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A Risk-based Methodology of Assessing the Adequacy of Charting Products in the Arctic Region: Identifying the Survey Priorities of the Future

Submitted by: ARHC

Executive Summary: This paper presents a risk-based methodology of prioritizing survey areas based on confidence of chart data, estimated depth, and dominant marine traffic patterns. While the study area was the Arctic Region, it is believed this methodology could have wider applications.

Related Documents: n/a
Related Projects: n/a

The IRCC and RHCs are invited to note this paper.

A Risk-based Methodology of Assessing the Adequacy of Charting Products in the Arctic Region: Identifying the Survey Priorities of the Future

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Abstract

Receding sea ice extent in the Arctic, due to a changing climate, has recently opened up corridors that were previously unnavigable. As Arctic waters become more accessible, there will be an increased need to provide updated nautical charts with modern depth data. The large areal extent, coupled with resource constraints and difficult surveying conditions, make a complete hydrographic survey of the Arctic logistically infeasible. In an effort to determine how best to deploy assets in an incremental survey approach, a comprehensive study was conducted to assess the current hydrographic holdings relative to potential areas of navigational risk. This study presents a risk-based methodology of prioritizing survey areas based on confidence of chart data, estimated depth, and dominant marine traffic patterns. While preliminary results show only a small percentage of the Arctic (~20%) could be characterized as having a low risk to surface navigation (i.e. having modern surveys, or being exceedingly deep), a disproportionately large percentage (~75%) of all Arctic vessel traffic transited within these regions. The results of this work can then suggest a systematic approach to targeting the remaining areas of navigational risk for modern surveys.

Key words: Arctic, Nautical Charting, Survey Priorities

Introduction

The relatively rapid retreat of impenetrable multi-year ice cover has made the Arctic region more accessible to surface navigation than ever before. This access comes largely in the form of marine transportation where existing sea routes could see more traffic and where new routes for transit and resource exploitation could open. Any expansion of maritime activity in the Arctic will increase the demand for navigational products.

The Arctic Ocean is the smallest of the world's oceans, measuring 14 million km^2 in size, comprising nearly 3% of the Earth's total surface. The Arctic Ocean is also the shallowest ocean, with an average depth of only 1,050 meters (the next most shallow being the Atlantic at 3,300 meters). Most important to the discussion of surface navigation, the Arctic Ocean is "the least sampled of the world's oceans and many areas remain where few, if any, soundings have been recorded" (Arctic Council, 2009).

The "Arctic" is generally considered the areas north of the Arctic Circle (66°33′45.6″ N), but can also include waters adjacent to it. Because the "Results & Interpretations" portion of this paper focus on the United States' interpretation of this research, for the purposes of this discussion, the areal definition of the "Arctic" will be expanded from all waters within the Arctic Circle, to include the boundary defined by the U.S. Arctic Research and Policy Act (Figure 1). This expansion includes the Bering Sea, down to the Aleutian Chain.

Currently, paper nautical charts are available for most parts of the Arctic (Figure 2, left). Unfortunately, in many areas, the presence of a chart is not a good proxy for "safe navigation". These products are often at such a small scale that they are only suitable for voyage planning as the underlying data may not support the requirements of modern navigation which includes precision positional accuracy and quality depth information. Coverage by large scale products are confined to small portions of the Arctic (Figure 2, right).

Demands for new or "better" navigational products in the vast areas of the Arctic pose a unique set of challenges to the hydrographic offices who are responsible for charting these waters. Given the remoteness of the area, narrow acquisition windows, and harsh environmental conditions, the deployment and support of assets in the field is extremely expensive and can seriously impact where and how much data can be collected.

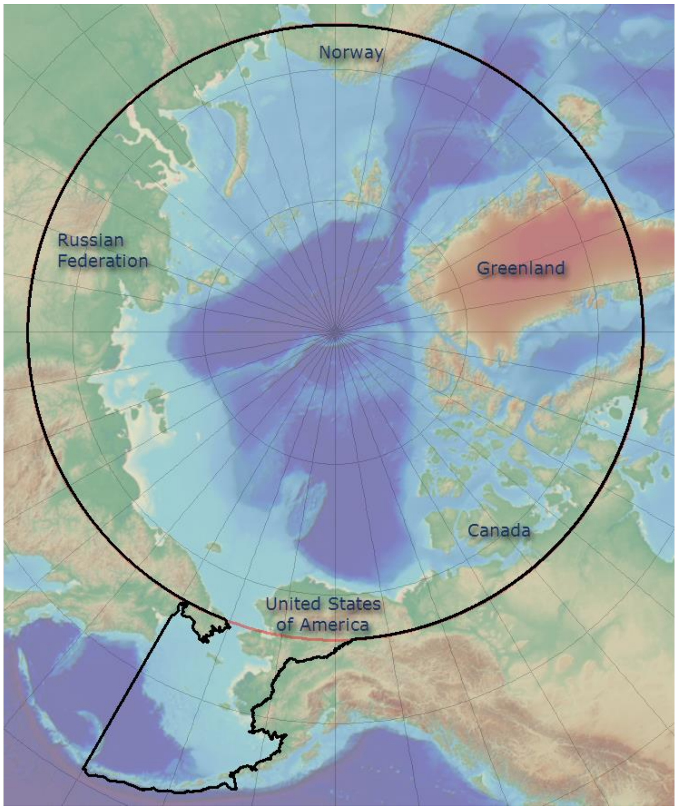
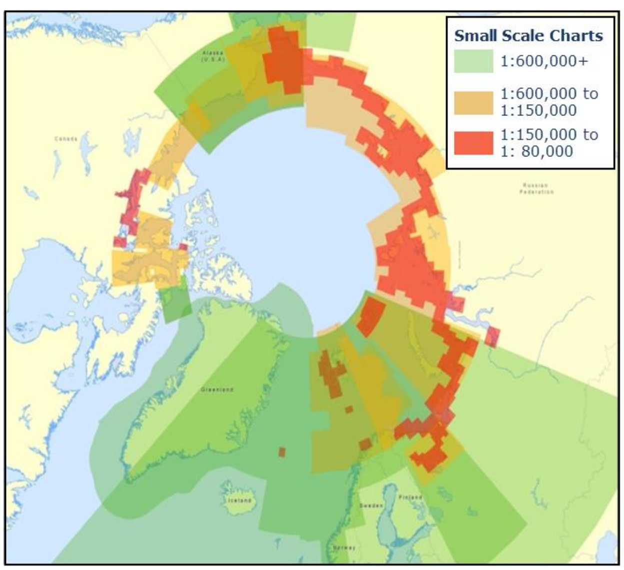


Figure 1 – Arctic region expanded to include the boundary defined by the U.S. Arctic Research and Policy Act (Founding members of the Arctic Regional Hydrographic Commission are highlighted). Note: background terrain model a composite from data sources from IBCAO, GEBCO, NESDIS and NGDC; see "Methods" section for further details.



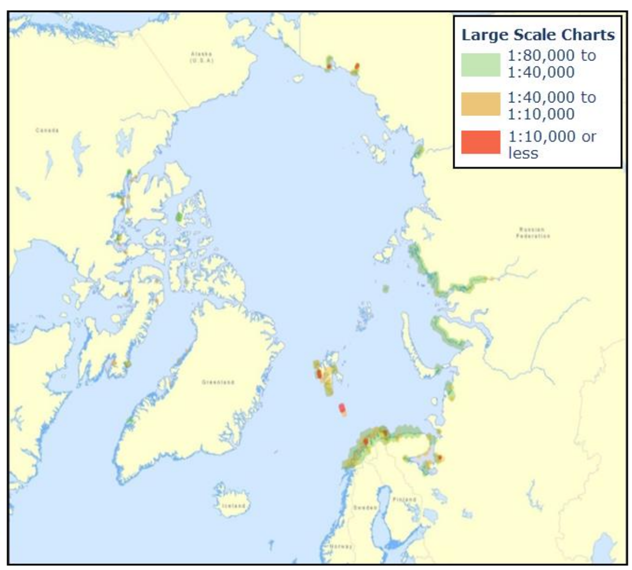


Figure 2 – Small scale nautical charts cover most of the Arctic; however these charts are only suitable for voyage planning (left). Larger scale nautical charts, suitable for most modern navigational needs, are only found in a small fraction of the Arctic (right) (image adapted from Hains, 2014).

