use of three-dimensional forward-looking (FL) sonar as a means to enhance the safety of navigation to avoid vessel groundings in areas where hydrographic surveys may not exist, bottom conditions have changed due to storm action, in natural disaster and war zones where navigation infrastructure has been destroyed, where physical aids to navigation (AtoN) are not available due to ice movement, and amongst coral reefs where sinkers to place AtoN cannot be used due to their adverse effect on the environment. The problem is defined in terms of navigation charts containing soundings that are incomplete or have sparse coverage making them unreliable, especially in the Arctic but also problematic worldwide. A review of IHO standards for hydrographic survey is provided, identifying the "order of survey" to which such data products must conform. A summary of the current state-of-the-art in multibeam and multiple transducer sonar systems for hydrographic survey is provided, followed by a description of current FL sonar technology with a comparison of their similarities and differences in capabilities. Experiments investigating its use as a means to navigate in uncharted and poorly charted areas are described along with their results illustrating the effectiveness of this technology and limitations that may restrict its use. Conclusions regarding the viability of FL sonar to aid in vessel navigation are provided, along with future directions in research likely to follow.

II. CHARTING DEFICIENCIES

The deficiencies of hydrographic surveys in areas such as the Arctic and the vast archipelagos of the Pacific Ocean have been demonstrated through dramatic groundings of vessels. One example is the cruise chip M/V *Clipper Adventurer* that ran aground on 27 August 2010 in Coronation Gulf, Nunavut in the Northwest Passage on an uncharted shelf in an area where the depths of the waters were virtually unknown [1]. Another is the United States Navy minesweeper USS *Guardian* that grounded on 17 January 2013 on Tubbataha Reef in the Sulu Sea near the Philippines due to a failure of the crew to reconcile a discrepancy of the 4 to 8 mile distance between the charted and actual positions of the reef [2]. A most recent example is MSV *Fennica* where, on 3 July 2015 while enroute between Dutch Harbor Alaska and the Shell Oil drilling field in the Chukchi Sea, the vessel was holed when it traveled near a previously uncharted rocky shoal [3].

The significance of these charting discrepancies is greatly heightened due to the increase in vessel traffic as a result of energy exploration in the Arctic itself as well as transit traffic seeking new trade routes between Europe and Asia. The *U.S. Coast Pilot* states that much of the Bering Sea area is "only partially surveyed, and the charts must not be relied upon too closely, especially near shore. The currents are much influenced by the winds and are difficult to predict; dead reckoning is uncertain, and safety depends upon constant vigilance" [4].

The problem being addressed is illustrated by Figure 1, which represents a portion of official National Oceanographic and Atmospheric Administration (NOAA) marine navigation chart: #16103 for Cape Beaufort, Alaska that is effectively devoid of soundings information. This is typical of many official nautical charts in the area where few, if any, soundings exist exemplifying the difficulties involved in ship navigation.

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Indeed, most soundings that do exist were taken during World War 2 when the first (and probably last) of these surveys was performed. The area represented in this chart situated on the northern slope of Alaska is regular and featureless, sloping gradually from the shoreline with low and grassy inland terrain. Assumptions may be made, with various degrees of accuracy, that the same land topography may also extend into the sea resulting in a fairly regular bottom. This theory is supported by other portions of this chart for which soundings do exist that depict such bottom topography.

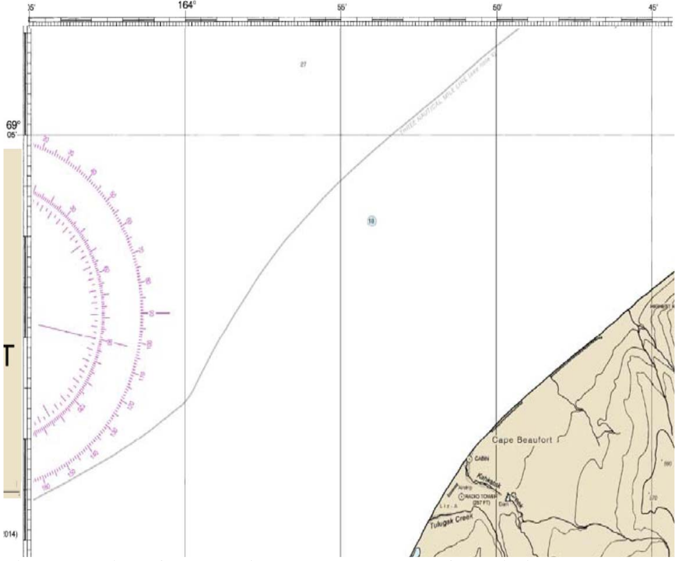


Fig. 1. Portion of NOAA Chart 16103, Cape Beaufort, Alaska.

However, of much greater concern are areas that are only partially surveyed that show highly irregular bottoms. Such an area is shown in Figure 2, with partial soundings where there is high potential for hazards to navigation to exist in the blank portions of the chart.

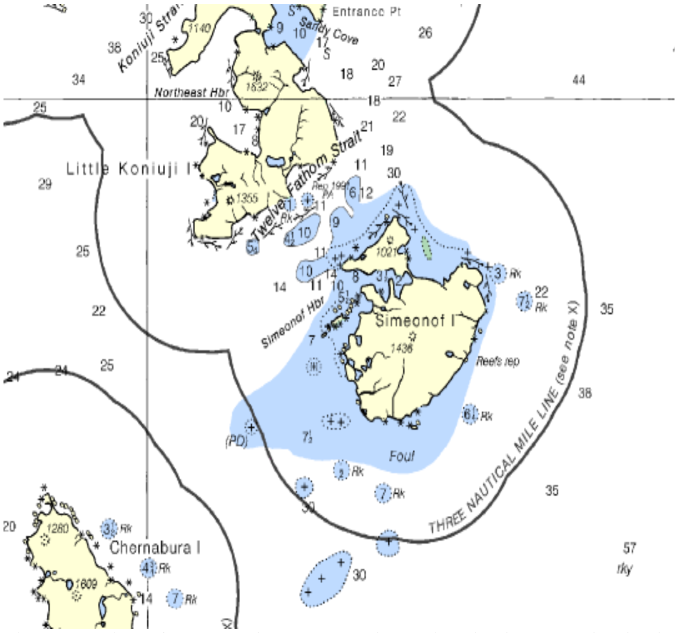


Fig. 2. Portion of NOAA Chart 16540, Shumagin Islands to Sanak Islands, Alaska Peninsula. (soundings in fathoms)

