Examination of Navigation Risk Assessment Methodologies with Particular Relevance to Arctic Regions

Prepared for:

TRANSPORT CANADA
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by:

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Examination of Navigation Risk Assessment Methodologies with Particular Relevance to Arctic Regions
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Executive Summary:
This report presents a study undertaken by CIDCO on risk assessment methodologies that could be applied to a prioritization process of hydrographic surveys in Arctic regions.

In the first part of the report, we compare various risk assessment methods already in use that incorporate multiple factors (information layers), including environmentally-sensitive and protected areas, marine traffic and vessel type, as well as potential benefits to resource developments and communities. We first present three existing methods. The first two, proposed by the Arctic Region Hydrographic Commission (ARHC) and the Canadian Hydrographic Service (CHS), deal with the Arctic and incorporate bathymetric issues and the concept of marine corridors. A third method was developed by the Land Information New-Zealand (LINZ). It defines a risk assessment method using a risk matrix concept and compiles the result with an economic cost/benefit study in order to prioritize survey areas in the south west Pacific.

According to the conclusions of our analysis of the foregoing methods, we present a novel risk assessment methodology that could be applied as part of a process for the prioritization of hydrographic surveys. This methodology combines concepts from the foregoing risk assessment methodologies, notably the LINZ risk assessment method and marine corridors concept used by CHS. This novel methodology could be particularly helpful in Arctic regions, as it is particularly suitable for areas with sparse hydrographic information.

In part II, we propose improvements to existing risk assessment methodologies based on risk matrices and modeling techniques of navigational risk that incorporate multiple, appropriately-weighted factors for the assessment of navigational risk that could be applied to nautical charts in Arctic waters as this method incorporates multiple risks factor, such like nautical chart quality vessel traffic, navigation aids, and the presence of marine protected areas and other coastal sites of interest.

A discussion of how the risk assessment methods developed in this study could contribute to the refinement of international approaches to risk assessment, particularly for regions where there are relatively lower levels of hydrographic coverage is presented in Part III.

This report reflects the views of the authors and not necessarily those of Transport Canada or the Canadian Hydrographic Service.

Sommaire:
Ce rapport présente l’étude faite par le CIDCO sur les méthodes d’évaluation du risque à la navigation dans l’Arctique Canadien.

Dans la première partie, nous passons en revue des méthodes de détermination du risque et de priorisation mettant en jeu plusieurs facteurs, liés en particulier à la présence de zones protégées, au trafic maritime, et au potentiel de développement économique. Nous présentons trois études qui ont été menées sur ce même sujet. Deux d’entre elles proviennent de l’ARHC (Arctic Region Hydrographic Commission) et du Service Hydrographique du Canada (SHC). Ces approches étudient la zone Arctique et les risques lié à la bathymétrie générale et au trafic afin de définir le concept de corridors maritimes. La troisième vient du LINZ (Land Information New Zealand) et définit une méthode d’évaluation du risque basé sur le concept de matrice de risque.

D’après les conclusions de notre analyse de ces études, nous expliquons notre nouvelle méthodologie pour la priorisation des levés hydrographiques. Notre étude recoupe les différents concepts étudiés comme l’évaluation du risque du LINZ et le concept des corridors maritime développé par le SHC.
Dans la partie II, nous proposons une amélioration des méthodes de priorisation basées sur des matrices de risque et des techniques de modélisation du risque de navigation incorporant plusieurs facteurs pondérés par des poids. Nous examinons comment ces méthodes peuvent être appliquées à l’arctique Canadien.

Une discussion sur les développements actuels des méthodes de priorisation au niveau de l’OHI-OMI est présentée dans la partie III.
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**General context and overview of the project**

Nautical charts are essential to safe marine navigation: they provide critical information on water depths and hazards such as shoals, navigational hazards, aids to navigation, currents, and tidal information.

With potential changes in shipping in Arctic regions due to economic development and facilitated by climate change, Transport Canada and the Canadian Hydrographic Service, have commissioned this examination of risk assessment methodologies that could contribute to the prioritization of hydrographic surveys in sub-regions such as the Arctic.

Navigation risk assessment methodologies have been developed and are in use in several hydrographic regions around the world to inform the prioritization of hydrographic surveys. Their objectives range from assessing the needs for re-survey in areas with dynamic sea-floors to risk assessments in non-surveyed or inadequately surveyed areas. The scope of the work presented in this report is:

- To review risk assessment that incorporate multiple factors (information layers), including environmentally-sensitive and protected areas, marine traffic and vessel type, and potential benefits to resource development sites and communities;
- To develop risk methods (i.e., modeling techniques) that incorporate multiple, appropriately-weighted factors (both causes and consequences) for the assessment of navigational and bathymetric-related risk that could be particularly relevant in Arctic waters (to include nautical chart quality factors as well as vessel traffic factors); and
- To discuss how the risk assessment methods developed herein could contribute to further refinement of international approaches to prioritization.
EXAMINATION OF NAVIGATION RISK ASSESSMENT

PART I: EXISTING RISK ASSESSMENT METHODS
INCLUDING ENVIRONMENTAL PROTECTION AND ECONOMIC DEVELOPMENT
1. Introduction

Given potential changes to shipping in the Arctic region due to economic development and facilitated by climate change, Transport Canada in collaboration with and the Canadian Hydrographic Service, commissioned this current study to examine various risk assessment methodologies that contribute to the prioritization of hydrographic surveys and to consider approaches that could be particularly relevant to sub-regions such as the Arctic. This first part examines three different approaches for risk assessment that were developed in the recent years and are in use today.

However, before describing these methodologies in detail, we briefly describe the question of navigational risk assessment.

When navigating a ship, the sole indicator of the sea-floor comes from a nautical chart, which is compiled from hydrographic data. When there is a high level of uncertainty with respect to the hydrographic data used in creating the nautical chart, there is a greater chance of the nautical chart depicting the sea-floor less accurately. This type of situation could lead a mariner to making an inappropriate navigational decision. As such, representing uncertainty in nautical charts in order to help mariners in making navigation decisions is being pursued by hydrographic service organizations from around the world.

Nautical charts may become less reliable or useful for the purpose of safety of navigation due to numbers of reasons. Among them are:

- Sea-floor dynamics (sand waves, effects of Tsunamis, etc...);
- Hydrographic data with uncertainty not compliant to modern Standards;

In the recent years, beyond the notion of data quality (related to IHO\(^1\) standards such as S-44 for hydrographic data and S-57 for cartographic information), the notion of risk assessment has gained in interest from the hydrographic community. Risk analysis admits the fact that nautical charts may not be conservative enough or may contain a high degree of uncertainty leading to possible groundings. The aim of a risk assessment method is to relate the navigation risk to sources of errors that can be found in the charting compilation process and the associated hydrographic survey data quality factors.

Instead of defining a hydrographic and/or cartographic data quality criterion, the goal of risk assessment is to define, characterize and compute the navigational risk due to actual hydrographic data and charting information.

Generally speaking, the notion of hydrographic risk can be defined (following a frequency expectation loss approach) by the expectation of vessel grounding, weighted by a measure of its consequences.

\(^1\) International Hydrographic Organization
Risk assessment can be viewed as the application of modeling techniques that can be used to capture all uncertainty factors due to hydrography, and relate them to a vessel grounding frequency analysis using existing or predicted traffic data.

Once risk assessment models are set, one can define the cost of vessel grounding consequences, and thus infer the risk factor as the probability of grounding multiplied by the cost of related consequences. Hydrographic risk analysis should therefore focus on multiple uncertainty factors that may cause vessels grounding and also on the multiple consequences due to grounding.

A major problem is to weight these multiple uncertainties and consequence costs, which is actually the main design problem of risk assessment methods. Indeed, the weighting policies of both risk source factors and consequence costs are left to the designer of the risk assessment method, and could be too subjective.

Therefore, a risk assessment depends highly on the data and expertise used to derive these weights (and in particular, on econometric modeling of consequence costs). Therefore, designing an objective hydrographic risk assessment tool requires the incorporation of well documented data, models and spatial analysis methods to produce results which can be well accepted by the stakeholders.

In this report we shall distinguish two types of risk assessment approaches:

The first is “risk matrix” approach, following a methodology inspired by the International Maritime Organization (IMO) Formal Safety Assessment (FSA), mainly developed by the LINZ (Land Information of New Zealand). This approach is a global approach in the sense that to define the risk at a given location, a “risk matrix” weights some high level information, which can be assimilated to survey meta-data. Several criterions composing the risk matrix are ranked, all of them being defined spatially, and therefore managed by a Geographical Information System through overlay analysis. The core of this type of method is the determination of the relative weighting between each overlay defining a component of the navigational risk which has a significant impact on the overall risk assessment method.

The second risk assessment approach is risk assessment via “under-keel clearance models”, which make use of comprehensive information at a given location (hydrographic data, tidal information, navigational information) and aims at computing a probability of grounding. These models take into account bathymetric information (but not charting information) such as soundings, tidal models, navigational parameters (draft, heave) and can be used to assess the risk as a probability of grounding multiplied by the cost of the associated consequences, depending of the severity of the grounding, the grounding location, current information, distance to sensitive areas and the type of vessel.