In an effort to address some of these challenges that face all nations with interests in the Arctic, the countries of Canada, Denmark, Norway, the Russian Federation, and the United States of America (USA), formed the Arctic Regional Hydrographic Commission (ARHC) under the auspices of the International Hydrographic Organization in 2010 (as of 2014, Finland and Iceland are associate members of the ARHC). Given the high cost of collecting data in the Arctic, of particular interest to this group was the development of a methodology that could be used throughout the region to assess and analyze where risks to navigation are the highest. By identifying these areas, hydrographic offices can more efficiently apply resources to acquire the hydrographic information necessary to get better hydrographic products in areas where the need (or risk) is the greatest.

This paper presents a preliminary methodology developed to assess the adequacy of Arctic charting, based on risk, and discusses the results along with a way forward using these advanced methods. The data used in the analysis was provided by Canada, Denmark, Norway, and the United States, to whom the authors are most grateful.

Methods

In developing a risk-based methodology of determining the adequacy of charting products in the Arctic (and by direct correlation, areas of greatest potential need for updated hydrographic data), three fundamental data sources were considered: confidence of existing hydrographic data, water depth, and density of vessel traffic. Independently, each of these data sources could be considered on a simple low-to-high risk continuum (Table 1). Ultimately, all three of these sources were examined simultaneously using Esri ArcGIS; however, the heart of the analysis is based on the suppositions presented in Table 1 (e.g. there is greater risk to vessel traffic in relatively shallow areas as compared to deep areas; likewise, there is greater risk to vessel traffic in areas with relatively older hydrographic holdings as compared to contemporary surveys). The extents of the study area were necessarily limited from that shown in Figure 1 to the areal extent of each member states' ability to contribute the needed data sources (Figure 3).

Table 1 – Data types considered within this risk-based analysis. Each type is viewed on a relative spectrum of low-to-high risk.

Data type:	Relative Risk: Low	Relative Risk: High
Confidence of Hydrographic Data	Newer; 'full' bottom coverage	Older; partial bottom coverage
Water Depth	Deep	Shallow
Density of Traffic	Light traffic	Heavy traffic

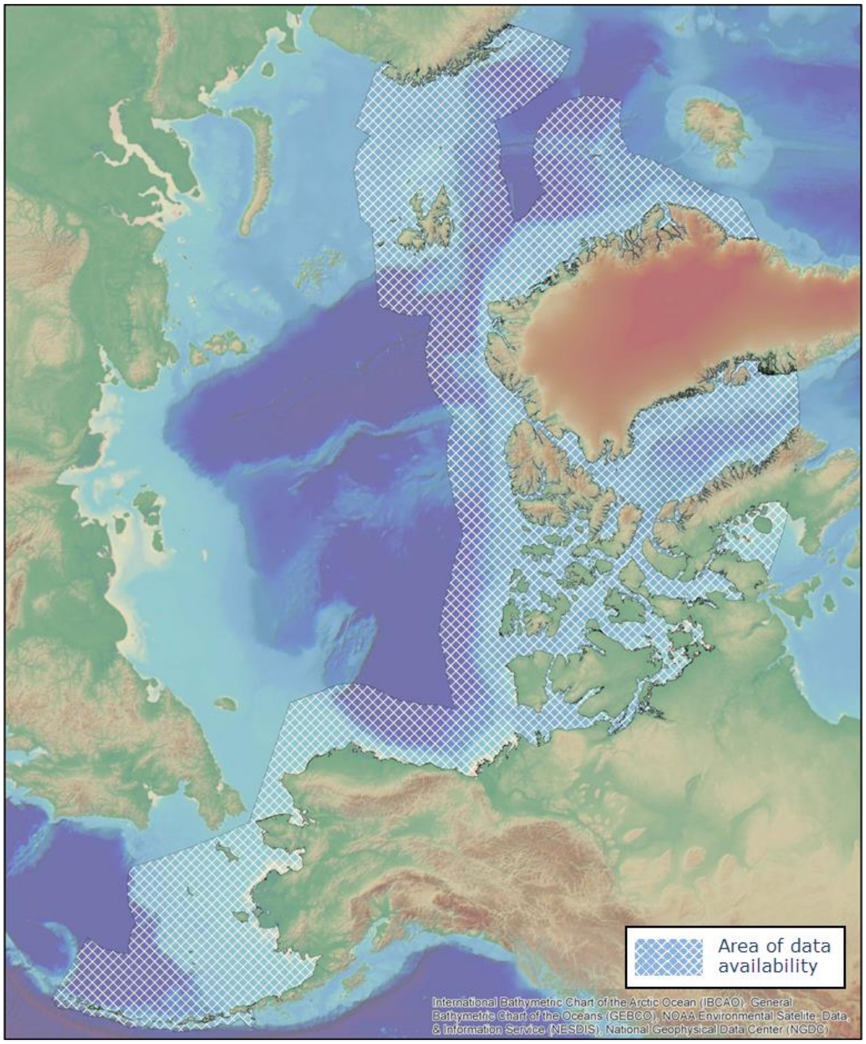


Figure 3 – Regions in which all desired data sources were available for this risk-based survey priorities study: coastal waters of Canada, Denmark, Norway and the United States.

- Confidence of Hydrographic Data

To begin, the confidence of the data supporting the presently existing nautical charting products was assessed by classifying each member state's current hydrographic holdings as having high, medium, or low survey confidence based on the surveying technique and/or type of equipment used for each survey. This assessment of confidence was based on a number of factors including the acquisition equipment used (e.g. echosounder versus lead line), vintage of the survey data, and surveying technique employed (e.g. full bottom search versus partial coverage). Because of the differing data sources, the confidence for data originating from the United States and Canada were derived differently than those of Denmark and Norway (Table 2).

The accuracy of American and Canadian surveyed regions was categorized using the S-57 CAtegory Zone Of Confidence (CATZOC) attribute associated with each Electronic Navigation Chart. CATZOC data are subdivided into three categories, A, B, and C, which denote a progressive decrease in bathymetric/hydrographic data quality. The confidence of the hydrographic holdings were subsequently categorized as high (Category A), medium (Category B), low (Category C), or unassessed (no coverage).

Table 2 – Metric used to assess the confidence level of hydrographic holdings for various nations: United States and Canada were assessed based on CATZOC, while Norway and Denmark were assessed based on type of sounding equipment.

		Confidence Level			
Country	**Data Quality Metric**	**High**	**Medium**	**Low**	**Unassessed**
United States and Canada	CATZOC	**Category A**: Controlled, systematic survey with high position and depth accuracy. Data acquired using multibeam echosounder, channel, or mechanical sweep system.	**Category B**: Controlled, systematic survey achieving similar depth accuracy to Category A surveys, but with less position accuracy. Data acquired using modern survey echosounder.	**Category C**: Opportunistic survey achieving low depth and position accuracy. Equipment not specified.	Unassessed
Norway and Denmark	Equipment Type	Multibeam echosounder.	Singlebeam echosounder.	Pre-acoustic survey equipment or equipment not specified.	Unassessed

As Denmark and Norway continue to build their Electronic Navigation Chart catalog, they have not yet delineated a CATZOC for the entirety of their navigable waters. As such, for those two nations, the confidence of the hydrographic data was classified based on the type of sounding equipment used for each survey. High confidence was assigned to surveys conducted using multibeam echosounders, medium confidence to surveys completed using singlebeam echosounders, and low confidence to surveys conducted prior to these acoustic systems. Unsurveyed areas were designated as unassessed.

Once delineated, the confidence of the hydrographic holdings can be visualized throughout the area of study. Figure 4 shows a sample visualization on the eastern side of the Bering Strait. This area will be displayed for illustrative purposes throughout this paper.