This same concern also extends to the Chukchi Sea in the Arctic Ocean within which Royal Dutch Shell is pushing ahead with plans to explore for oil with two or three wells using as many as 30 or so vessels to support their activities. Sparse hydrographic coverage in a highly travelled area can lead to an unwarranted level of confidence in chart content that may result in an accident. Such a theory has already gained support through the holing of MSV *Fennica*. The official NOAA chart near Dutch Harbor Alaska, shown in Figure 3, depicts water sufficient for navigation where an uncharted shoal exists and holing occurred.

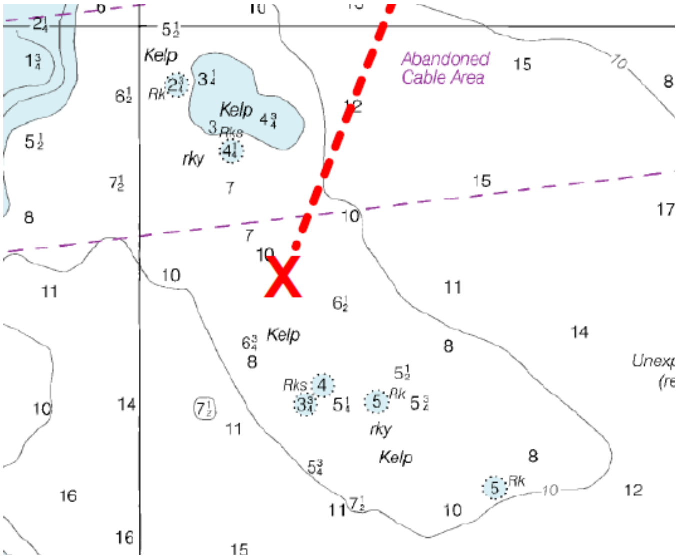


Fig. 3. Portion of NOAA Chart 16530, Captains Bay, Unalaska Island. (soundings in fathoms)

Given the inaccuracies and the unreliable nature of navigation charts in these areas it is prudent for mariners to consider the use of three-dimensional FL sonar to display real time hydrographic imagery of the underwater environment directly ahead of the vessel that may help to avert a grounding, or worse: casualty that results in loss of life or a major oil or chemical spill.

III. INTERNATIONAL HYDROGRAPHIC ORGANIZATION STANDARDS

The IHO establishes international minimum standards for the performance of hydrographic surveys that are used as the source of soundings information on navigation charts by national hydrographic authorities. The currently established guidance is the February 2008, IHO Special Publication No. 44, *IHO Standards for Hydrographic Surveys* [5].

Hydrographic surveys are performed based upon the "orders of survey considered acceptable to allow hydrographic offices / organizations to produce navigation products that will allow the expected shipping to navigate safely across the areas surveyed" [6]. The most rigorous of the orders is the Special Order survey intended for use where under-keel clearance is most critical, generally in waters less than 40 meters in depth.

As the purpose of FL sonar is to detect hazards to navigation that may jeopardize safe navigation, one would presume that data obtained should be in accordance with the requirements for Special Order surveys. The next level of survey is Order 1a, “intended for those areas where the sea is sufficiently shallow to allow natural or man-made features on the seabed to be a concern…” The elements that comprise these standards relevant to this discussion are summarized in Table I and include horizontal and vertical uncertainties to specified confidence levels.

Total Horizontal Uncertainty (THU) or position uncertainty is determined based upon a reference to a datum, e.g., WGS84, consisting of the combined contributions of all uncertainty sources using a statistical method to establish the position uncertainty at the 95% confidence level. This would also apply to hazards to navigation suspended within the water column.

Likewise, Total Vertical Uncertainty (TVU) or depth uncertainty is the uncertainty of the reduced depths determined based upon reference to a vertical datum, consisting of the combined contributions of the individual uncertainties. Uncertainties include both depth dependent and depth independent factors according to the formula [7]:

$$\pm \sqrt{a^2 + (b \times d)^2} \tag{1}$$

Where:

a	represents that portion of the uncertainty that does not vary with depth,
b	is a coefficient which represents that portion of the uncertainty that varies with depth,
d	is the depth, and
$b \times d$	represents that portion of the uncertainty that varies with depth.

The Confidence Level (CL) is the probability that the true value of a measurement will lie within the specified uncertainty from the measured value. An additional factor is the consideration of tides and water level observations across the entire area of the survey while measurements are taken.

TABLE I. MINIMUM STANDARDS FOR HYDROGRAPHIC SURVEYS

	Special Order	**Order 1a**
Area Description	Areas where under-keel clearance is critical	Areas where under-keel clearance is less critical but features of concern may exist.
Depth	< 40 meters	< 100 meters
Maximum Allowable THU (95% CL)	2 meters	5 meters + 5% of depth
Maximum Allowable TVU (95% CL)	a = 0.25 meter, b = 0.0075	a = 0.5 meter, b = 0.0013
Coverage	Full Sea Floor Search	Full Sea Floor Search
Feature Detection	Cubic features > 1 meter	Cubic features > 2 meters to 40 meters 10% (> 40 meters)

IV. HYDROGRAPHIC SURVEY TECHNOLOGY

Modern hydrographic surveys are performed using multibeam echo sounders that transmit hundreds of beams of sound through the water to acquire water depth information in a survey area; capturing images of the seabed and determining least water depths over critical items such as wrecks, obstructions, and dangers to navigation; and to detect objects in general. Using this method a “swath” of soundings (i.e., depths) is produced across an area of approximately two to four times, and up to twelve times the water depth depending upon the instrument.