Under-keel clearance models have been used in order to assess the navigational risk in local areas, mainly in harbors, channels and access channels while the purpose of risk assessment is at a sub-regional scale. Therefore these two classes of methods seem at a first glance not to pursue the same objective and do not require the same type and amount of data in input. But, as we shall see later, they can actually be linked in a risk matrix weights-calibration approach.

A full description of bathymetry and tidal models and their associated level of uncertainty are required for under-keel clearance models. On the other hand, to apply a “risk matrix” approach
requires GIS overlays populated with data on chart quality attributes (as defined in the IHO S-57 Standards), proximity to sensitive areas, and the type of navigation required.

2. The North Canadian Context

Over the last so many years, there have been increases in the number of ships voyages in the Arctic, as shown in Figure 1 below. According to [1], “this trend is expected to continue in coming years, driven largely by growing northern communities, expanding resource development projects, and increasing tourism”. The problem of estimating the navigational risk due to the lack of reliable hydrographic data populating nautical charts is a need that CHS addressed through a prioritization tool based on the application of “risk matrices” in marine corridors, defined a priori high priority areas to survey.

![Figure 1: Number of voyages in the Arctic since 1990 (Source: Canadian Coast Guard)](image)

2.1. Overall state of cartography

Due to particularly difficult surveying conditions and to the size of the Canadian Arctic region, the state of hydrographic and charting information does not ensure the quality level required for modern navigation. Most of data used come from pre-1970 surveys. Soundings were measured by lead lines, are geo referenced by legacy and inaccurate positioning system data.
Figure 2: Status of Arctic Surveying, 2013 (provided by CHS)

Figure 3 shows state of hydrographic data quality in 2013. Note that the two major routes (Hudson Bay and Northwest Passage) only have CATZOC C attributed. In addition, most of ports approach areas does not reach the required CATZOC A.
CATZOC is a fundamental attribute associated to a nautical chart. It defines the reliability of the chart, by defining the quality of the underlying hydrographic information. As mentioned in the S57 caption under the CATZOC table, the definition of CATZOC is still under discussion, and we note that the rules for populating CATZOC attributes may be different in some countries, due to different interpretations of the right side column description associated to each category. Therefore CATZOC is not an absolute nor objective criteria. Its attribution is left to the Hydrographic Service.

### ZOC Table:

<table>
<thead>
<tr>
<th>ZOC</th>
<th>Position Accuracy</th>
<th>Depth Accuracy</th>
<th>Seafloor Coverage</th>
<th>Typical Survey, Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>± 5 m</td>
<td>a = 0.5, b = 1</td>
<td>Full seafloor ensonification or sweep. All significant seafloor features detected and depths measured.</td>
<td>Controlled, systematic high accuracy Survey on WGS 84 datum; using DGPS or a minimum three lines of position (LOP) with multibeam, channel or mechanical sweep system.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>± 0.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>± 0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>± 1.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>± 10.5</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>± 20 m</td>
<td>a = 1.0, b = 2</td>
<td>Full seafloor ensonification or sweep. All significant seafloor features detected and depths measured.</td>
<td>Controlled, systematic survey to standard accuracy, using modern survey echosounder with sonar or mechanical sweep.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>± 1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>± 1.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>± 3.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>± 21.0</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>± 50 m</td>
<td>a = 1.0, b = 2</td>
<td>Full seafloor coverage not achieved; uncharted features, hazardous to surface navigation are not expected but may exist.</td>
<td>Controlled, systematic survey to standard accuracy.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>± 1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>± 1.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>± 3.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>± 21.0</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>≥ 500 m</td>
<td>a = 2.0, b = 5</td>
<td>Full seafloor coverage not achieved, depth anomalies may be expected.</td>
<td>Low accuracy survey or data collected on an opportunity basis such as soundings on passage.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>± 2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>± 3.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>± 7.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>± 52.0</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>worse than ZOC C</td>
<td>worse than ZOC C</td>
<td>Full seafloor coverage not achieved, large depth anomalies may be expected.</td>
<td>Poor quality data or data that cannot be quality assessed due to lack of information.</td>
</tr>
</tbody>
</table>

**Note:** The CATZOC attribute definitions are currently the subject of review and the results of this review will be promulgated as soon as possible in the S-57 Corrections Document.

**Figure 3: Definition of Catzoc categories (IHO S-57, Annex A)**
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which may apply its own interpretation of CATZOC attributes. However, CATZOC are displayed in electronic nautical charts, and this information is used by the mariner to plan its voyage.

According to CHS, Approximately 10% of the Canadian Arctic waters are adequately surveyed, with 1% surveyed to modern standards and approximately 32% of the Arctic Marine Corridors are adequately surveyed, with an additional 3% of them surveyed to modern standards.

- Marine traffic in Canadian Arctic Seas is increasing;
- The need for hydrographic and cartographic data is important, and existing data do not match the required quality due the age of surveys which underlie a high level of uncertainty, the lack of coverage (most data are legacy leadline sounding or pre-1960 single beam surveys), the lack of accurate water level vertical references
- These previous points raise navigation safety issues for human, economic and environmental reasons.

### 3. Risk Assessment methods

Risk assessment methods were developed in many areas in order to understand causes and consequences of risked events. These formal studies began in the nuclear industry, where risk control was essential. Since then, many risk assessment methods and tools have been developed for specific uses in industries and organisations where important risks need to be understood and appropriately mitigated.

In this section we briefly describe several risk definitions and provide an overview of existing risk assessments methods.

#### 3.1 Preliminary definitions

The following definitions are not universal ones. They may change according to the context of risk studies.

- **Risk**: Product of the frequency and consequence of an event.
- **Frequency**: Measure of the occurrence (actual or probabilistic) of an event. Frequency can be derived from statistics study (absolute frequency) or from an estimation of the likelihood of an event occurring (subjective frequency).
- **Consequence**: Can be positive or negative (in the case of an accident). It can be expressed in terms of “most likely” and “worst credible”. It also can be measured with the financial consequences cost of an event.
- **Risk analysis**: Systematic use of information and expert judgment to identify hazards and estimate their risks to people, property, environment and stakeholders.
- **Risk evaluation**: Establishing the tolerability level of a risk and an analysis of risk control option.
- **Risk assessment**: Risk analysis and evaluation.
3.2. Outline of some risk analysis methods

According to these definitions, many different methods have been developed for different problems. We will quickly describe some of these methods.

3.2.1. Coarse Risk Analysis

This method only presents a risk picture with relatively modest efforts. Risk, hazards, causes and consequence are quickly assessed by an expert judgment. Results are presented in a graphical format, which presents different arguments of probability and consequence. Another graph will present different categories of consequence: risk to people, property, environment etc.

3.2.2. Hazard and Operability Studies

HAZOP is a qualitative risk analysis method that tries to identify facility-design weaknesses and hazard impacts if they are realised. The process studies causes and consequences in a case of a design intent failure. It is used in some sectors of the oil and gas industry to review and sequence operations to ensure appropriate safeguards systems.

3.2.3. Structured What-if Technique

SWIFT technique is lead by the question “what if?”. It is used to identify deviations from normal conditions. SWIFT is a brainstorming technique where personnel familiar with the system under examination identify possible problems and combination of conditions that can create a risk. It is a preliminary technique and it is usually used before a more in-depth HAZOP process.

3.2.4. Risk analysis methods in the maritime industry

International Maritime Organization (IMO) defined a risk assessment analysis process for shipping safety in 1997. Designated as the Formal Safety Assessments (FSA) process, it is a “rational and systematic process for assessing the risks relating to maritime safety and the protection of the marine environment and for evaluating the costs and benefits of IMO’s option for reducing these risks”. This process follows five steps:

- Hazard identification: definition of the present possible hazards according to the case being examined. It usually involves collisions, fire, and grounding.
- Risk analysis: cause, frequency and consequence analysis.
- Risk control options: definition of possible countermeasures and their effects on risk causes, frequency and consequences.
- Cost/Benefit assessment of these risk control options.
- Recommendations for decision making.

This method is comprehensive and can be adapted in many different frameworks. For navigational risk assessment issues, the FSA process meets our requirements through seeing hazards as possible causes of grounding, risk analysis as defining risk levels in areas, and risk control options as marine chart production.
Different approaches have sought to address these issues; we will present them in the next section.

3.3. **Navigation risk assessment methods used as part of hydrographic survey prioritization**

3.3.1. **The ARHC Approach:**

The ARHC (Arctic Regional Hydrographic Commission), which includes the United States, Norway, Denmark, Canada and Russia, presented its work on risk assessment at the 7th meeting of the Inter-Regional Coordination Committee (IRCC)² in Mexico in June 2015. This approach is mainly based on [Gonsalves, 2015] and mostly reflects the NOAA³ Approach to risk assessment.

Their identification of survey priorities is based on three fundamental data sources: confidence of existing hydrographic data, water depth, and density of marine traffic. These three data can be considered independently on a low-to-high risk table:

<table>
<thead>
<tr>
<th>Data type:</th>
<th>Relative Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confidence of Hydrographic Data</td>
<td>Low: Newer; ‘full’ bottom coverage, High: Older; partial bottom coverage</td>
</tr>
<tr>
<td>Water Depth</td>
<td>Low: Deep, High: Shallow</td>
</tr>
<tr>
<td>Density of Traffic</td>
<td>Low: Light traffic, High: Heavy traffic</td>
</tr>
</tbody>
</table>

Table 1: ARHC risk table

3.3.1.1. **Hydrographic data state**

The level of confidence of hydrographic data (classified in “high”, “medium”, or “low”) is derived from different factors: acquisition equipment used, vintage of the survey data, and surveying technique employed and CATZOC (which stands for Category of Zone of Confidence) attributes. Note that the data quality metric associated to high is CATZOC A (without distinction between A1 and A2), the one associated to medium is B, and to low, C.