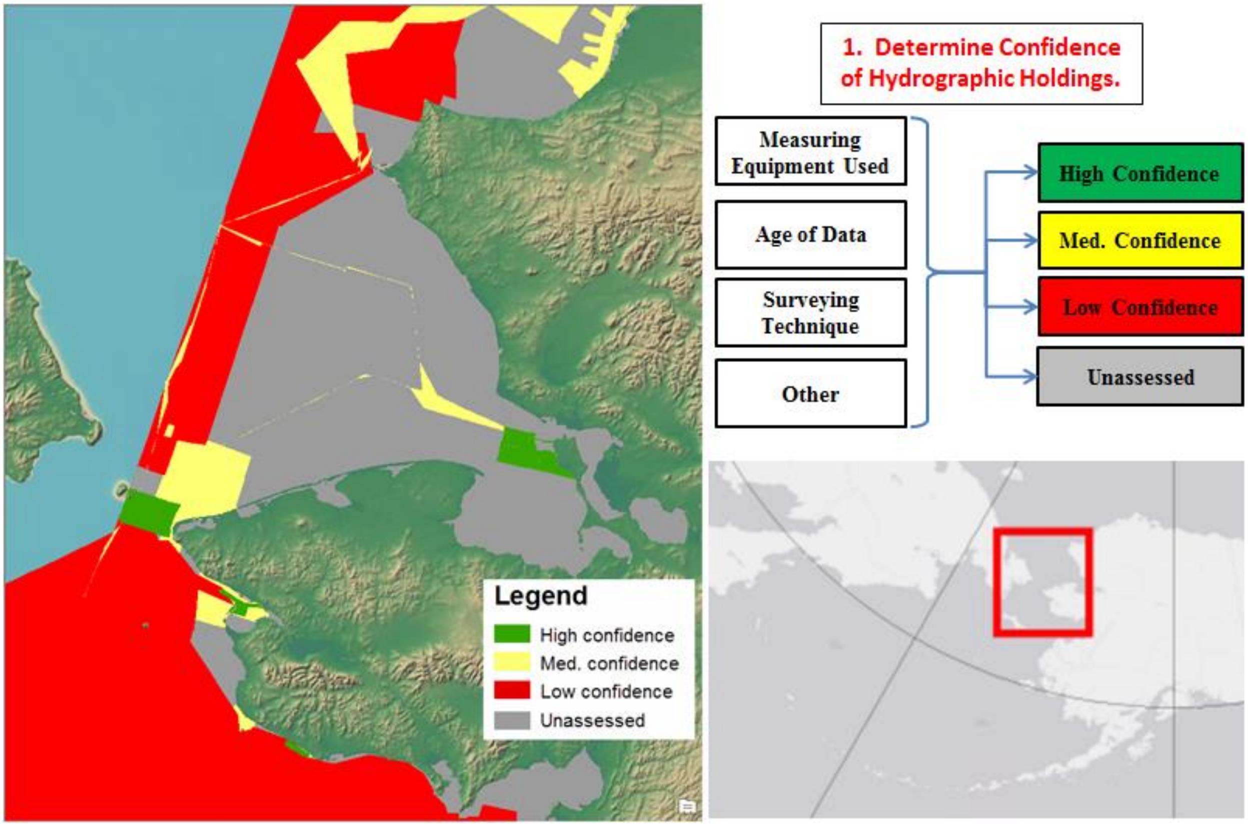


Figure 4 – Visualization of confidence of hydrographic holdings in region on the eastern side of the Bering Strait. Greens depict areas of high confidence (with contemporary coverage from modern sonars), while reds depict areas of lower confidence (pre-1940's data with partial bottom coverage).

- Water Depth

The next layer for this analysis consisted of depth data extracted from both the International Bathymetric Chart of the Arctic Ocean (IBCAO) version 3.0 and the Southern Alaska Coastal Relief Model. The IBCAO version 3.0 bathymetric grid has a 500 m^2 resolution and was compiled from opportunistic data sources from fishing vessels, U.S. Navy submarines, and international research ships (Jakobsson et al., 2012). The IBCAO bathymetric grid was used for all analyses completed in this study north of the Arctic Circle; depth data south of the Arctic Circle were extracted from the Southern Alaska Coastal Relief Model published by the National Oceanic and Atmospheric Administration. This 24 arc-second digital elevation model of southern Alaska was compiled from shoreline, bathymetric, and topographic datasets from multiple U.S. federal agencies, academic institutions, and international agencies (Lim et al., 2011).

With the depth data broadly extracted across the study area, the intent was to then subdivide the region into various depth bands (as before, based on risk to surface navigation). Nominally, vessels in shallower water are at a greater risk due to their proximity to the sea floor; however, the dynamics of the seafloor must play a part in the determination of how "shallow" the waters must be before a certain risk threshold is crossed. For example, in regions in which there is a broad, flat, simple seafloor, it is unlikely that the depths will suddenly "spike". There is a relatively lower degree of risk navigating within waters of a given depth, say 25 meters, in this benign environment; as opposed to an equivalent depth in a region characterized by glacial deposits or tectonic uplift. In these more complex environments, the likelihood of the depths jumping from 100 meters to 10 meters in a very short time is much higher than the simple environment. To that end, before delineating regions of "shallow" or "deep" water, the areas must first be delineated based on each member state's local coastal geology, categorizing the seafloor as either "simple" or "complex" (Figure 5).

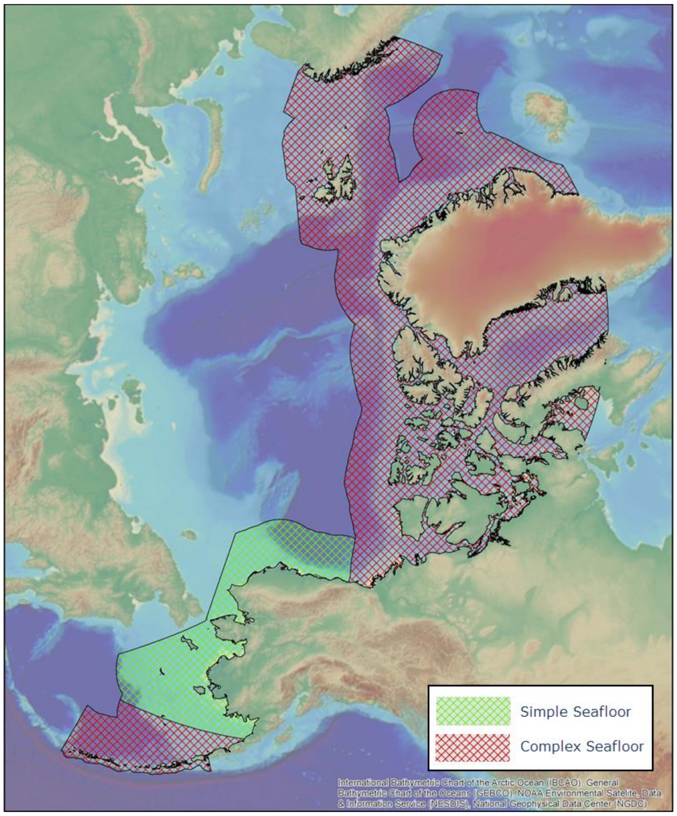


Figure 5 – Anticipated seafloor characteristics throughout the survey area. The majority of the region is classified as "complex", setting a deeper threshold for an area to be classified as "shallow".

The depth scheme characterized as "simple" was applied to regions of relatively benign seafloor morphology; whereas, the complex depth scheme was applied to regions possessing a more irregular signature. Within the simple depth scheme, "shallow" was defined as 0-20 meters, "mid-depth" as 20-50 meters, and "deep" as exceeding 50 meters depth. This depth classification was applied to all U.S. waters, within the Exclusive Economic Zone, and north of 57 degrees (NOAA, 2012). The complex depth scheme was partitioned into the same depth bins (shallow, mid-depth and deep), but with a deeper depth threshold for each category. Depth bins ranged from 0-100 meters for shallow areas, 100-200 meters for mid-depth areas, and exceeding 200 meters for deep areas. The complex depth scheme was applied to all waters around Canada, Denmark and Norway, as well as U.S. waters around the Aleutian chain (NOAA, 2012). A sample visualization of the depth bands, based on seafloor complexity, is shown in Figure 6.