Measurements can be taken using a signal generated at the vessel in a fan-shaped pulse that propagates vertically down to the sea bed and is reflected back to the vessel. A towed-array following a vessel from which measurements are taken may also be used. Measured values include depth along with heave, roll, pitch, yaw, positioning and timing to precisely determine water depths and locations.

There are many manufacturers of multibeam echo sounders used extensively on a variety of hydrographic survey vessels worldwide. These include Kongsberg, Teledyne RESON, Teledyne ODOM, R2Sonic, L-3 Communications, SiMRAD and others; most of whose products can produce IHO-compliant hydrographic data. The focus of this research is on shallow waters within which hazards to navigation are likely to be found. Therefore, the analysis considers only products designed for use in shallow water environments, excluding those for deep-sea survey.

Technical specifications for shallow-water survey multi-beam sonar vary widely, with depth measurement capability ranging from 75 to 300 meters. Range resolution can vary across a wide span from 1.5 mm to 100 cm, although most lie within a span from 1 to 6 cm. Operating frequencies are between 100 to 500 kHz and exhibit capabilities to transmit signals on one or more fixed and variable frequencies. The number of beams used for measurement can also vary widely, from as few as 10 to as many as 1024, with most in the range of 512 beams. Ping rates can range from 6 to 60 Hz. Output powers between 500 to 3,000 $\text{Watts}_{\text{RMS}}$ are prevalent.

V. FORWARD-LOOKING SONAR TECHNOLOGY

A variation of the echo sounder and multi-beam sonar is FL sonar used to detect bottom features and objects within the water column forward of the bow. Despite its usefulness and the availability of this technology in the commercial marketplace, it’s inclusion within ships’ complement of navigation sensors is a rare occurrence. This is most likely due to a combination of 2-dimensional displays that were difficult to interpret and a lack of IMO carriage requirements.

The methods used for detecting bottom features, objects and soundings by determining range, azimuth and elevation information can generally be described as variations on transmitting a steerable sonar signal ahead along the path of the vessel or transmitting a single ping from which snapshots of the environment are obtained. A mosaic representing a swath of the bottom topography and specific targets ahead is then created as the vessel progresses along its course.

The horizontal range of FL sonar can extend from eight to twenty times the depth ahead, depending on bottom and target conditions. It is most effective when the bottom topography slopes upwards and when targets are large and consist of hard rock and/or coral that provide good acoustic signatures. Products with 3-dimensional imagery offer a realistic portrayal of the course ahead. Systems have been developed with different capabilities, most being intended for pleasure and small fishing boats. Systems with range and resolution adequate for use on larger vessels such as workboats, offshore service vessels, merchant and passenger vessels have only recently become available in non-military applications. However, operational constraints may create limitations on their usefulness. For example, effective range may be limited by tradeoffs in transducer design to minimize water resistance and drag.

Experiments have been performed throughout the course of this research in diverse locations and bottom configurations along the east coast of the United States using two different systems to assess their capabilities: the EchoPilot 3D and FarSounder-500. The experiments described in this paper reflect the use of the FarSounder-500 FL sonar system to take advantage of greater range capabilities and access to digital data products created during operation. This system is capable of 100, 200 and 500 meter (x90°) forward range, limited by approximately 8 times the water depth [8]. Bottom features are detectable to a maximum depth of 50 meters, more than sufficient for hazard to navigation detection. Its operating frequency is 61 kHz. Output power is less than 1.5 kW RMS. Data obtained from a single ping is used to create an image of the bottom and to detect targets that may exist within the water column at a particular point in time. Multiple ping data are used to create contiguous underwater imagery. A more capable, higher resolution system also exists. The FarSounder-1000 can provide up to 1,000 meter (x60°) forward coverage.

VI. FORWARD-LOOKING SONAR CAPABILITY ASSESSMENT

The findings described in this paper result from an investigation into the use of FL sonar for ship navigation in poorly and uncharted regions as part of a strategy for the implementation of virtual aids to navigation in real time [9]. A "ship-centric" approach is followed to advance vessel usage of new environmental sensor technology such that expeditionary and commercial vessels may safely navigate using real-time information supplied by the vessel's own sensors.

The premise for the experiments described is that, given a specific geographic position, the corresponding position on a nautical chart should accurately represent the depth and bottom configuration of that position. Likewise, should the actual geographic position be different from the indicated or believed position, the depth and bottom configuration is at best uncertain and indeed likely to be wholly inaccurate and not representative of the actual position. Where soundings and bottom configuration are inaccurate or not available due to lack of hydrographic survey, own ship sensors should be adequate to detect bottom configurations and create soundings at its current position as well as forward of the vessel in the path of transit sufficient to ensure safe navigation.

In this implementation, FL sonar is investigated as the means to accomplish this goal. This approach is contrasted against the traditional approach to hydrographic survey as a means to increase safety of navigation, taking advantage of the presence of vessels already operating within the Arctic and other remote locations. Data products created as a normal consequence of such operations are envisioned to become available to national hydrographic authorities as a resource for the creation and update of nautical charts.