The following figures are part of the presentation made by ARHC at IRCC⁴. Figure 4 is a sample visualization of the compilation of this information on the eastern side of Bering Strait:

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² The IRCC was established by the International Hydrographic Organization (IHO) in 2009.
³ U.S. National Oceanic and Atmospheric Administration
⁴ 7th meeting of IHO’s Inter-Regional Coordinating Committee
3.3.1.2. **Bathymetric component**

The next layer in the ARHC analysis is the water depth. From the International Bathymetric Chart of the Arctic Ocean (IBACO), one can separate them into three classes: Shallow, Mid-depth and Deep.

The ARHC method then addresses the question of seabed complexity, since navigational risk is seen as higher where the seabed is complex (e.g., where the depth can jump from 100 to 10 meters in a short distance compared to an area where the seabed depth is consistently below 25m). The approach thus separates the seabed complexity in two groups, simple and complex, using the Southern Alaska Coastal Relief Model. Then depths limits for Shallow, Mid-depth and Deep classes are adjusted according to whether the seabed is complex or simple. The next figure is a visualization of the results of incorporating seabed complexity factors, again using the eastern side of the Bering Strait:
Figure 5: Bathymetric depth classification

As a result of intersecting these two map layers, areas of potential concern are delineated (as seen in Figure 6). Areas of potential concern are then ranked from low to high based on their potential for navigational risk. Concern increases from “low” to “high” depending on depths shoaled and/or local survey confidence. For instance, high concern was attributed to shallow waters with low survey confidence. The way the different layers are weighted is not documented in the ARHC scheme, thus this approach can be assimilated to a black box risk matrix.

Figure 6: Combination of hydrographic data state and bathymetric classification score

3.3.1.3. Marine traffic Analysis

A third data source that is then incorporated into this approach is marine traffic from an Automatic Identification System (AIS) database. This is done since it follows that a high concern area with no
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actual vessel traffic should be accorded a relatively low priority. AIS data used in the Easter Bering Strait example spanned June 2012 to July 2013. It also includes ship type information and therefore permits one to characterize “higher consequence” tracks lines, based on their potential for loss of life, property and environmental integrity in the event of a grounding.

Finally, traffic is intersected with the area of potential concern map layer and gives “risk area” locations.

This risk assessment approach is explained by the following flow diagram:

![Figure 7: ARHC complete algorithm](image)

The ARHC method gives high priority to relatively shallow areas, with poor confidence hydrographic data, which are subjected to heavy transits. The type of vessel/cargo is taken into account in the definition of a weighting policy of the consequences associated to a grounding. Note that the consequences are in this scheme only determined by the type of vessel, but not on proximity criteria such like distance to environmentally protected areas, site of cultural heritage, etc…

To conclude, the ARHC developed a procedure to highlight areas of concerns from the point of view of

- nautical chart information quality level,
- type of a priori bathymetric morphology,
- vessel traffic (intensity and type).

The notion of navigational risk is not explicitly stated, however, the combination of the above information is a likelihood multiplied by consequence analysis which indeed represents a risk. However, the way the combination is actually computed is neither explicit nor documented from the available documentation.
3.3.2. The Canadian Hydrographic Service

The Canadian Hydrographic Service (CHS) developed a tool for planning hydrographic surveys and charting, which forms the basis of their prioritization tool. The CHS method is based on a hybrid model that combines the analysis of a GIS system and a risk matrix. One of the primary layers used in the GIS tool is the marine corridors. As a response to the increase of the number of Arctic voyages, the marine corridors provide a focus on areas where there is greater incidence of ship navigation and for which nautical chart would have a(?) quality standard compatible with a safe navigation. Thus, at short and medium term, prioritization of hydrographic and charting activities is focused on areas delineated by the marine corridors.

Marine corridors have been categorized as follow:

- **Primary**: Major well known routes to access other corridors characterized by relatively greater traffic density
- **Secondary**: Routes to communities characterized by lesser traffic density.
- **Tertiary**: Routes to North Warning System sites and places of refuge, also with lesser traffic density.
- **Fourth**: Routes to existing resources development sites, having lesser traffic density.
- **Fifth**: Routes to proposed resource development sites, currently with minimal traffic density.

Corridors have been computed by combining and analyzing the following information:

- Tide and current
- Environment data
- Populated place.
- Port tonnage
- traffic from AIS data
- Safety zones.
- Resources development and projections
- CHS charts
- Hydrographic data
- Ice data
- Anchorage data
- Place of refuge
- Aids to navigation

The next figure shows the preliminary location of northern marine corridors in Canada:
Notice that primary corridors are located on the two major routes: access to Churchill Port and the North West passage. Once the corridors are defined, the next step is to compute a “Level of Effort” for maintaining the navigational risk within acceptable bounds, based on various hydrographic survey planning options. This step evaluates the cost of work to be undertaken for ensuring a level of quality.

Then a priority is given based on all layers in the GIS tools and risk matrix. As an example a complex seabed and where under keel clearance concerns would naturally drive the need for products supported by high resolution bathymetric data source. So, primary corridors, within deep water and non complex seabed would not necessarily have a high priority. A template for modern bathymetric source data coverage requirements was proposed as follows:

- 0-50m water depth to be covered by CATZOC-A surveys.
- 50-100m water depth to be covered by CATZOC-A surveys where seabed is complex or CATZOC-B surveys where seabed is non-complex.
- 100-200m water depth to be covered by CATZOC-B where seabed is complex or CATZOC-C where seabed is non-complex.

The complex/non-complex classification of the seabed is derived from the General Bathymetric Chart of the Oceans (GEBCO).

The prioritization process is based on a difference between the actual and the required quality of nautical charts. It enables one to highlight areas which really need modern hydrographic survey data. Then, considering that ports and port approaches are high priority areas, a second-phase
prioritization is performed on a port by port basis. This prioritization is based on risk matrix including the following factors:

- Traffic frequency;
- Tonnage;
- Extent of the approach area where water depths are less than 50m;
- Seabed complexity;
- Type of traffic; and
- Risk of Grounding.

To conclude this examination, it is noted that the CHS planning tool combines significant levels of geo-spatial information and also includes a risk matrix analysis. This solution permits CHS to:

- Improve the safety of navigation in areas where the risk of an incident is higher,
- Ensure that CHS survey and production plan are align with navigation needs,
- Create a long term plan to cover all Canadian water with modern survey, and
- Create a short term plan to address the most critical areas for charting and survey

CHS prioritization process is based on a GIS analysis and a risk matrix model. The primary GIS layers included in the analysis are the marine corridors, water depth, CATZOC coverage, port locations, and seafloor complexity. The secondary layers used in the GIS tool are ice data, tide gauge information and wind speed. The risk matrix includes the risk of grounding that is based on the criteria of the Permanent International Association of Navigation Congresses (PIANC – Report 121, 2014) and the US Corps of Engineering (EM 1110-2-1100, 2006). The risk of grounding was calculated for all ports in the Arctic. Other factors included in the risk matrix are, the tidal window information, pilotage service, currents information, quality of existing charts, tonnage, number of transits, population, ship type, scale of chart, and gauge information

3.3.3. The LINZ approach:

Land Information of New-Zealand (LINZ) proactively defined risk assessment tools for the South West Pacific Hydrographic Commission (SWPHC) of the IHO. They had driven a study based on the FSA process (adopted by the IMO) and risk matrix concepts for risk analysis.

Risk can be defined, and therefore assessed, in a multitude of ways. The LINZ approach is clearly based on a commonly adopted definition of risk as the product of an event frequency and consequence.

The next figure shows a basic risk matrix. For a given event, the risk score is computed from its probability (from Very Low to Very High) and its impact (from Very Low to Very High).
Examination of Navigation Risk Assessment
Methodologies with Particular Relevance to
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Figure 9: Example of risk matrix. Risk increase with the frequency and consequence.

In the framework of this study, the sole event to consider is the grounding of a vessel.

The grounding event frequency cannot be computed from historical data, as too few grounding events would not represent the actual grounding risk. Moreover, the probability of grounding depends on multiple inputs (e.g., meteorological conditions, chart quality, human factors).

In the LINZ approach, the grounding frequency is defined as the combination of likelihood risk criteria (type of navigation, quality of nautical charts...) and traffic intensity. By combining them, a frequency can be estimated, as it is implemented in the CHS method. Grounding event impact is considered as a combination of possible consequences (pollution of an environmentally protected area for example).