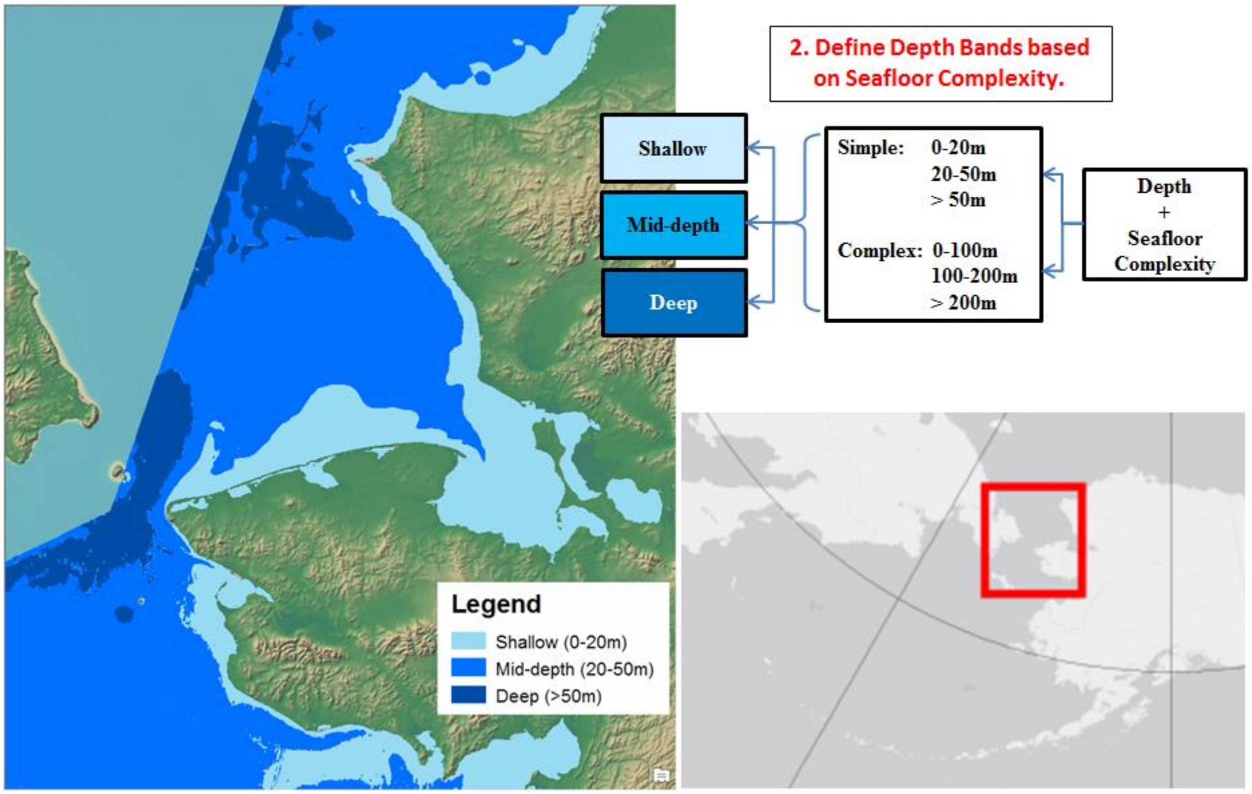


Figure 6 – Visualization of depth regions on the eastern side of the Bering Strait – a region characterized having a "simple" seafloor. Darker shades of blue depict deeper depths (and ultimately lower areas of risk).

- Intersection of Confidence & Water Depth (Areas of Potential Concern)

Once the delineation based on survey confidence and depth was completed, the two map layers were intersected to delineate the areas of potential concern (Figure 7). Areas of potential concern were ranked from low to high based on their potential for navigational risk. Concern progressively increased from low to high as depths shoaled and/or local survey confidence decreased. Low concern was assigned to areas of high survey confidence, independent of depth; whereas, high concern was attributed to shallow areas with low survey confidence. Highest concern was assigned to areas with unassessed survey quality and progressively increased as depths become shallower.

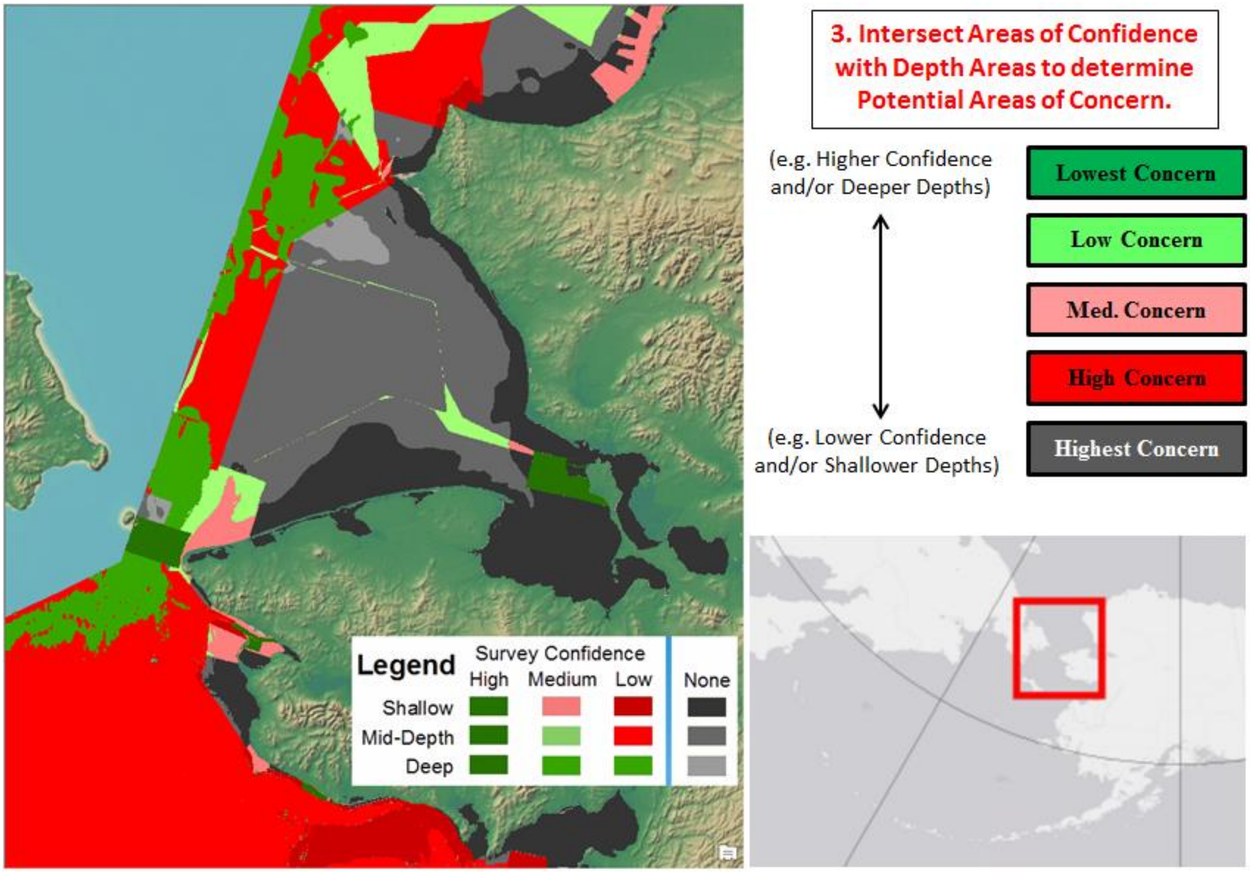


Figure 7 – A two-way visualization of areas of potential concern on the eastern side of the Bering Strait. Regions with some combination of high confidence bathymetry and/or deep depths are of relatively lower concern; whereas, regions of lower confidence bathymetry and/or shallower depths are of relatively greater concern.

- Density of Traffic

The previous section culminated in the definition of the areas of potential concern. While a hydrographic office could proceed with the development of a set of survey priorities based exclusively on these areas of potential concern, these areas can be further prioritized based on vessel traffic. An area of high potential concern with correspondingly high vessel traffic should be considered as a highest priority with respect to acquiring updated bathymetric data. Conversely, an area of high potential concern, which sees no vessel traffic, could be considered an inappropriate use of state assets, were it to be addressed sooner than a more heavily transited region. To that end, vessel transit data must be considered.

Automatic Information System (AIS) data is a shipboard broadcast system that transmits a vessel's identification, position, and other critical data which can be used to assist in navigation and improve maritime safety. There are two different forms of large scale recordings of AIS data: terrestrial, which relies on shore-based AIS receivers; and satellite, which rely on satellites to receive and track the AIS transmissions. Due to the remote location of the study area, it was necessary to use strictly satellite AIS for this project.

AIS data was obtained through ORBCOMM, a private provider of satellite AIS data throughout the world. ORBCOMM collects satellite AIS using a method called Spectrum Decollision Monitoring (On Board), which helps extract AIS messages and distinguish them from VHF noise that satellites may pick up. Since ORBCOMM satellites are mainly polar orbiting, the Arctic is an optimal place to use satellite AIS for analysis and vessel tracking. This data used for this study spanned a time frame of one year between June 2012 and July 2013 and included all traffic transiting in the confines of the Arctic.