A. Test Platform Configuration

The system used in this demonstration comprises a fusion of positioning, timing and environmental sensor data obtained locally using vessel assets. This system may be used in combination with GNSS and other methods of establishing vessel position such as inertial navigation. The vessel upon which experiments were performed and data was acquired is the R/V *Cap'n Bert*, a 53 foot stern trawler with draft of 6 feet owned and operated by the University of Rhode Island Department of Fisheries, Animal and Veterinary Sciences. Ship's equipment relevant to experiments includes:

- FarSounder-500 3D FL sonar mounted at the very bow, 3 feet below the waterline and along the centerline of the vessel.
- Furuno SC-30 GPS/satellite compass using the WGS84 datum; antenna located 20 feet astern of the FarSounder-500 FL sonar and offset 3 feet to port of the centerline,
- Furuno FCV-7151 video sounder operating on 200 kHz; transducer located 23 feet astern of the FarSounder-500 FL sonar, 3 feet below the waterline and offset 2 feet to starboard of the centerline,

Sensor data sampling was performed continuously over a NMEA 0183 bus.

B. Experiments

A series of experiments were performed using data acquired from several different areas of Narragansett Bay in Rhode Island, coverage for which is included in NOAA chart 13223. Vessel echo sounder transducer offset has been recorded, height of tide has been adjusted to reflect mean lower low water (MLLW) using the appropriate tide station at the time of measurement. GNSS estimated positioning error (EPE) was not recorded and has been calculated based upon different values which may or may not be representative of the actual EPE at the time the data was acquired. Nautical chart representations were created using ArcGIS and ArcMap products with the S-57 Viewer add-on. The results presented are representative of and consistent with all locations examined. The processes and procedures are described along with the presentation and explanation of the results. The data presented reflects a sampling of the thousands of data points obtained from these experiments shown in reduced form for clarity.

Weather conditions at the time this experiment was conducted consisted of calm seas, partly cloudy skies, wind at a light breeze from the NNW at 4 knots, air temperature 39° F and a barometer of 30.10 inches steady. There was essentially a slack tide with high at 1430 GMT (within 6 minutes of track completion) and water temperature of 38°F.

The specific area from which the experimental data was acquired spans 0.41 nautical miles along the track from Start to End positions as illustrated in Figure 4. This area represents a bottom slope descending in depth from approximately 60 to 80 feet along the route.

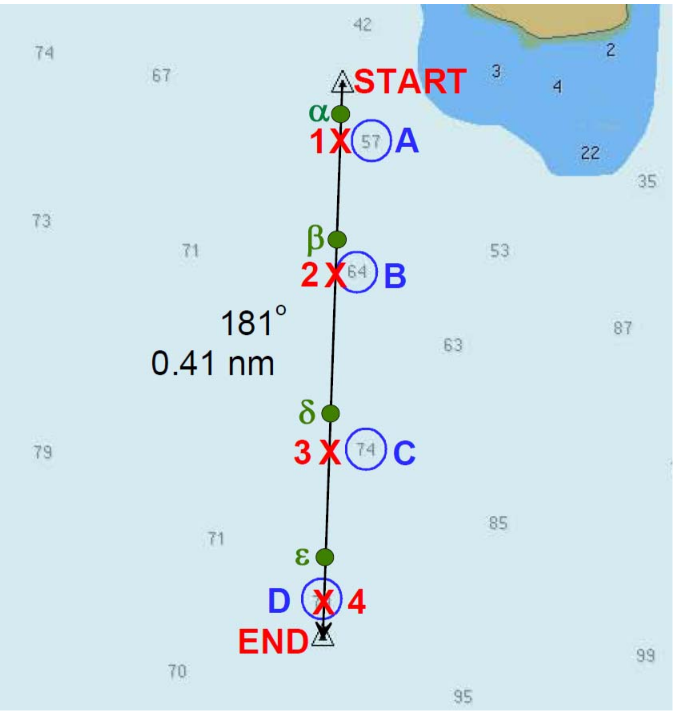


Fig. 4. Portion of NOAA Chart 13223, Narragansett Bay, Rhode Island. (soundings in feet)

The track followed a course of 180° (± 2°) at a speed of 5 knots (approximately) and was chosen due to the nearby proximity of depth soundings on the chart at locations A through D within the range of FL sonar that can form the basis for comparison, as well as the slope characteristics of the bottom. The elapsed time to transit the route was just under 5 minutes, beginning at 14:19 and concluding at 14:24 GMT during which 190 sonar pings were obtained; approximately one ping every 1.6 seconds and 4 meters between pings resulting in 2.1 gigabytes of data collected.

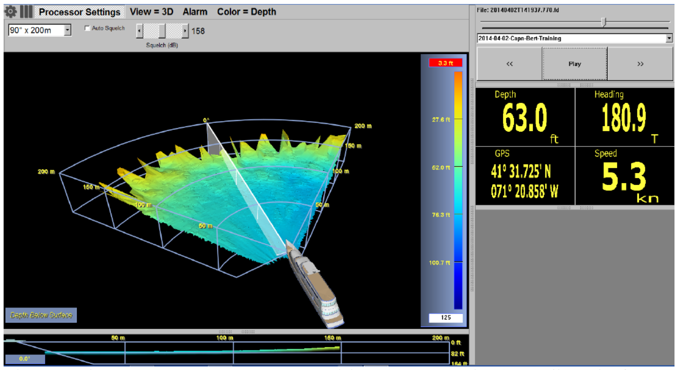
Locations 1 through 4 were identified on the NOAA chart as being approximately at right angles to the depth soundings (locations A through D) on the chart. An appropriate position on the track (α through ε) was then selected from which specific sonar data would provide an accurate coverage of the depth soundings locations (A-D). The charted locations α-ε were then correlated with the closest position from which sonar ping data was available, and these data were selected for analysis.