For each risk matrix criterion, a mark (from 0 to 5) is given. Marking system may change from one criterion to another. It can be for example a level of proximity of an important economic site (consequence criteria), or CATZOC attribute for the charts quality criterion (frequency criteria). Then a weight is applied to each criterion in order to express its relative importance in the global risk model. The last step is to compute all criteria marks and weights to express first the frequency and consequence marks, and then a risk level. The next table explains this process:

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Marks e [0...5]</th>
<th>Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Traffic</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion 1</td>
<td>M₁</td>
<td>W₁</td>
</tr>
<tr>
<td>Criterion 2</td>
<td>M₂</td>
<td>W₂</td>
</tr>
<tr>
<td>Criterion 3</td>
<td>M₃</td>
<td>W₃</td>
</tr>
<tr>
<td><strong>Likelihood Risk Criteria</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion 4</td>
<td>M₄</td>
<td>W₄</td>
</tr>
<tr>
<td>Criterion 5</td>
<td>M₅</td>
<td>W₅</td>
</tr>
<tr>
<td>Criterion 6</td>
<td>M₆</td>
<td>W₆</td>
</tr>
<tr>
<td>Criterion 7</td>
<td>M₇</td>
<td>W₇</td>
</tr>
<tr>
<td><strong>Consequence</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion 8</td>
<td>M₈</td>
<td>W₈</td>
</tr>
<tr>
<td>Criterion 9</td>
<td>M₉</td>
<td>W₉</td>
</tr>
<tr>
<td>Criterion 10</td>
<td>M₁₀</td>
<td>W₁₀</td>
</tr>
<tr>
<td>Criterion 11</td>
<td>M₁₁</td>
<td>W₁₁</td>
</tr>
</tbody>
</table>

\[
\text{Traffic} : \sum_{i=0}^{3} M_i \cdot W_i \\
\text{Frequency} : \sum_{i=0}^{10} M_i \cdot W_i \\
\text{Likelihood} : \sum_{i=4}^{7} M_i \cdot W_i \\
\text{Consequence} : \sum_{i=0}^{11} M_i \cdot W_i \\
\text{Frequency} \times \text{Likelihood} \\
\text{Risk Mark} : \\
\text{Frequency} \times \text{Consequence} \\
\]

Table 2: Risk matrix concept
3.3.3.1. Risk Matrix criteria

Each criterion is defined by a risk assessment expert. It seeks to express specific navigational hazards and grounding consequences in the studying area.

*It is our determination that the weighting system is arbitrarily defined.* It is intended to express the importance of each criterion in the system. A certain level of subjectivity is introduced in the risk assessment process.

**Marine traffic**

Traffic matrix risk section is computed from the marine traffic analysis. The two important components and potential consequences of grounding are the loss of life and pollution. LINZ chose to divide its traffic analysis according to these two criteria:

- Potential loss of life.
- Pollution potential.

**Likelihood risk criteria**

This section regroups navigation hazards and elements which may involve a grounding event. These criterions may be defined differently from an area to another, taking into account local navigational hazards (volcanoes, proximity to WWII military sites in (South-West Pacific) versus presence of ice in Arctic). However some of them are more general and are adapted to any hydrographic region.

- Sea floor morphology.
- Proximity to the 15m isobaths.
- Current oceanographic and meteorological conditions.
- Hydrographic and cartographic data state.
- Proximity to known shoals

**Consequences**

Consequences also depend on the area under study and are generally related to pollution impact and the unavailability of access channels due to a grounding accident. These are categorized in three sections: economic, environmental and cultural. It should be noticed that consequence criteria are usually defined as “Proximity to an important site” and defined by an expert judgment. LINZ defines for example:

- Proximity to Large Reef
- Proximity to world Biological Protected site
- Proximity to Local cultural protected or important sites

As with the likelihood criteria, consequences are defined locally.

3.3.3.2. Cost benefit assessment
After assessing navigational risk level of the different areas under study, LINZ applies a cost-benefit method in order to relate hydrographic survey costs to their benefits for economical development of an area. They also assess the cost of the absence of survey, in terms of potential negative impact on economic development due to inadequate navigational risk level. Indeed, if an area remains un-surveyed, the grounding probability will increase, as well as the potential cost of grounding.

This methodology has been applied and tested at a sub-regional scale to many areas in the SWPHC (Tonga, Cook Island, Vanuatu).

3.3.4. Discussion on the three approaches:

3.3.4.1. Weighted overlay analysis

All of these approaches make use of GIS system in order to combine several layers of geo-spatial information. Each criterion is assigned a mark from “lower risk” to “higher risk”. Then the combination of these criteria results in a risk map.

3.3.4.2. The definition of risk

The notion used for risk is important for prioritization studies.

In the LINZ study, risk is clearly defined as a combination of the frequency and consequence of an event.

In the ARHC and CHS approaches, risk is defined using a measure of bathymetric complexity, chart quality information (CATZOC) and traffic information (which is in the case of CHS embedded in the corridors definition). For instance, a shallow and complex seabed will get a higher risk level over a deep and non complex one. This is not a comprehensive definition of likelihood of grounding. In addition, these approaches do not consider other navigational criterion, such as meteorological or currents conditions, as contributing to likelihood risk criterions. However, charting risk areas (with high currents, tidal hazards, etc...) may enable mariners to better plan their routes, and to avoid possible groundings.
Finally, thanks to AIS information analysis, ARHC and CHS can express a frequency of grounding. But they do not clearly examine the consequences of groundings in terms of loss of life, pollution, potential loss of property and for economical development. CHS will give the priority to port approaches with a port by port analysis which acts as a direct weighing of ports areas, instead of using a mode general scheme that would give high risk to some ports areas based on multiple consequence factors, which can be seen as a consequences examination.

### 3.3.4.3. Marine corridors concept

The creation of well surveyed marine corridors is the objective followed by the CHS and taken up by the ARHC. It enables a reduction of the hydrographic survey efforts to smaller zones where ships can transit with a controlled level of hydrographic risk. The LINZ risk matrix also refers to these corridors indirectly: indeed the risk score will be null if there is no navigation in an area, and so they will be seen with lower priority.

The CHS marine corridors definition gives us, in addition to the traffic density information, a global map of the maritime traffic. In the Arctic, communities re-supply highly depends on the viability of maritime routes and is taken into account in the risk assessment process.

### 3.3.4.4. Summary

ARHC and CHS methodologies are objectives approaches. Areas of concern are areas with poor hydrographic dataset, shallow water and high traffic density. The proposed risk assessment process is informed by few but clear criteria.

But the underlying risk definition does not incorporate all navigational risk components and or consequences of grounding. In summary, we could say that these approaches address the issue of chart quality versus density and type of traffic, but not in terms of a comprehensive definition of navigational risk due to hydrographic and charting information quality, and to a comprehensive list of factors on grounding consequences.

The LINZ risk assessment methodology is more comprehensive in terms of risk definition and computation. Traffic analysis, likelihood criteria, consequences are clearly defined. A cost benefit analysis is done in order to help experts in their decision-making process. However, due to a large number of criteria, they need to quantify their importance in the model by a weights system. By doing it they involve more subjectivity in risk matrix results.
PART II: RISK ASSESSMENT METHODS INCORPORATING NON BATHYMETRIC UNCERTAINTY AND SIMULATED TRAFFIC
4. Adaptation of a risk matrix to the Arctic region

In the previous section, we have sought to demonstrate that a risk matrix approach seems to be the most reliable method for assessing navigational risk due to hydrographic and nautical charting information of a given area. In this section, we present a possible risk matrix, adapted to the Arctic region. This matrix incorporates the following three of categories of criteria: traffic, likelihood criteria and consequences.

4.1. Risk matrix definition

A risk matrix design can be divided in three parts:

- Traffic analysis
- Navigational hazards identification
- Consequences identification

Each of these parts needs to be studied by a group of experts who would express all possible criterion and their associated weights.

Marine traffic analysis

According to the studies examined herein, two different traffic approaches could be used:

- A marine corridors concept;
- Potential of loss of life and pollution.

Marine corridors concept is defined in order to help focus surveying efforts in a vast geographic region and to provide at short or medium term well charted shipping lanes.

In addition to this and to be consistent with the definition of risk, the traffic section needs to express a frequency. Therefore, the criterion for traffic analysis should be the traffic density. However, density can be expressed in many ways: number of vessel per years, subdivision per ship types and size.

In relation to grounding consequences, two important topics drive our analysis:

- Potential of loss of human lives.
- Pollution Potential.

Likelihood criteria

Likelihood criteria draw upon possible causes of grounding. It can be divided in two sections: navigational hazards and aids to navigation state.

Navigational hazards

The following navigational hazards could be introduced:
Examination of Navigation Risk Assessment Methodologies with Particular Relevance to Arctic Regions

- Sea floor morphology
  - Complexity
  - Bottom type
  - Proximity of known shoals

- Current and meteorological conditions
  - Current speed
  - Wind conditions
  - Visibility

- Ice coverage
  - Ice coverage period
  - Type of ice (soft, hard)

**Navigation complexity and aids to navigation**

Marine charts and buoys permit ships to avoid possible hazards. But, a poor condition of these aids will give the ship false information and potentially lead to inappropriate decisions, which may lead to grounding. The following criteria represent this risk:

- Marine charts state
  - CATZOC attribution

- Aids to Navigation (port approach buoys…)
  - Accuracy and conditions
  - Possible drift to ice

Buoys can be, in the first place, not properly installed. They can also be shifted by bad weather conditions or by ice. A bad position of these aids will create a difference between the marine chart and the navigator visualization, which can introduce a risk.