The AIS point data was transformed to vessel tracklines using the ArcGIS trackline builder tool. This ArcGIS Toolbox ArcPy script designed for ArcGIS Desktop version 10.1 was developed by the National Oceanic and Atmospheric Administration (NOAA) and converts a collection of point features to tracklines using a unique identifier field and the date and time associated with each point. This tool combines related points to form tracklines based on a user-specified time and distance threshold. The resulting trackline dataset was categorized based on vessel type. A subset of tracklines denoted as “higher consequence”, based on their potential for loss of life, property, and/or environmental integrity in the event of a disaster were extracted and used in this study. This subset of higher consequence vessel traffic included passenger, tanker, cargo, towing, and tug vessels.

Once these higher consequence vessel tracklines are developed, they can then be rendered atop the earlier areas of potential concern (Figure 8). The presence, or lack thereof, of vessel traffic within the various areas of potential concern can assist in better informing a survey priority scheme. Further, the adequacy of navigational products within the Arctic can begin to be assessed relative to current navigational needs, by both measuring the size of the aforementioned areas of concern, and the linear miles of vessels transiting within these areas of higher/lower concern (Figure 9). Higher navigational risk is attributed to shallow, poorly surveyed areas with dense vessel traffic; as opposed to deeper, well-surveyed areas with sparse vessel traffic.

The full data workflow is summarized in Figure 10.

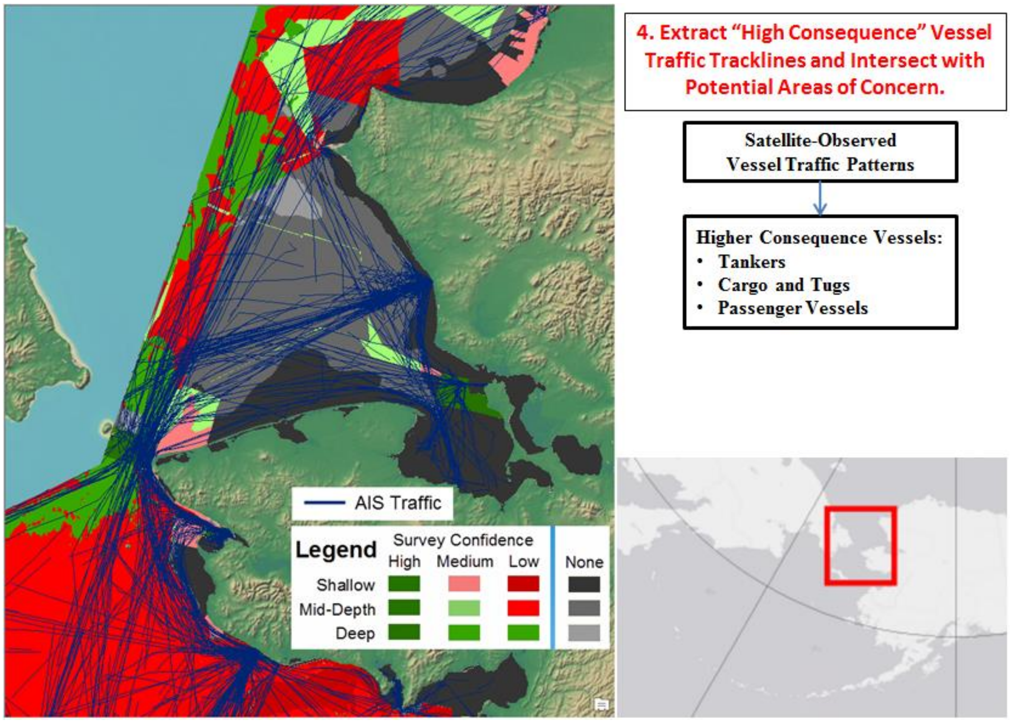


Figure 8 – Visualization of higher consequence traffic overlaid with areas of potential concern on the eastern side of the Bering Strait. Presence (or lack thereof) of traffic helps dictate which areas of higher potential concern should considered for addressing first.

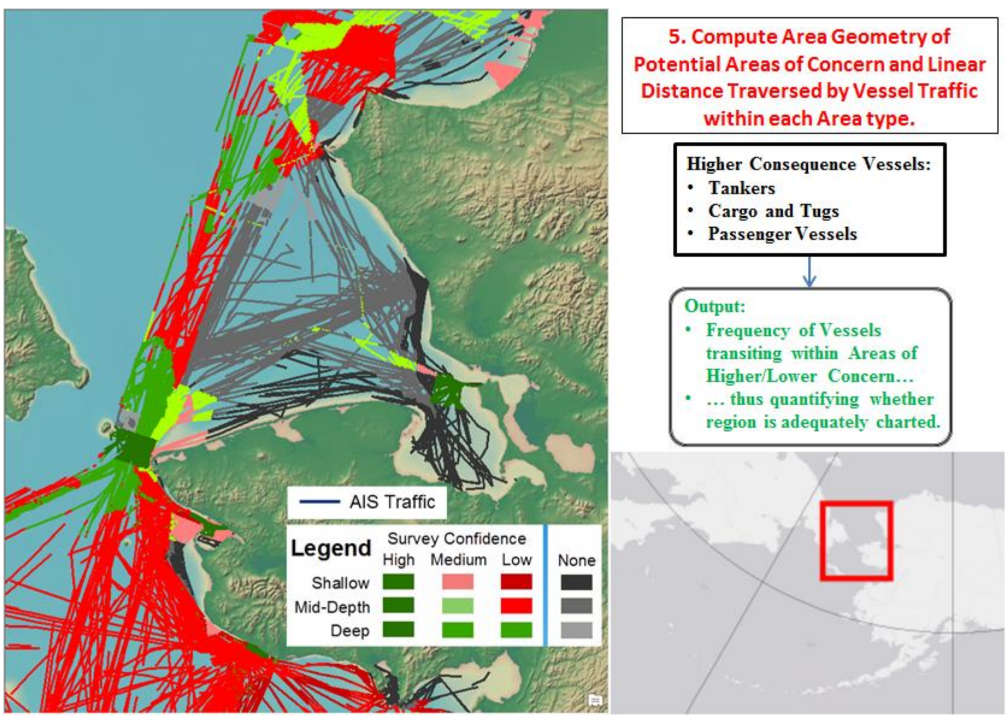


Figure 9 – Visualization of higher consequence tracklines delineated based upon the classification of the potential concern on the eastern side of the Bering Strait.