Table II provides details regarding the track followed, with each of these locations identified by latitude and longitude in Figure 4. Positions of locations obtained from the chart are distinguished from those provided within the data. Additional sensor data obtained from the vessel are included regarding heading, echo sounder measurements at each of these positions on the track and the corresponding time. Bearings to each of the depth soundings locations identified on the chart (A-D) from the locations at which FL sonar data was obtained (α-ε) as well as directly abeam the soundings locations (1-4) are also included. Information marking each depth sounding is shown, along with the depth displayed at that location.

The graphical representation of the user interface at the Start position is shown in Figure 5. This figure depicts imagery of the bottom configuration, position information expressed in latitude and longitude; along with vessel speed information obtained from GNSS and depth obtained from the vessel echo sounder. The bottom contour directly ahead of the vessel on a bearing of 0° corresponding to the movable arm is also shown at the bottom. This arm may be repositioned along any bearing within the 90° zone of coverage to show depths.

TABLE II. SUMMARY OF TRACK POSITIONS AND SOUNDINGS LOCATIONS

Vessel Location								**Depth Soundings** (NOAA Chart #13223)					
Position • X	**Nautical Chart #13223**		**Vessel Sensors**					**Track to Sounding**		**Mark**	**Latitude**	**Longitude**	**Depth (ft)**
	Chart Latitude	**Chart Longitude**	**Ping Latitude**	**Ping Longitude**	**Heading**	**ES (ft)**	**Time**	**Bearing**	**Distance**				
START	41° 31.7250 N	071° 20.8578 W	41° 31.725 N	071° 20.858 W	181°	63	14:19:37						
α	41° 31.7051 N	071° 20.8583 W	41° 31.705 N	071° 20.860 W	181°	66	14:19:52	35° Port	62 m	**A**	41° 31.6775 N	071° 20.8327 W	57
1	41° 31.6781 N	071° 20.8592 W	41° 31.679 N	071° 20.862 W	182°	67	14:20:11	88° Port	36 m				
β	41° 31.6058 N	071° 20.8634 W	41° 31.606 N	071° 20.869 W	182°	71	14:21:05	29° Port	52 m	**B**	41° 31.5813 N	071° 20.8464 W	64
2	41° 31.5816 N	071° 20.8647 W	41° 31.582 N	071° 20.871 W	182°	71	14:21:22	88° Port	25 m				
δ	41° 31.4806 W	071° 20.8689 W	41° 31.480 N	071° 20.875 W	178°	78	14:22:35	35° Port	73 m	**C**	41° 31.4490 N	071° 20.8377 W	74
3	41° 31.4497 N	071° 20.8703 W	41° 31.449 N	071° 20.875 W	179°	78	14:22:58	91° Port	45 m				
ε	41° 31.3551 N	071° 20.8747 W	41° 31.368 N	071° 20.877 W	179°	79	14:23:53	14° Stbd	56 m	**D**	41° 31.3376 N	071° 20.8804 W	74
4	41° 31.3376 N	071° 20.8759 W	41° 31.338 N	071° 20.878 W	180°	79	14:24:16	270° Stbd	5 m				
END	41° 31.3125 N	071° 20.8782 W	41° 31.313 N	071° 20.879 W	177°	81	14:24:33						



Depth 63.0 ft
Heading 180.9 T
GPS 41° 31.725' N 071° 20.858' W
Speed 5.3 kn

Fig. 5. Fl Sonar Image at START Position, 200m Scale. (soundings in feet)

Proceeding along the track on a 180° heading, the data obtained at position α is illustrated in Figure 6.

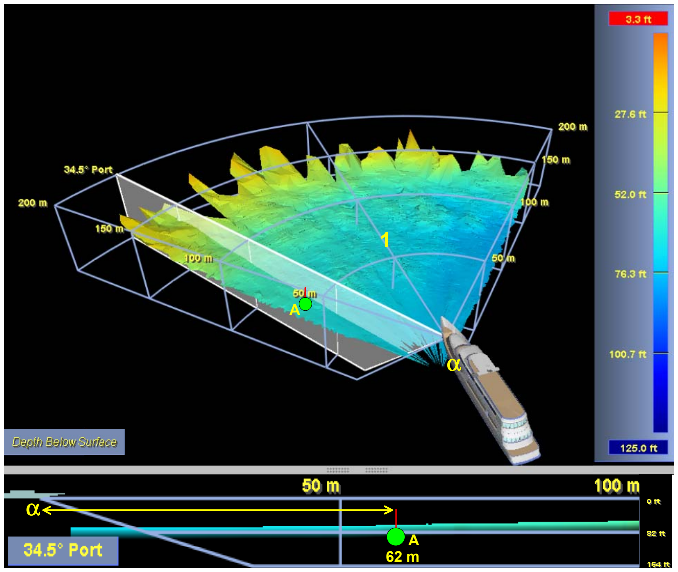


Fig. 6. Fl Sonar Image Showing Depth **A** from Position α, 200m Scale. (soundings in feet)

The charted sounding of 57 feet, illustrated as mark A, is located approximately 62 meters from measurement position α on a bearing of 35° to port. The movable arm depicting bearing projecting forward from this measurement position moves at increments of 1.5°, and is set at 34.5°. The horizontal bottom contour profile located below the bottom imagery in this figure depicts this location using a broad blue line that roughly corresponds to this depth. However, the width of this line is intended for visual display suitable for human factors associated with viewing and does not provide adequate resolution for detailed measurements. Examination of the digital target data resulting from sonar processing directly from the hydrophone measurements reveals that the depth associated with this location appears to be 60 feet based upon the angle and range upon which it was detected in the horizontal and vertical elements of the hydrophone grid.

The charted soundings of 68, 76 and 78 feet are illustrated as marks B, C and D and located approximately 52, 73 and 56 meters from measurement positions β, δ and ε on bearings of 29° and 35° to port and 14° to starboard, respectively, in Figures 7 and 8. The movable arms depicting bearings are set at 28.5° and 34.5° to port and 13.5° to starboard, respectively. Examination of the digital target data resulting from sonar processing directly from the hydrophone measurements reveals the depths associated with these locations are determined to be 68, 76 and 78 feet.