According to S-57 specification, CATZOC attribution reflects the state cartographic data. But in selected Arctic regions, the following typical issues may exist:

- Vertical references;
- Horizontal datum shifts;
- Shoreline delineation position accuracy;
- Inaccurate tidal models.

These issues can be explained by the difficulty of getting data in the North, but they are not always clearly defined and may be concealed in the CATZOC attribution process. So, in areas where there is a doubt on hydrographic and cartographic data quality assessment, a further study needs to be done on:

- Age of surveys
- Type of instruments used
- Marine positioning system used
- Possible horizontal datum shifts
Examination of Navigation Risk Assessment
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Arctic Regions

- Accuracy of tide model used for sounding reduction

The type of navigation is also a source of risk. A port approach area seems riskier than off-shore navigation. It is typical to use the 15m isobaths to reference areas where under-keel clearance is an issue:

- Type of navigation
- Distance to 15m contour

Consequences

Consequence criteria are essential in a risk assessment process. They represent the likelihood of a possible consequence of grounding, such as a pollution incident in a protected environmental area. We need here to express several of the most relevant possible consequences of grounding. They can be divided into three categories:

- Economic
  - Proximity to sites of high economic contribution
  - Proximity to sites of moderate economic contribution
  - Proximity to ports
  - Proximity to Tourism sites
- Environment
  - Proximity to protected area of high importance
  - Proximity to protected area of moderate importance
- Cultural
  - Proximity to communities

Proximity to communities also raises another problem. Some communities depend on supply ships, which in some cases, pass once per year. If one of these ships cannot supply the community, it would put the entire community in a difficult situation. Therefore, we express a criterion that represents the purpose of navigation and give a higher importance to certain types of traffic.

CHS defined marine corridors by the traffic density and the purposes of navigation. We can use this information in order to create a new consequence criteria based on the type of marine corridor.

- Marine traffic purpose

The use of marine corridors concept is to ensure higher priority to areas used by vessels. The presence of marine corridors is independent of the risk matrix to be used. In other words, the risk matrix items should remain the same with or without the definition of marine corridors.

The next table presents a proposed risk matrix that would be suitable for the Arctic region. This approach / risk matrix could be further refined through involving in the design process stakeholders directly implicated in navigating Arctic regions.
### Examination of Navigation Risk Assessment Methodologies with Particular Relevance to Arctic Regions

#### Risk Score

<table>
<thead>
<tr>
<th>Risk Score</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
</table>

#### Traffic

<table>
<thead>
<tr>
<th>Type of Traffic</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
<th>Catastrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pollution Potential</td>
<td>Insignificant</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Potential Loss of Life</td>
<td>Insignificant</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
</tr>
</tbody>
</table>

#### Sea Floor Morphology

<table>
<thead>
<tr>
<th>Seabed Complexity</th>
<th>Very Low Complexity</th>
<th>Low Complexity</th>
<th>Medium Complexity</th>
<th>High Complexity</th>
<th>Very High Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom Type</td>
<td>Soft</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximity to Known Shoal</td>
<td>&gt;10nm</td>
<td>5-10nm</td>
<td>2.5-5nm</td>
<td>1.5 to 2.5nm</td>
<td>1 to 1.5nm</td>
</tr>
</tbody>
</table>

#### Meteorological Conditions

<table>
<thead>
<tr>
<th>Prevailing Condition Exposure</th>
<th>Sheltered at most time</th>
<th>Mainly Sheltered</th>
<th>Moderate Exposure</th>
<th>Mainly Exposed</th>
<th>Exposed on most days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring Mean Current Speed</td>
<td>Open Sea</td>
<td>1-2 knots</td>
<td>2-3 knots</td>
<td>3-4 knots</td>
<td>&gt;5 knots</td>
</tr>
<tr>
<td>Visibility</td>
<td>Unknown</td>
<td>Poor Visibility Very Unlikely</td>
<td>Poor Visibility Unlikely</td>
<td>Occasional Poor Visibility</td>
<td>Often Poor Visibility</td>
</tr>
<tr>
<td>Ice Coverage</td>
<td>Free at most time</td>
<td>Mainly Free</td>
<td>Moderate Exposure</td>
<td>Mainly Exposed</td>
<td>Exposed on most days</td>
</tr>
</tbody>
</table>

#### Complexity of Navigation

<table>
<thead>
<tr>
<th>Type Of Navigation</th>
<th>Open Sea &gt;10nm</th>
<th>Offshore Navigation (5-10nm)</th>
<th>Coastal Navigation (1-5nm)</th>
<th>Port Approaches</th>
<th>Constrained Navigation (Within 1nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to 15m Contour</td>
<td>&gt;10nm</td>
<td>5-10nm</td>
<td>2.5-5nm</td>
<td>1.5 to 2.5nm</td>
<td>1 to 1.5nm</td>
</tr>
</tbody>
</table>

#### Aid to Navigation

<table>
<thead>
<tr>
<th>CATZOC Attribute</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buoy Conditions</td>
<td>Very Good</td>
<td>Good</td>
<td>Bad</td>
<td>Very bad</td>
<td>Nonexistent</td>
</tr>
</tbody>
</table>

#### Environmental Impact of Grounding

| Proximity to Protected Area of High Importance | >10nm | 5-10nm | 2.5-5nm | 1.5 to 2.5nm | 1 to 1.5nm | Within 1m |
| Proximity to Protected Area of Moderate Importance | >10nm | 5-10nm | 2.5-5nm | 1.5 to 2.5nm | 1 to 1.5nm | Within 1m |

#### Economical Impact of Grounding

| Proximity to Economical Area of major importance | >10nm | 5-10nm | 2.5-5nm | 1.5 to 2.5nm | 1 to 1.5nm | Within 1m |
| Proximity to Economical Area of moderate importance | >10nm | 5-10nm | 2.5-5nm | 1.5 to 2.5nm | 1 to 1.5nm | Within 1m |
Examination of Navigation Risk Assessment Methodologies with Particular Relevance to Arctic Regions

<table>
<thead>
<tr>
<th></th>
<th>Possible distances (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximity to important infrastructure (Ports)</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Proximity to Tourism Site</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Cultural Impact of Grounding</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Proximity to Community</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Traffic impact</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Proposed risk matrix for Arctic Regions
4.2. Risk matrix calibration.

Risk matrix methods can integrate a large number of criterions and can express the navigational risk for large zones. But weights are often subjectively defined by expert judgment. By doing so, frequency and consequence are subjectively scored, and as a consequence, the risk result may be biased. In order to overcome the subjectivity of the weight determination, we propose to estimate the weights by adjusting the risk matrix results with the outcome of an objective risk computation model, which will compute actual frequency and consequences of grounding.

Let us express the result from the risk matrix as a function of risk marks and weights:

\[ R = F \times C \]  

(2)

<table>
<thead>
<tr>
<th>Traffic</th>
<th>Marks ( X_T )</th>
<th>Weights ( W_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Likelihood</td>
<td>Marks ( X_L )</td>
<td>Weights ( W_L )</td>
</tr>
<tr>
<td>Consequence</td>
<td>Marks ( X_C )</td>
<td>Weights ( W_C )</td>
</tr>
</tbody>
</table>

Table 4: Weights independency

\[ R = (X_T \cdot W_T) \cdot (X_L \cdot W_L) \cdot (X_C \cdot W_C) \]  

(3)

The equation (3) expresses the risk result for an area, considering marks and weights as vectors and risk result as combination of these vectors. Weights are considered as unknowns and marks as known variables. Complete weights estimation will need to express the influence of all risk matrix criteria on the final result.

We observe that the traffic section only has two criteria and weighting them does not require a mathematical estimation, as they can be derived directly from traffic analysis.

The consequence weights would be quite complex to estimate as it would require, for a given simulated grounding, to determine a consequence price. In a first step, we can consider that these weights can still be determined by expert judgment and estimation. Hence, only the likelihood weights should be estimated, in other words: the influence of sea bed, cartographic state and weather criteria on the risk result.

We consider now that \( X_T, W_T, X_C, W_C \) are constant. The equation (3) is now a linear one:

\[ R = \alpha (X_L \cdot W_L) \]  

(4)

Let us suppose that we can estimate (by any means) an objective value of the risk of grounding corresponding to the situation depicted by parameters \( X_L \), supposed to be known. Let us denote this reference risk by \( \tilde{R} = (r_1, r_2, ..., r_n) \), where \( n \) is the number of simulated scenarios for which each analysis cell in a given region has a reference value of risk.
Examination of Navigation Risk Assessment Methodologies with Particular Relevance to Arctic Regions

The optimal risk matrix weights minimizing the distance between the actual risk, as estimated by an objective risk engine simulator and the risk matrix output is then (the development of this estimation is postponed in Appendix B):

\[
\begin{pmatrix}
\sum_j X_{1j}^2 & \ldots & \sum_j X_{1j}^* X_{nj} & \frac{1}{2} \\
\vdots & \ddots & \vdots & \vdots \\
\sum_j X_{nj}^* X_{1j} & \ldots & \sum_j X_{nj}^2 & \frac{1}{2} \\
\frac{1}{2} & \ldots & \frac{1}{2} & 0
\end{pmatrix}
\begin{pmatrix}
W_1 \\
\vdots \\
W_n
\end{pmatrix}
= \frac{1}{\lambda}
\begin{pmatrix}
\sum_j X_{1j}^* r_j \\
\vdots \\
\sum_j X_{nj}^* r_j
\end{pmatrix}
\tag{5}
\]

Where:
- \(X_{ij}\) is the mark on criteria \(i\) and risk matrix scenario \(j\).
- \(r_j\): Risk matrix result combined with traffic and consequence marks and weights on scenario \(j\) (see appendix B).
- \(W_i\): Weights to be estimate.