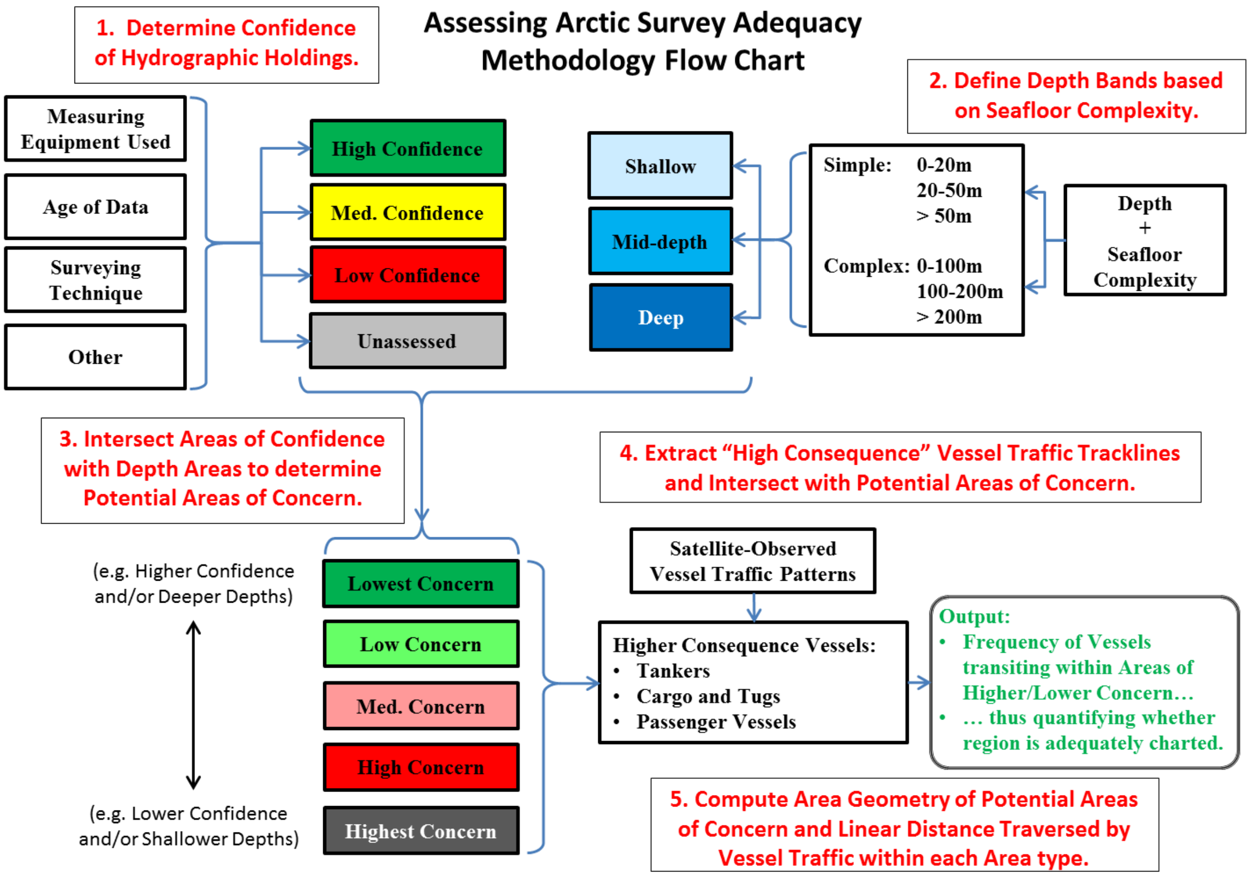
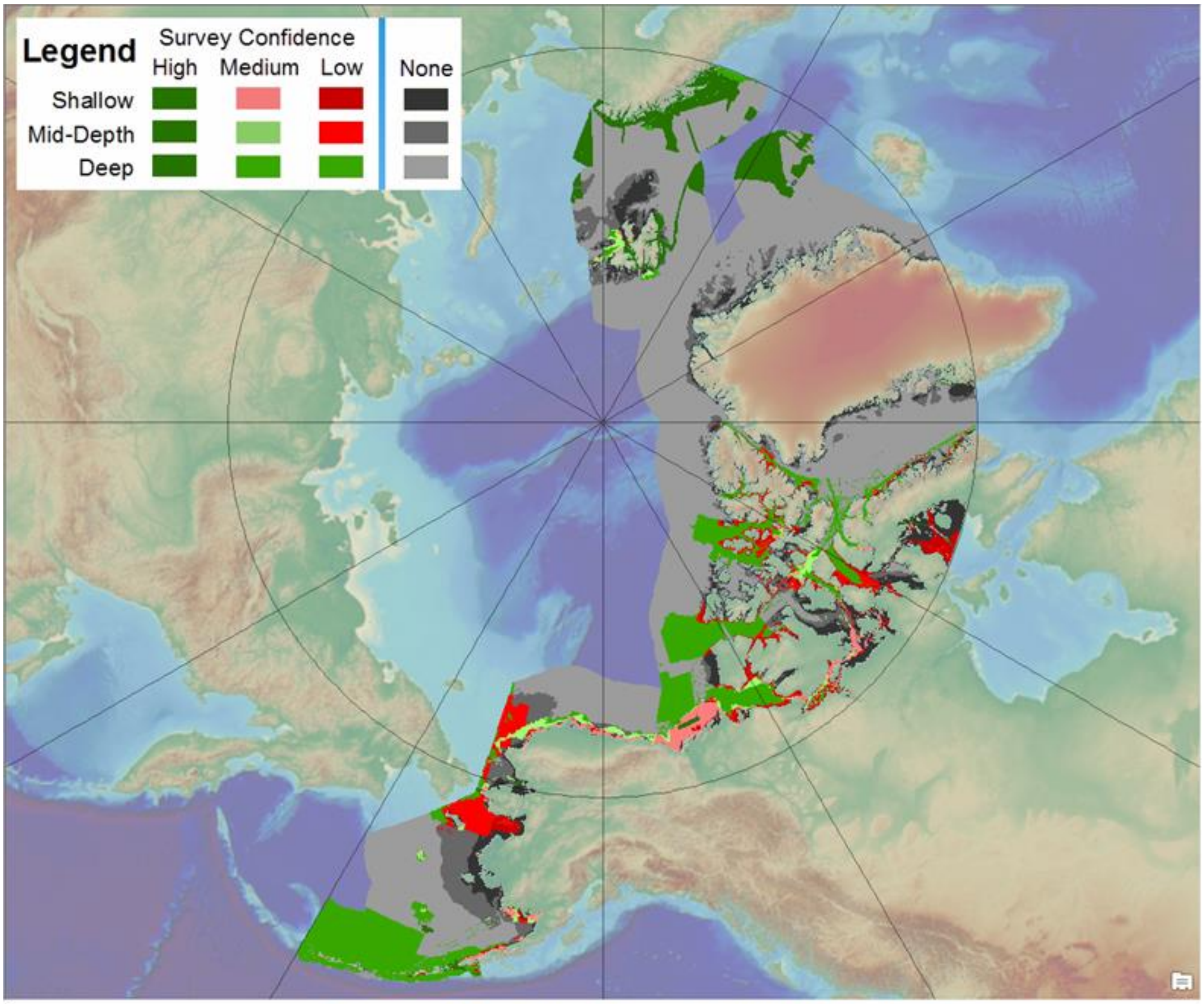


Figure 10 – Composite of data workflow for assessing charting adequacy based on confidence of hydrographic holdings, water depth (coupled with seafloor complexity) and vessel traffic patterns.

Results & Interpretations

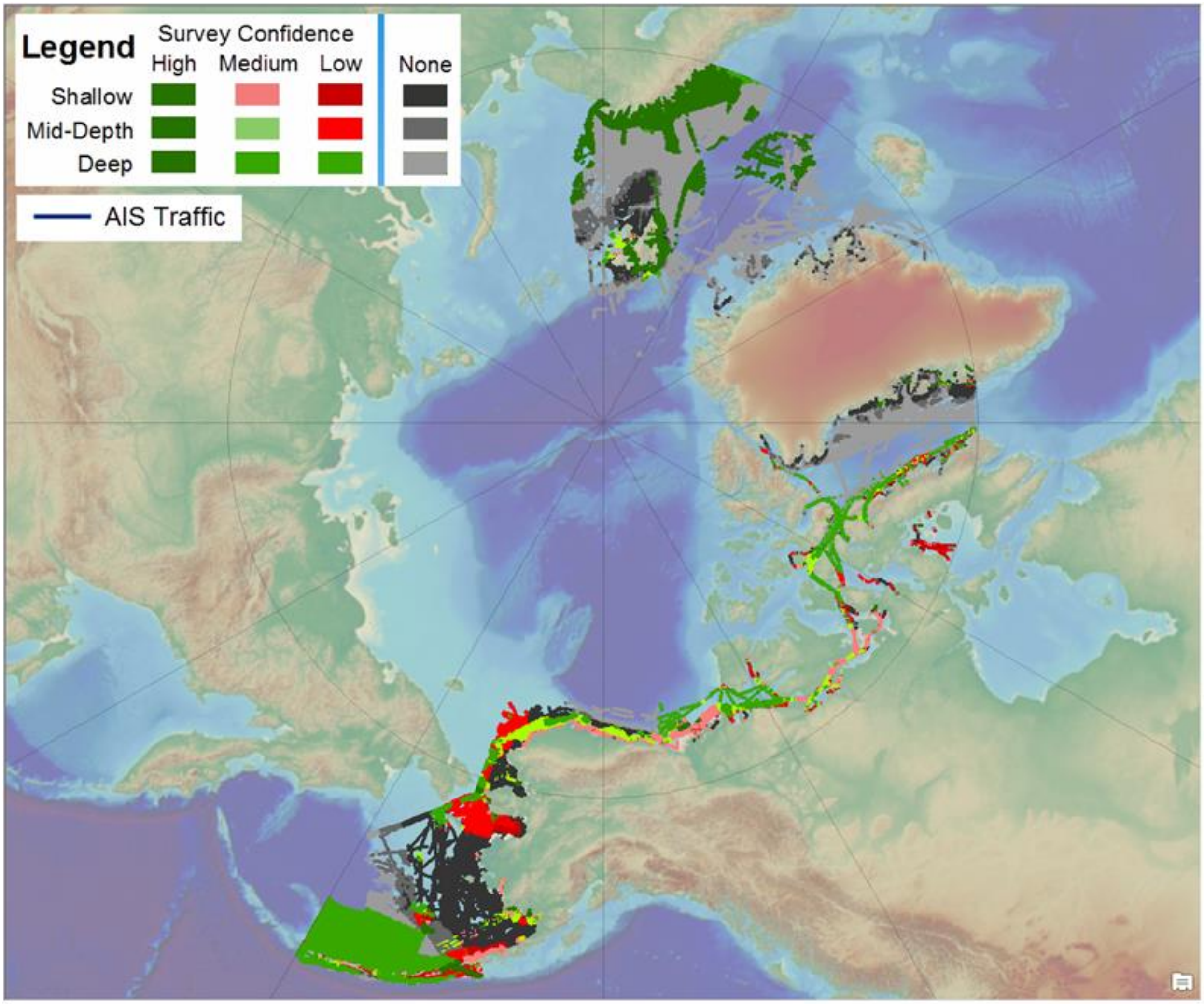
When the first three steps of the preceding methodology are applied to the full Arctic dataset depicted in Figure 3, the initial picture is troubling (Figure 11). Within the study area, 80% of the waters (5.8 million km^2) could be characterized as medium to highest concern (sum of pink, red and black regions); whereas, only 20% of the waters (1.4 million km^2) are of lower concern (sum of green regions). However, the regions of potential concern are only half of the story; we must understand where vessels are navigating to get a true sense of the adequacy of Arctic charting (Figure 12). While 80% of the waters could be characterized as medium to highest concern, only 23% of all traffic is within these waters; conversely, 77% of all traffic is occurring within the 20% of the regions of lower concern.