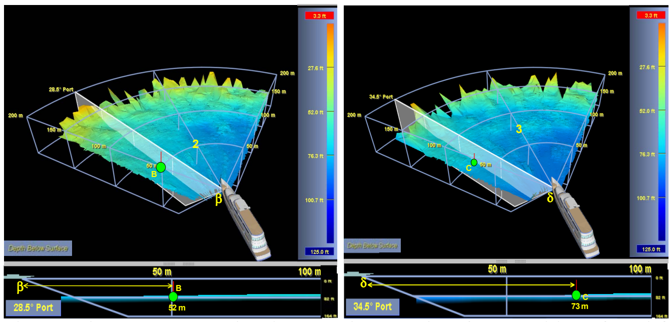


Fig. 7. Fl Sonar Image Showing Depths B and C from Positions β and δ; 200m Scale. (soundings in feet)

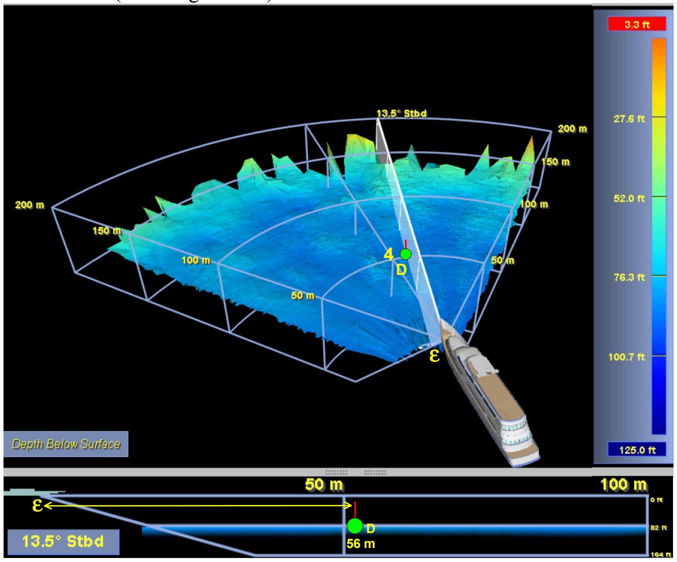
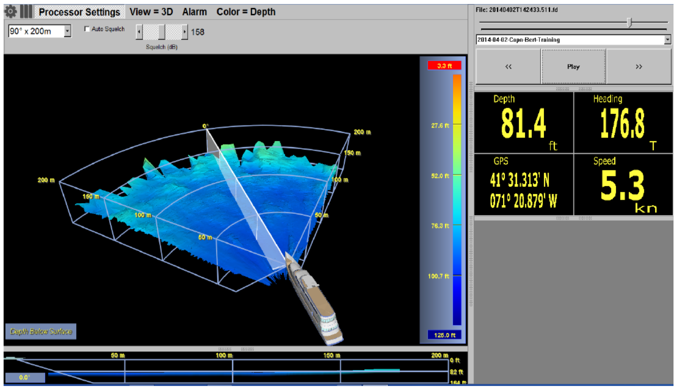


Fig. 8. Fl Sonar Image Showing Depth D from Position ε, 200m Scale. (soundings in feet)

Sonar imagery and data at the End position is shown in Figure 9.



Depth 81.4 ft
Heading 176.8 T
GPS 41° 31.313' N 071° 20.879' W
Speed 5.3 kn

Fig. 9. Fl Sonar Image at END Position, 200m Scale. (soundings in feet)

C. *Experiment Analysis*

All vessels are legally bound to use nautical charts issued by national hydrographic authorities for voyage planning and navigation while underway. The basis upon which this analysis of FL sonar measurement results is made is nautical chart 13233 issued by NOAA as the official hydrographic organization of the United States to meet the requirements of marine navigation in accordance with the IMO Safety of Life at Sea (SOLAS) convention [10]. Reference is made to the soundings provided at four specific positions on the chart identified as Marks A through D in Table II. These soundings are based upon millions of highly detailed measurements made over the area using hydrographic sonars. A small subset of these measurements are placed on charts following a conservative pattern to provide safety and ensure an uncluttered chart appearance by representing least depths where the chart scale is too small to permit all soundings to be shown [11]. Also, relatively few soundings are shown where the bottom is flat, or gently or evenly sloping [12].

Similar to hydrographic sonar, FL sonar also makes hundreds of thousands of measurements that form a swath of the bottom topography. The intent of this analysis is to determine the degree to which FL sonar measurements appear to conform to the soundings depicted in NOAA chart 13233 corresponding to the area observed. Subsequent analysis will examine correlation to IHO S44 standards for Special Order and Order 1a surveys.

A comparison between soundings that appear on NOAA chart 13233 and adjusted depths measured using FL sonar at locations A-D illustrated in Table III shows similar results within a tolerance of around 6%. The value for Horizontal Uncertainty using Wide Area Augmentation System (WAAS) approaches 5 meters, and the value for Vertical Uncertainty averages just under 0.4 meters, or 1.3 feet.