We can notice two important points:

- First that the matrix \(A\) looks like a Variance/Covariance matrix. We actually express the influence of criteria on risk result.
- Secondly, the number of scenario \(j\) is important. The more scenarios we have, the better we will see the influence of the different criteria and so the more general estimated weights will be. Therefore, if we want universal weights, we will need to express all possible scenarios.

According to these observations, in order to estimate likelihood weights, we need to express an objective model which will compute a risk result on all possible scenarios. We will present in the next section one of these model and its application.

### 3.2.1. Under-keel clearance models and risk assessment

Weights estimation can be done in order to reduce the subjectivity part of the risk matrix weight determination. We therefore need to find an objective risk model which follows the two following characteristics:

- It gives values which have the same nature as the risk matrix outputs.
- It should be as objective as possible.

As we already mentioned in the previous section, we will only estimate frequency weights. So our grounding model will need to compute the actual grounding frequency following different scenarios.
3.2.1.1. Preliminary definitions

Let us recall some basic definitions on hydrographic data, which comprises soundings, tidal information, current information, and type of sea-floor.

A sounding represents the available navigable depth on a given location, with respect to a vertical datum. The location of a sounding is coordinated in a map projection frame with respect to a given Horizontal Datum, relative to a chosen geodetic system. The vertical datum is generally the Chart Datum (CD), which is defined in relation the lowest astronomical tide level. Within a relatively small area the CD can be considered as a constant, but its variation with location maybe significant in coastal areas.

Depth measurements can be given from a wide variety of instruments, from legacy instruments to modern survey systems: lead lines, Single-Beam Echo-Sounders, Multi-Beam Echo-Sounders and Bathymetric LiDAR. At a given location depth measurements are reduced from the tidal water level to provide sounding, this is to say the distance from the sea-floor to the Chart Datum.

The sounding uncertainty is thus depending on depth measurement, position, tidal information, and vertical reference uncertainties.

3.2.1.2. Under-keel clearance

The Under-Keel Clearance (UKC) of a vessel is the available depth between the lowest point of the keel and the sea-floor at a given location \( P \) and a given time \( t \). It will be denoted hereafter by \( u(P, t) \).

\[
u(P, t) = Z(P) + T(P, t) - (d + h(t))
\]  

Figure 11: Definition of Under-Keel Clearance (UKC).

- \( u(P, t) \) is the under-keel clearance. It depends on the vessel position \( P \) and on the time \( t \).
- \( Z(P) \) is the sounding at the location \( P \). The sounding given by the sea chart is defined by the distance between the vertical Chart Datum (CD) and the sea floor.
- \( T(P, t) \) is the water level at position \( P \) and time \( t \).
- \( d \) is the vessels draft including navigational clearance. It does not depend on the time \( t \) neither on the location \( P \).
- \( h(t) \) is the vessel’s heave at time \( t \).
Let us note that this definition depends on two types of parameters:

- Vessel’s navigation parameters: heave \( h(t) \) and vessel’s draft \( d \). Heave depends on the sea state and the type of vessel. The draft is known from vessel’s loading information and is supposed here to include navigation clearance.
- Hydrographic information: Water level, soundings and Chart.

### 3.2.1.3. UKC error analysis.

The definition of under-keel clearance underlies different sources of error, as it depends on sounding, tidal information, and navigational information. In this section we detail the sources of error for all the model components. A synthetic UKC uncertainty model will then be derived.

**Sources of error**

- Draft uncertainty: Its static component may be due to measurement errors after a vessel’s loading. A dynamic component may be due to the squat effect (static negative heave motion in case of low UKC). This effect is particularly sensitive in ports and shallow access channels.
- Heave uncertainty: This component is directly linked to the sea state and will differ for each class of vessel.
- Position \( P \): May be corrupted by positioning errors, and also by a static component which depends on the horizontal chart datum shift.
- \( Z(P) \): The sounding location at the position \( P \) admits an error due to the position uncertainty and a depth error.

### 3.2.1.4. The UKC uncertainty model

**Probabilistic model**

As detailed in Appendix A, an under-keel clearance uncertainty model can be derived from a propagation of errors analysis from the various components of the UKC model. It can be shown that if sounding, tide models, position, draft and heave follow normal laws, then the under-keel clearance, as a linear combination of those components also follows a normal law, which most probable estimate and variance are as follows:

\[
 u(P, t) = Z_{\text{obs}}(P) + T_{\text{obs}}(P, t) - (d_{\text{obs}} + h_{\text{obs}}(t)) 
\]  

(7)

\[
 \sigma_{\text{ukc}}^2 = \frac{\partial Z_v}{\partial E} (E_0)^2 \sigma_{\delta E}^2 + \frac{\partial Z_v}{\partial N} (N_0)^2 \sigma_{\delta N}^2 + \sigma_{Z(P)}^2 + \sigma_{\delta T(P)}^2 + \sigma_{d}^2 + \sigma_{h}^2 
\]  

(8)

Where:

- \( \left( \frac{\partial Z_v}{\partial E} \right)^2 \sigma_{\delta E}^2 + \left( \frac{\partial Z_v}{\partial N} \right)^2 \sigma_{\delta N}^2 \): is a term which depends on the expected or estimated terrain morphology. It should be noticed that this term can only be defined locally, in other words, terrain morphology can’t be extrapolated for significant positional errors.
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- $\sigma_Z^2(P)$: sounding uncertainty;
- $\sigma_T^2(P_0, t_0)$: tide uncertainty;
- $\sigma_d^2$: draft uncertainty;
- $\sigma_h^2$: heave uncertainty.

UKC model will follow a normal law centred on $u(P, t)$ with an uncertainty of $\sigma_{uke}^2$. Hence, probability of the event “grounding” (denoted by $G = true$) is linked to the under-keel clearance by

$$Prob(G = true) = Prob(u(P, t) < 0)$$

(9)

$$Prob(G = true) = Prob(u(P, t) < 0)$$

(11)

In a similar way, one can define the probability of grounding at $k$ meters height by

$$Prob("G = k") = Prob(u(P, t) = -k)$$

(13)

We notice that the probability of grounding, as the under-keel clearance is defined locally in space and time.

With a position $P$, one can define the risk of grounding as the product of the probability of grounding and the cost of the consequences linked to this event. One can therefore define the risk of grounding at position $P$ by

$$r(P) = \int_{k=-\infty}^{0} Prob("G = k") \cdot C(P, k) \, dk$$

(15)

Where $C(P, k)$ denotes the cost function associated to the event “grounding at position $P$ with $k$ meters”. Notice that this cost function may be computed from grounding consequence models for different classes of vessels (see for instance [Sven 2002]).

**MinMax analysis**

Another way to compute a UKC model is to make a “worst case” analysis. Instead of seeing each UKC model component as following a normal law, we will consider them as constant, but still submitted to a certain level of uncertainty.

- Sounding $Z(P)$: let us consider $\Omega_P$ the set of sounding included in the position uncertainty ellipse of the vessel, and $Z_{\min}$ the minimum sounding within this subset, submitted to a level of uncertainty $\delta_{Z_{\max}}$

$$Z_{\min} = \text{Min}\{Z(P)\} \mid_{P \in \Omega_P} - \delta_{Z_{\max}}$$

(17)

- Tide $T(P, t)$:

$$T_{\min}(P, t) = T + \delta T_{\max}$$

(19)

- Draft $d$:
Examination of Navigation Risk Assessment Methodologies with Particular Relevance to Arctic Regions

\[ d_{\text{max}} = d_{\text{true}} + \delta d_{\text{max}} \]  

(21)

- Heave \( h(t) \): heave can be seen as a sinusoidal function. Here we will see it as a constant (sinusoidal function amplitude):

\[ h_{\text{max}}(t) = h_{\text{true}}(t) + \overline{\delta h_{\text{max}}} \]  

(23)

Each UKC component represents the worst possible value for navigation safety considering all uncertainties and errors. The UKC result, for a vessel, at position \( P \) and time \( t \), will express the worst possible scenario.

\[ u(P, t) = Z_{\text{min}} + T_{\text{min}}(P, t) - (d_{\text{max}} + h_{\text{max}}(t)) \]  

(25)

Notice that this under keel clearance definition gives us a constant, not a normal distribution. This facilitates the model computation over a ship trajectory.

Figure 12: Example of under-keel clearance computation along vessel trajectories.

The sector around each vessel location is the set of possible vessel positions considering possible marine chart horizontal shift, meteo-oceanographic conditions, navigator decisions, and manoeuvrability constraints.