Taking this further, while only 5.6% of the study area has been surveyed by the most up-to-date sonar systems (Figure 11 – High confidence), 47.1% of all surface navigation occurs within this region (Figure 12 – High confidence). This disproportionately high amount of navigation within these well-surveyed waters is likely the confluence of two factors: 1) hydrographic offices are focusing their efforts where mariners are navigating, and 2) mariners are navigating where there is high confidence bathymetry. These observations can help steer future survey priorities.



Combination of Canada, Denmark, Norway and United States study areas									
	Confidence Level								
	High		Medium		Low		Unassessed		
	sq. km	%Total	sq. km	%Total	sq. km	%Total	sq. km	%Total
Depth (m)	Shallow	51,151	0.7%	154,062	2.1%	186,537	2.6%	562,359	7.8%
	Mid-Depth	53,158	0.7%	102,116	1.4%	241,096	3.3%	664,923	9.2%
	Deep	301,997	4.2%	166,100	2.3%	772,807	10.7%	3,981,741	55.0%
Total		406,306	5.6%	422,278	5.8%	1,200,440	16.6%	5,209,023	72.0%

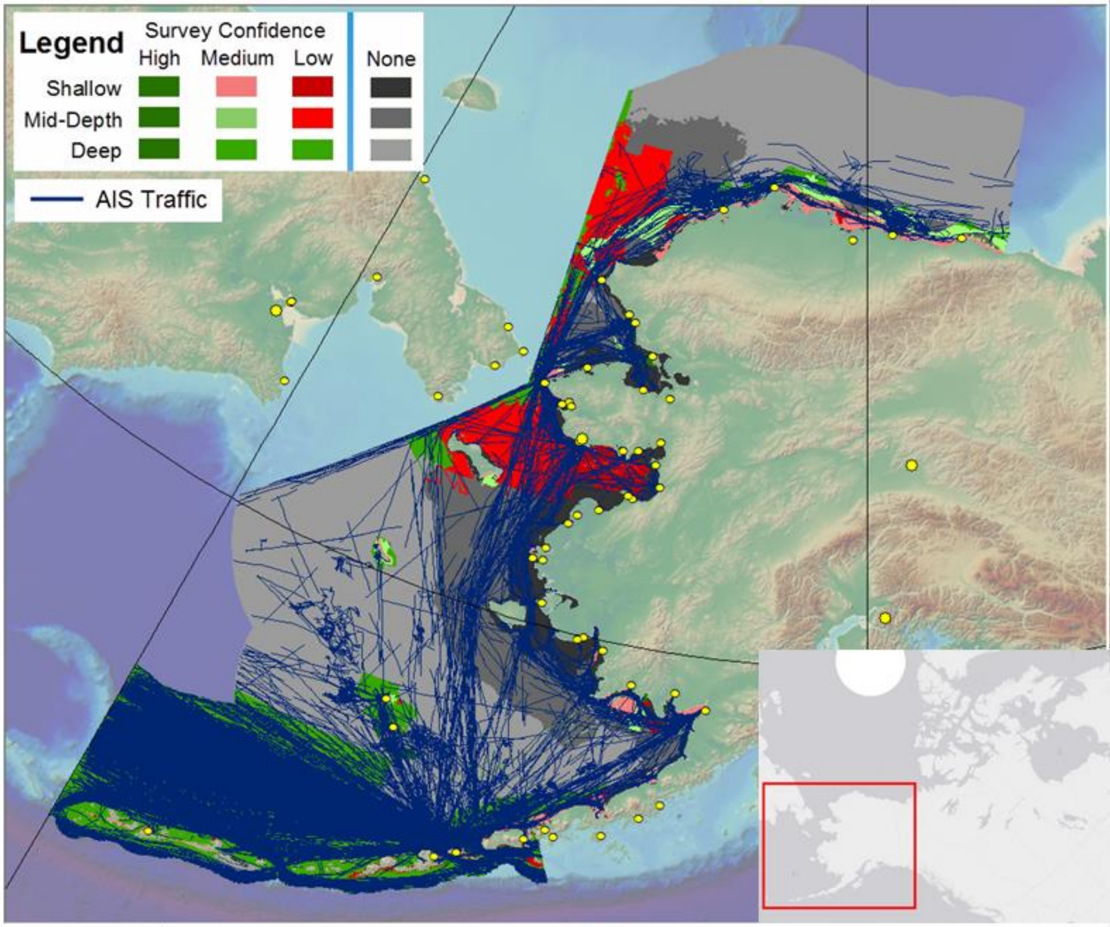
Figure 11 – Areas of potential concern throughout the Arctic. Within the table, entries further to both the bottom and left represent areas of lower concern (e.g. high confidence with deep depths); whereas entries higher and to the right represent areas of highest concern (e.g. unassessed confidence with shallow depths).



Combination of Canada, Denmark, Norway and United States study areas									
		Confidence Level							
		High		Medium		Low		Unassessed	
		LNM	%Total	LNM	%Total	LNM	%Total	LNM	%Total
Depth (m)	Shallow	477,412	9.1%	127,673	2.4%	17,800	0.3%	211,972	4.0%
	Mid-Depth	576,983	11.0%	71,396	1.4%	69,372	1.3%	70,048	1.3%
	Deep	1,419,646	27.0%	103,136	2.0%	1,399,784	26.6%	711,046	13.5%
	Total	2,474,041	47.1%	302,205	5.7%	1,486,956	28.3%	993,066	18.9%

Total Linear Nautical Miles of Traffic (Combined): 5,256,268

Figure 12 – Vessel transits through the areas of potential concern. Within the table, entries further to both the bottom and left represent transits of lower navigational risk (e.g. navigating within areas of high confidence bathymetry with deep depths); whereas, entries higher and to the right represent transits of higher navigational risk (e.g. navigating within areas of unassessed confidence with shallow depths).



		Confidence Level							
		High		Medium		Low		Unassessed	
		sq. km	%Total	sq. km	%Total	sq. km	%Total	sq. km	%Total
Depth (m)	Shallow	7,151	0.4%	46,340	2.4%	61,288	3.2%	101,443	5.3%
	Mid-Depth	2,280	0.1%	48,647	2.6%	150,830	7.9%	252,610	13.2%
	Deep	3,613	0.2%	26,111	1.4%	368,836	19.3%	838,347	44.0%
	Total	13,044	0.7%	121,098	6.3%	580,954	30.5%	1,192,400	62.5%

		Confidence Level							
		High		Medium		Low		Unassessed	
		LNM	%Total	LNM	%Total	LNM	%Total	LNM	%Total
Depth (m)	Shallow	5,595	0.3%	31,657	1.4%	11,598	0.5%	160,641	7.3%
	Mid-Depth	2,034	0.1%	40,244	1.8%	66,028	3.0%	24,854	1.1%
	Deep	320,822	14.5%	21,633	1.0%	1,393,156	62.9%	137,675	6.2%
	Total	328,451	14.8%	93,534	4.2%	1,470,782	66.4%	323,170	14.6%

Figure 13 – Summary of area of potential areas of concern, in km^2, (middle) and lengths of transits through said regions, in linear nautical miles, (bottom), in the vicinity of the United States.