a) Horizontal Uncertainty (HU): Sources of uncertainty in this calculation include the transducer used to measurement depth, the action of the vessel itself manifested during measurement, and the accuracy of the positioning, navigation and timing instruments that form the datum against which measurements are referenced. Based upon manufacturer specifications, the FL sonar transducer has an angular accuracy (AA) in the horizontal plane of approximately 1.6°, or ±0.8°. Roll and Pitch error (R/PE) is in the range of 0.4°, or ±0.2° [8]. The GNSS instrument used has a published WAAS GPS accuracy of 3 meters [13]. A value for GPS estimated positioning error (EPE) was not measured during this experiment, and was initially estimated at a value of 0. When EPE increased beyond 0, HU increases significantly. An additional factor is that horizontal measurements become more accurate as the locust of points measured moves closer to the transducer and additional sonar pings are processed. However, the magnitude of this contribution is as yet undefined and assumed to be 0. The values used for determining horizontal uncertainty are summarized in Table IV. Calculation of a value for HU instance is accomplished using the equation:

$$HU = AA + R/PE + WAAS + EPE \qquad (2)$$

HU is not to be confused with THU described previously since no previous bottom survey has been accomplished to a high degree of resolution, and the resolution of NOAA chart 13233 does not provide an adequate reference against which comparison may be made. However, it may possibly be useful as a guide for rough comparison in a frontier environment.

b) Vertical Uncertainty (VU): Sources associated with vertical uncertainty include constants and those that vary with depth. Constants include the vertical offset of the transducer from the water's surface and adjustments for tide. Error sources that are depth-dependent include FL sonar transducer

TABLE III. COMPARISON BETWEEN CHART AND FL SONAR SOUNDINGS

Depth Soundings (NOAA Chart 13223)		FL Sonar			
		Adjusted FL Sonar Depth (ft)	Vertical Uncertainty		Horizontal Uncertainty (±m)
			(±ft)	(±m)	
A	**57**	**59**	**1.0**	**0.32**	**4.6**
B	**64**	**67**	**1.2**	**0.36**	**4.4**
C	**74**	**75**	**1.3**	**0.40**	**5.1**
D	**74**	**77**	**1.4**	**0.41**	**4.5**

TABLE IV. FACTORS COMPRISING VERTICAL AND HORIZONTAL UNCERTAINTY DETERMINATIONS

FL Sonar										
Measured Depth (ft)	**Vertical Offset** (ft)	**Angular Accuracy** (±0.8°)			**Roll/Pitch Error** (±0.2°)			**Other Adjustments**		
		±V Error	**H Dist.**	**±H Error**	**±V Error**	**±H Error**	**Trk** (±0.5°)	**Tide Adj.**	**±WAAS**	**EPE**
		Vert. (ft)	**Horiz.** (m)		**Vert.** (ft)	**Horiz.** (m)	**Horiz.** (m)	**Vertical** (ft)	**Horiz.** (m)	**Horiz.** (m)
60	3	**0.8**	62	**0.9**	**0.2**	**0.2**	**0.5**	**-4.3**	**3**	**0**
68	3	**0.9**	52	**0.7**	**0.2**	**0.2**	**0.5**	**-4.3**	**3**	**0**
76	3	**1.1**	79	**1.1**	**0.3**	**0.3**	**0.7**	**-4.3**	**3**	**0**
78	3	**1.1**	56	**0.8**	**0.3**	**0.2**	**0.5**	**-4.3**	**3**	**0**

angular accuracy in the vertical plane of 1.6°, or ±0.8°. Roll and Pitch error is in the range of 0.4°, or ±0.2°. The values used for determining vertical uncertainty are also summarized in Table IV.

VU should also not be confused with TVU since the vertical uncertainty of all sources of individual uncertainties has not been quantified. Further, lacking previous bottom survey to a high degree of resolution there does not exist an adequate reference against which comparison may be made. But again, it may possibly be useful as a guide for rough comparison in a frontier environment.

c) *Order of Survey Correlation:* The premise of this paper is not to infer FL sonar is equivalent to hydrographic sonar for survey purposes. Although the technologies used are similar, each is designed to fulfill different requirements and to accomplish two very different missions: FL sonar to acquire data and display 3D images in real time for a large field of view ahead of a vessel, and hydrographic sonar to capture very high resolution imagery of the seabed below a vessel for subsequent post processing and the creation of nautical charts to IHO S44 standards. However, if you are navigating in the Arctic and the chart you are using is incomplete it is quite reasonable to ask how well would FL sonar work to assist in navigating safely under these circumstances.

The experimental outcome shows FL sonar provides less than Order 1a survey accuracy, however full sea floor coverage for a swath is provided. This seems to result in a hybrid data product somewhere between those provided by Order 1a, and 1b surveys that do not require full sea floor search. Specific details of compliance with the feature detection requirements of these Orders are not yet available. However, the ability to detect features of >2 cubic meters required for Order 1a surveys appears to be quite achievable in the short term. However, no previous high-resolution survey of the area examined in these experiments has been accomplished to provide a baseline reference. This leaves the only reference being the official nautical chart averaging around 20 meters or so between soundings. The results obtained from these experiments clearly show far greater bottom depiction capabilities are available from FL sonar than provided by a nautical chart. Further, this is live, real-time data of the actual environment ahead of the bow rather than a secondary reference obtained through another source from a survey that is likely to be decades old and may no longer reflect the actual environment imminent under the keel. It must also be mentioned in that GPS WAAS capabilities are fairly non-existent in the Arctic, increasing the horizontal GPS accuracy to around 10 meters rather than 3 meters used in these experiments, further increasing HU values.

D. *In-Water Target Detection*

Detection of in-water targets is accomplished separate from bottom targets. They are distinguished by their existence in the water column absent a connection with the bottom. Their detection and display is accomplished using target modeling and classification algorithms to process large amounts of live data in real time. A simple sphere is used to represent each in-water target data location, as shown in Figure 10. As the vessel continues on its path the in-water target location moves closer to the vessel. Research to determine the exact size and characteristics of features detectable using this capability, and under what circumstances has yet to be completed.