To each vessel location (defined along an AIS track), one can associate a position uncertainty, depending on current condition, wind conditions, vessel manoeuvrability, and sounding position uncertainty. Based on the knowledge of:

- Vessel position;
- Time;
- Bathymetric information derived from vessel position;
- Tide information derived from vessel position and time thank to a given tide model;
- Vessel draft and possible heave,
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one can compute the worst case under keel clearance along the vessel trajectory. In case of grounding, the result will gives us:

- Grounding height \( k \)
- Ship speed \( S \)
- Sea floor type (rock, sand…)

Then, by computing the UKC MinMax analysis over the entire existing marine traffic we can express:

- The grounding frequency over the study area:
  \[
  F = \frac{\text{Number of Groundings}}{\text{Number of Vessels}}
  \]  
  \( (27) \)

- Cost of these groundings:
  \[
  C = \sum_{i=0}^{n} C_i(P_i, t_i)
  \]  
  \( (29) \)

Where \( n \) is the number of groundings, and \( C_i(P_i, t_i) \) is the cost function associate for the grounding \( i \).

Then the risk associate to the studying area will be:

\[
R = F \times C
\]  
\( (31) \)

MinMax analysis does not provide any risk charts as does a probabilistic study [Calder, 2008]. It focuses on the “worst possible case”. It gives us a frequency and a cost of groundings. This analysis can easily be computed over a test-bed area where there is AIS traffic data and complete hydrographic information. In addition, the risk definition in this analysis is semantically similar to the one from a risk matrix: a frequency computing with a consequence. We will choose this analysis in the risk matrix weights estimation process.

### 3.2.1.5. UKC model for risk matrix weights estimation

In this section, we present the different steps of the proposed weights estimation methodology using UKC model. As we said before, the main objective is to compute UKC model for different situations in order to compare its results with those in the risk matrix. We will focus only on likelihood criteria.

As we seen in the first section of this report, risk matrix dimensions change from one area to another. Here we will focus on those which are invariant from a study to another:

- Marine traffic
- Hydrographic and cartographic state
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**Test zones**

As the UKC model requires vessel trajectories and hydrographic information, the following information is required for test zones:

- AIS traffic data
- Full bathymetric coverage
- Tide model

On each test zone, we can compute a UKC model by varying any of these criteria. Let us mention that the test zones do not necessarily need to be within the Arctic region. Indeed, as the reference risk computation model relies only on some parts of the risk matrix model which are not specific to the Arctic, they could be chosen in any region where accurate hydrographic and traffic information is available.

**Marine traffic**

Marine traffic analysis is usually done by analyzing AIS data. The following information can be computed from these data: ship type, position, speed, destination, time of departure and arrival. It has been used to study ship risk of grounding [Calder, 2009] according to type of navigation and ports characteristics.

Marine traffic simulation would need to match ship behaviours considering risk matrix situations: lack of bathymetric information, meteorological conditions, tide issues, type of navigation.

**Hydrographic survey simulation**

Hydrographic data quality over an area is maybe one of the most important risk matrix parameters. A lack of bathymetric information can generate poor visualization of navigational hazards, and poor sea bed morphology understanding. Ship routes and navigation margins will be biased by this lack of data. In this section, we try to express this risk by using UKC model on sparse bathymetric data cases.

The problem is to design an estimator of the grounding frequency when there is a lack of bathymetric data. Indeed, our UKC model depends on this information. We propose therefore to simulate a lack of data from an exhaustive bathymetric data set. This solution allows us to compute our grounding risk model with actual and accurate data.

Let us take a test zone, where we have a full hydrographic information. In such an area, a UKC model computation is possible. From this, we can simulate a degradation of the CATZOC attribute in selecting sparse data subsets from the original dataset.

**Data sampling**

The sampling process needs to represent a hydrographic survey related to a typical CATZOC attribute. So, for each CATZOC class, we will divide it in two parts: survey lines design and instrument choice (or sounding accuracy). For the first two CATZOC classes (A1 and A2):

- **CATZOC A1**: Not simulated because our bathymetric model already has CATZOC A1 attributes: full coverage, multi-beam echo-sounder system.
- **CATZOC A2**: No need of data sampling here, but we will decrease sounding accuracy.
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For the next CATZOC classes, we need to sample the existing information and to simulate hydrographic surveys. The instrument used will be a single beam echo-sounder (SBES) in order to create a partial coverage. The line design can follow two definitions: IHO standards for hydrographic surveys S-44 and a function of nautical scale. We will use these two definitions as hereafter:

- CATZOC B: Line spacing defined by the S-44 order 1b.
- CATZOC C: Line spacing function of nautical scale
- CATZOC D: Line spacing function of nautical scale, but we simulate a virtual increasing of the nautical scale (a Port approach scale became a coastal scale).
- CATZOC U: Same as CATZOC D, instrument choices: sounding lead.

Figure 13: example of data sampling according to a hydrographic survey design

Data interpolation

After the sampling step, we need to interpolate these new data in order to create a new bathymetric model. Interpolating the sparse soundings subset will create interpolation errors, and sampling will distort the bathymetric surface.

Let us note:

\[ \Omega_E: \text{set of entires zone soundings} \]
\[ \Omega_S: \text{set of sampling soundings} \]
\[ \Omega_I: \text{set of interpolate soundings} \]

We have:

\[ \Omega_S \subset \Omega_E \]

So

\[ \text{Min}(\Omega_S) \geq \text{Min}(\Omega_E) \]

From the interpolation process, we have:

\[ \text{Min}(\Omega_I) \geq \text{Min}(\Omega_S) \]
By sampling and interpolating the existing bathymetric data, the minimal interpolated sounding will be deeper or equal than the actual one. The next figure illustrates this difference and illustrates the method described previously:

By induction, the minimum of under keel clearance along the ship trajectory will be higher with interpolated data, and so the risk will seem to be lower. Let us note $\text{Min}(\text{UKC}_{\text{True}})$ the under keel clearance minimum using the actual bathymetric data and $\text{Min}(\text{UKC}_{\text{Thought}})$ the one using the interpolate data.

We consider that the minimum under keel clearance result $\text{Min}(\text{UKC}_{\text{True}})$ is the navigation margin chosen by the navigator. We can consider that the navigator will take the same margin in a case of a lack of data. Therefore, we will subtract the two minimum differences from the UKC model (it can represent a higher draft or a difference in the tide) in order to get the same navigation margin on
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UKC model computation. Grounding event will be true if the difference is higher than the actual under-keel clearance along the vessel track.

\[
\text{Grounding event is true if: } UKC - \left( \text{Min}(\text{UKC}_{\text{Thought}}) - \text{Min}(\text{UKC}_{\text{True}}) \right) < 0
\]

![Graph showing under-keel clearance](image)

**Figure 16:** Lack of data risk. A grounding event will be true if the difference between the true and thought under-keel clearance is higher than the actual under-keel clearance minimum

Sampling bathymetric data will not always imply a grounding event. We propose to follow a Monte Carlo method to simulate typical hydrographic surveys. It will allow us to get the impact of hydrographic data state on grounding frequency.

In addition to this interpolation error, we need to take care of possible cartographic error, and in particular horizontal chart shifts.

**Currents and meteorological conditions**

Currents and winds influence ship handling and trajectory and can thereby cause grounding. For example, currents and/or winds can cause a ship to drift into a shoal or out of entrance channel.

In our simulation, these meteorological conditions can be expressed by an increase in the size of the position uncertainty ellipse. It can be defined by using guidelines for marine corridors design [Canadian Coast Guard, 2001]. Indeed, marine corridors sizes are designed to permit ships to be able to mitigate risks according to various conditions. According to the Canadian Coast Guard report, we will define the uncertainty ellipse length by:

<table>
<thead>
<tr>
<th>Ship Type</th>
<th>Handling</th>
<th>Handling Coefficient</th>
<th>Room for manoeuvre length</th>
</tr>
</thead>
<tbody>
<tr>
<td>War vessel, Victory cargos</td>
<td>Excellent</td>
<td>1.6</td>
<td>1.6*Ship Width</td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Ship Type</th>
<th>Maneuverability</th>
<th>Width Offset (m)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tankers, New ore carriers, Liberty cargo</td>
<td>Good</td>
<td>1.8</td>
<td>1.8*Ship Width</td>
</tr>
<tr>
<td>Old ore carriers, damaged ships</td>
<td>Poor</td>
<td>2.0</td>
<td>2.0*Ship Width</td>
</tr>
</tbody>
</table>

Table 5: Room for manoeuvre length according to ship type

Then, we add the wind and current contribution to the position uncertainty:

<table>
<thead>
<tr>
<th>Wind intensity</th>
<th>Width offset by ships handling</th>
<th>Excellent</th>
<th>Good</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>0.0*Ship Width</td>
<td>0.0*Ship Width</td>
<td>0.0*Ship Width</td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>0.6*Ship Width</td>
<td>0.7*Ship Width</td>
<td>1.0*Ship Width</td>
<td></td>
</tr>
<tr>
<td>Strong</td>
<td>0.8*Ship Width</td>
<td>1.0*Ship Width</td>
<td>1.3*Ship Width</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Wind contribution in position uncertainty according to wind strength

And the current contribution:

<table>
<thead>
<tr>
<th>Current intensity</th>
<th>Width offset by ships handling</th>
<th>Excellent</th>
<th>Good</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not significant (&lt;0.2 knts)</td>
<td>0.0*Ship Width</td>
<td>0.0*Ship Width</td>
<td>0.0*Ship Width</td>
<td></td>
</tr>
<tr>
<td>Light (0.2-0.5 knts)</td>
<td>0.2*Ship Width</td>
<td>0.3*Ship Width</td>
<td>0.5*Ship Width</td>
<td></td>
</tr>
<tr>
<td>Moderate (0.5-1.5 knts)</td>
<td>0.7*Ship Width</td>
<td>1.0*Ship Width</td>
<td>1.3*Ship Width</td>
<td></td>
</tr>
<tr>
<td>Strong (&gt;1.5 knts)</td>
<td>1.0*Ship Width</td>
<td>1.5*Ship Width</td>
<td>2.0*Ship Width</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Current contribution on ship position uncertainty according to current strength

Then, by computing these three tables, we will be able to define the position uncertainty due to wind and currents conditions.