Analysis for the United States shows trends similar to those of the collective Arctic nations (Figure 13). While 76% of the waters assessed in the vicinity of the United states could be characterized as medium to highest concern (sum of pink, red and black regions), only 20% of vessel traffic occurs within this region. Similarly, while only 0.7% of the region has modern, high confidence bathymetry, 14.8% of all traffic is within this region. In this respect, the United States is lagging behind the overall Arctic charting effort (with respect to providing modern coverage for a higher percentage of vessels transiting the region). To that end, NOAA and the Office of Coast Survey are adopting two short-term strategies to improve the charting infrastructure of the Arctic: targeted surveying of heavily transited areas of high potential concern (Figure 14), and the development of offshore transit corridors in areas of high potential concern (Figure 15).

- Targeted surveying

Port Clarence and Kotzebue Sound (Figure 14) represent the type of regions that this study set out to identify: relatively shallow areas, with poor confidence hydrographic data that are heavily transited. These regions will be placed at the top of the survey priority list.

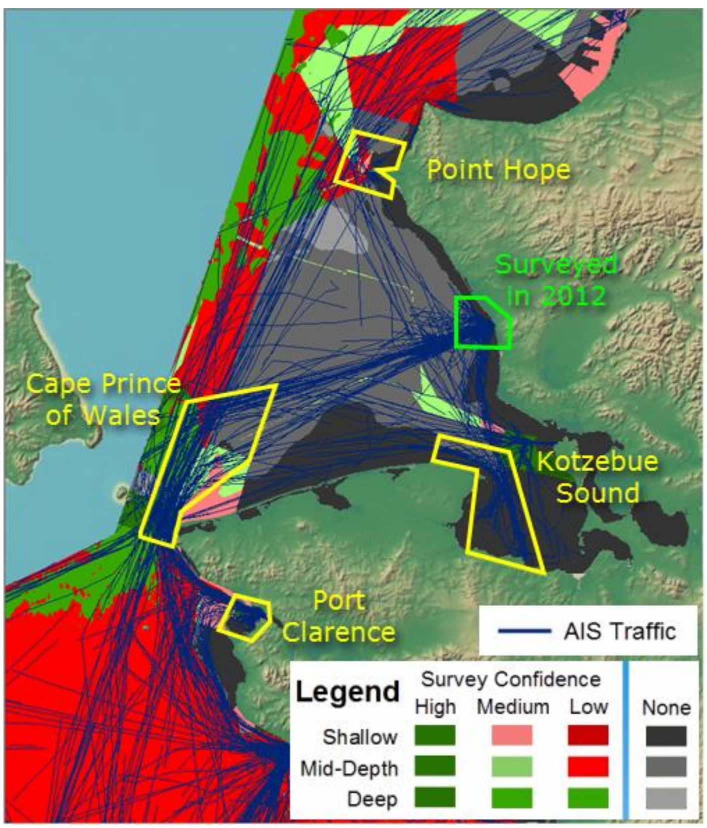


Figure 14 – Office of Coast Survey, preliminary 2015 survey plans for the Arctic region. Port Clarence and Kotzebue Sound address areas of highest concern with heavy traffic. Cape Prince of Wales and Point Hope show examples of mariners navigating out of their way due to lower confidence bathymetry.

Meanwhile, Cape Prince of Wales and Point Hope represent a slightly different type of survey area. In both cases, the mariners are diverting farther offshore than (potentially) strictly necessary due to the lower confidence bathymetry extending from the mainland. Modern surveys may permit the mariner to navigate in a more direct manner, with greater confidence.

- Transit corridor

The U.S. Coast Guard (USCG) has identified a proposed transit corridor between the Aleutian Islands and the Bering Strait (Figure 15). As it happens, this corridor transects through large swaths of areas of high or highest concern. By NOAA partnering with the USCG to provide modern survey coverage within this area (which is planned for 2015), NOAA will increase the percentage of vessels navigating within modern coverage in two ways: 1) obviously, vessels that already transit within the corridor will now be transiting in modern coverage, but 2) vessels presently transiting adjacent to the proposed corridor will likely divert within the corridor when presented with modern coverage.

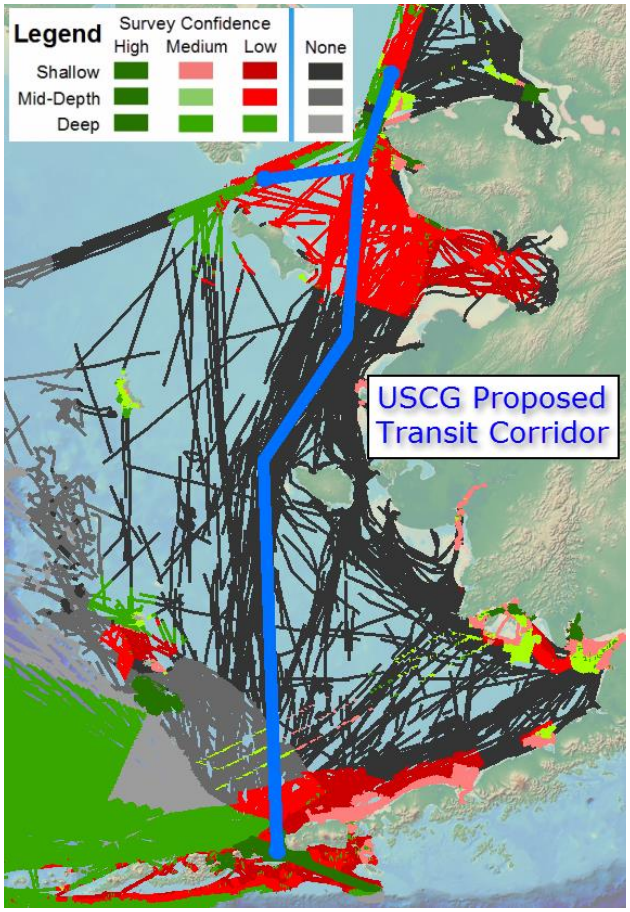


Figure 15 – Transit corridor proposed by the U.S. Coast Guard, and scheduled for investigation by NOAA's Office of Coast Survey in 2015. Note the majority of the corridor is through waters of either high or highest concern (shallow with low confidence bathymetry).

Conclusions & Future Work

Preliminary analysis of this work suggests that there are still vast portions of the Arctic that are not adequately surveyed for the present use, implying there is navigational risk. That written, a disproportionate amount of traffic transits within the relatively smaller areas that do have modern bathymetric coverage. This is likely due to a two-fold effect of hydrographic organizations focusing their surveying efforts in areas with higher traffic densities, and mariners altering their transit routes (as practicable) to ensure that they are navigating on the most up-to-date coverage available.

Given the scope of the problem, there is no definitive next step with regard to where to direct one's surveying efforts, and likely each nation will draw their own conclusions based upon further analysis; however approaching the problem from the perspective of navigational risk is a prudent first step. For the 2015 field seasons, NOAA and the Office of Coast Survey are taking two steps: 1) diverting resources to Port Clarence and Kotzebue Sound, regions which are relatively shallow, poorly surveyed, and heavily transited, and 2) partnering with the USCG to better develop offshore transit corridors, to provide mariners with known safe passages (mitigating the need to survey everywhere, and instead focusing on getting the mariner safely from Point 'A' to 'B').

A final note of caution with regard to interpreting AIS data: all AIS data analyzed in this report was acquired in the 2012-2013 time frames. Generally speaking, AIS data will only reveal where vessels have been transiting, not where vessels will be transiting. Portions of this proposed methodology will fall short when applied to regions like emerging traffic lanes due to receding ice cover. To that end, even areas of high potential concern, that do not have heavy traffic patterns (at present), should not be lightly dismissed from consideration for future survey work.

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