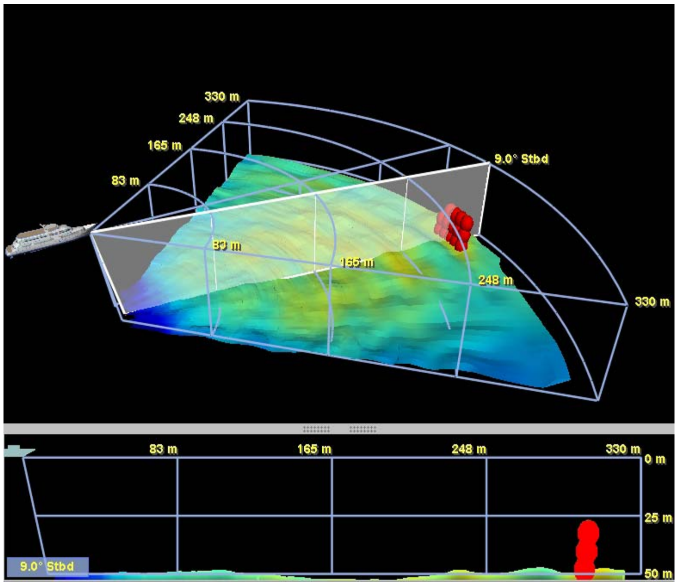


Fig. 10. FL Sonar Depiction of In-Water Targets (shown as Red Spheres)

Such capabilities are useful for detecting and avoiding hazards to navigation that may be floating on or near the surface such as shipping containers, buoys that are adrift, icebergs and large growlers, and even large flotsam such as debris resulting from the tsunami that hit northeastern Japan in 2011. The hull forms of vessels ahead are also detectable using FL sonar, and can provide affirmative confirmation of a radar contact on the same bearing.

Additional protection may also be afforded whales, especially to those crossing ahead of a vessel as well as sleeping on the surface that are difficult to detect in good weather as well as in bad and in conditions of low visibility. The capability to detect whales and take evasive action to avoid them is essential, especially in critical habitat areas while participating in mandatory ship reporting systems where the penalties for whale strikes can be severe.

VII. CONCLUSIONS

The goal of this research is to determine what capabilities may be afforded an expeditionary, work or commercial vessel using own-ship sensors to navigate in remote and challenging environments, aided by services that are generally expected to be available in these areas. A rigorous, complete and detailed analysis of the many factors associated with determining horizontal and vertical uncertainties of FL sonar measurements in accordance with IHO S44 has not been attempted in this text. Such an undertaking requires significant planning, large investment in high precision instrumentation and systems through which delivery and use of the instruments is accomplished, and assets required for post processing and analyzing the resulting data.

The results appear to support the conclusion that a hybrid of IHO S44 Orders of Survey 1a and 1b is possible using FL sonar and assets identified to perform a full sea floor search over a predetermined swath. Further, it has been demonstrated that FL sonar can provide an accurate characterization of the sea floor useful to the improvement of safety of navigation for vessels operating in remote regions where nautical chart coverage is less than adequate. FL sonar can also provide much higher detail at greater resolution when compared to the legal minimum requirements established for navigation in the form of nautical charts issued by national hydrographic authorities showing distances of meters between soundings, if they exist at all.

VIII. FUTURE DIRECTIONS

Further research is required across several disciplines to achieve the full potential in increasing the safety of navigation for vessels in challenging environments such as the Arctic. This includes further expansion of services throughout the Arctic to support increased vessel traffic, improving the hydrographic survey capabilities of national hydrographic authorities serving these areas, enhancing nautical chart content and delivery technology, and exploring improvements to FL sonar technology and the development of metrics to verify and validate these improvements.

The expansion of WAAS coverage in the Arctic would assist GNSS users by providing much greater accuracy in the positioning and timing functions required for vessel navigation. At present the U.S. Coast Guard assists NOAA in performing hydrographic surveys in the Arctic by providing enhanced GPS signal augmentation to increase the accuracy of survey results. Establishment of a more permanent presence of this capability should be considered in high traffic areas.

Hydrographic agencies produce surveys resulting in very large volumes of high resolution imagery and digital files representing the configuration of the sea floor. However, only a very small portion of this survey data is incorporated into the final nautical chart. There are many reasons for this, not least of which is that charts are traditionally organized to ensure the user can best interpret the meaning and context of the information represented by the data. Too much information would clutter the chart and make it unusable. Now that an electronic nautical chart (ENC) format exists, much greater volumes of survey data can be included within distinct layers of the chart that can be dedicated for machine use through electronic interfaces, and are independent of human factors requirements associated with the user interface. Such data could be used in conjunction with live FL sonar data as a means to cross check to verify correct vessel positioning along the planned route of transit, and to identify areas where changes in bottom configurations may warrant conducting updated hydrographic surveys. Data acquired by vessels during transits of unsurveyed waters could also be made available to national hydrographic agencies to assist in chart production in much the same manner as crowd sourcing of echo sounder data, only with much greater resolution. This data could also be used to counter the effects of GNSS spoofing and aliasing designed to lead a vessel off course and along an unintended and unplanned route without the knowledge or consent of the Master. Combined with inertial navigation and FL sonar, detailed hydrography data present in the ENC could also be used for navigation by georeferencing during GNSS services outages or denial of service attacks.

Finally, updating the Polar Code and IMO carriage requirements should be considered to require FL sonar use to supplement bridge navigation procedures where nautical chart hydrographic coverage is sparse, and worldwide for vessels navigating critical areas with hazardous cargos. Further research into enhancing FL sonar performance in terms of higher range, useful speed, resolution and accuracy should be considered. This would also include development of methods and procedures for verifying FL sonar THU and TVU factors.

DISCLAIMER

The opinions, conclusions and recommendations within this paper are solely those of the authors and do not represent any official position or endorsement of the United States Coast Guard, the National Oceanographic and Atmospheric Administration or any Government or non-governmental organization or entity.

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