3.2.2. Conclusion on weights estimation

By computing the UKC model for different situations, we would be able to express the influence of the risk matrix likelihood components on the grounding frequency. These components can be divided in two groups: those that cannot and those that can be simulated.

For the first group (those that cannot be simulated), test zones must be representative of all possible scenarii to estimate the most representative weights. Indeed, the variation of risk matrix entries (i.e.; Marks) corresponding to these criterion naturally change with location, as they mostly are proximity criterion.

The second group’s criteria will be simulated. These simulations should accurately represent hydrographic survey plans corresponding to CATZOC attribution. The more criteria we are able to simulate, the less actual data we will need and therefore the more scenarii we will be able to study.

Let us summarize the different steps of the risk matrix weights estimation method we propose:
The weights estimation is an iterative process and can be improved. It also can be used in order to study the impact of a hydrographic survey on grounding frequency. In the same way, we would be able to study the impact of a horizontal chart datum or tidal model improvement on the grounding frequency. This kind of information would be helpful in the prioritization process. It can improve the Level of Effort estimation for reaching a given level of service of a corridor or a given area.

Figure 17: Weights Estimation Process
PART III: IHO-IMO APPROACHES FOR PRIORITIZATION
4. Risk Assessment method development

In the recent years, risk assessment methods and the prioritization processes that they inform have been subject to rapid development. The International Hydrographic Organization seeks a unified/universal methodology for prioritization of hydrographic surveys. For the time being, prioritization is pursued at the state level. The international community may need Standards or at least Guidance to define or choose the appropriate methodology that could best fit the specificity of each region. The development of risk assessment methods is mainly driven by the important need for hydrographic data in some regions (South West Pacific (SWP), Africa, Arctic, Antarctica and Caribbean in particular).

Among the approaches that have been developed, some of them are at the prototype level, while other have been already adopted by Member States as “official” tools for assessing navigation risk to prioritize hydrographic surveys (Canada, New-Zealand).

One should also distinguish risk assessment methods in at least three classes:
1. Risk assessment methods intended to be usable at a sub-regional scale;
2. Risk assessment methods at local scale
3. Risk assessment methods intended for use in re-survey prioritization processes which take into account the additional complexity of temporal variation of the sea-floor (presence of moving dunes for instance).

This present study focused on the first class of risk assessment methods, those appropriate for use at the sub-regional, such as in the Arctic.

A fundamental issue in risk assessment lies in the quality of charting that is available. Indeed, charting quality indicators (CATZOC) are generally a fundamental ingredient of all risk assessment methods. One should therefore question how CATZOC attribution is designated and how objective is their determination.

The IHO Data Quality Working Group (DQWG) has raised this issue since 2010, motivated by the Grounding of the Octopus and the Marine accident investigation Board recommendation to the IHO: “Relevant IHO/IMO working groups should investigate ways of ensuring that ECDIC displays provide a clear warning or indication to the mariner whenever the survey data used to produce the electronic chart in use is of poor quality”.

A risk assessment problem is not exactly the same as the chart quality indication to the mariner, but quite related, as chart quality serves as a basis of prioritization processes.

It seems that any risk assessment method should incorporate a description of the process used to designate CATZOC attribution, as well as other S-57 attribution, such like M_SREL (Survey reliability), M_ACCY (Accuracy), and M_QUAL (Quality). Indeed, a risk assessment scheme should be more reliable, efficient, and targeted to hydrographic requirement if it would incorporate comprehensive information on existing hydrographic data sources.

Current IHO activity

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5 Electronic Chart Display & Information System
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Development of risk assessment to inform prioritization is a priority of the IHO. An IHO working group is expected to be created in 2015 which first objective is to compare the different approaches and requirements from the Member States.
**Conclusion**

Risk assessment for hydrographic surveys prioritization is a sensitive topic. Some hydrographic services initiated research and development following different approaches and goals.

In this report we explained three of these approaches. All of them process geo-spatial information using a weighted overlay analysis approach. We saw that the definition of “navigational risk due to hydrographic and charting information” requires some attention.

We have shown that the ARHC and CHS risk notion is based on a limited number of grounding consequences. It is the view of the author that the notion of risk and the risk assessment methodologies examined in the preceding report each have their limitations. In our view, by focusing their methods on bathymetric issues they have produced a quasi objective model, but that other potentially important grounding causes could improve these methods.

The LINZ methodology follows an existing marine risk assessment process (FSA) originally proposed by the IMO. The scheme, which was developed and applied in the South West Pacific Hydrographic Region, clearly defines risk as the computation of a frequency and a consequence. The risk matrix is adapted to the needs and specificity of a sub-region, and refers to a well-grounded notion of risk. All criteria are defined, documented, graded, and weighted. The computation of this matrix is done in the same way as the ARHC and CHS GIS tools. But, due to the large number of criteria, they need to quantify the importance of each criterion in the model. It raised the issue of weights estimation, which is still a major source of subjectivity in the risk assessment process.

Weight estimation is needed in order to represent the relative importance of each criterion in the risk matrix. We have shown a method wherein the estimation of risk matrix weight can be achieved by degrading a set of full hydrographic information on a test region, in order to both simulate partial or poor quality charting quality, navigation conditions, and traffic. The solution we propose uses a mathematical and objective grounding model as a reference model. Our objective is to make the risk matrix coefficient to “learn” this model through an objective weighting policy.

The approach we presented can be used only in areas where comprehensive knowledge of hydrographic and nautical charting information is available. In simulating a subset of the risk matrix criterions (i.e., CATZOC, type of navigation), and by using a mathematical risk model, we determine the risk of grounding over the area, which enables us to calibrate the risk matrix coefficients.

This approach could be implemented as a prototype software enabling institutions which make use of risk matrices to determine the objectively their coefficients.

The use of risk matrix combining traffic, likelihood and consequences of groundings seems to be the most promising approach for risk assessment applied to hydrographic survey prioritization. Through a clear definition of the navigational risk due the hydrography, this approach could be supplemented by GIS and computational tools enabling the user to determine risk matrix weight in an objective way.
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Bibliography


**Appendix A: Under-Keel clearance uncertainty model**

**Sounding error**

In this section we will define the sounding term and its error components. Let us note $P_0 = (E_0, N_0)$ the position, $Z(P_0)$ the assumed sounding at the position $P_0$, $Z_v(P_0)$ the true sounding at the position $P_0$ and $\delta Z_v(P_0)$ the sounding uncertainty. We have:

$$Z(P_0) = Z_v(P_0) + \delta Z_v(P_0)$$

At a position $P_0 + \delta P$ and at order one in $\delta P$, we have:

$$Z(P_0 + \delta P) = Z_v(P_0) + \delta Z_v(P_0) + \frac{dZ}{dP}(P_0) \delta P$$

$$= Z_v(P_0) + \delta Z_v(P_0) + \frac{dZ_v}{dP}(P_0) \delta P + \frac{d\delta Z_v}{dP}(P_0) \delta P$$

Where

- $\frac{dZ_v}{dP}(P_0)$ is the local slope of the sea-floor

- $\frac{dZ_v}{dP}(P_0) \delta P$ define the error due to the position uncertainty

- $\frac{d\delta Z_v}{dP}(P_0)$ is the local variation of the sounding uncertainty. Assuming that the sounding error is be the same over a small area, this component is equal to zero.

Then

$$Z(P_0 + \delta P) = Z_v(P_0) + \delta Z_v(P_0) + \frac{dZ_v}{dP}(P_0) \delta P$$

Where $\frac{dZ_v}{dP}(P_0)$ is the gradient of the sea-floor at the position $P_0$ defined by:

$$\frac{dZ_v}{dP}(P_0) = \begin{bmatrix} \frac{\partial Z_v}{\partial E}(E_0) & \frac{\partial Z_v}{\partial N}(N_0) \end{bmatrix}$$

And

$$\frac{dZ_v}{dP}(P_0) \delta P = \frac{\partial Z_v}{\partial E}(E_0) \delta E + \frac{\partial Z_v}{\partial N}(N_0) \delta E$$
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**Tide error**

Following the same lines, we will define the tide error. Let us write \( P_0 = (E_0, N_0) \) the position, \( t_0 \) the time, \( T(P_0, t_0) \) the assumed model tide at position \( P_0 \) and time \( t_0 \), \( T_v(P_0, t_0) \) the true tide at position \( P_0 \) and time \( t_0 \) and \( \delta T(P_0, t_0) \) the tide uncertainty. We have:

\[
T(P_0, t_0) = T_v(P_0, t_0) + \delta T(P_0, t_0)
\]

At a position \( P_0 + \delta P \) and at a time \( t_0 + \delta t \) we have:

\[
T(P_0 + \delta P, t_0 + \delta t) = T_v(P_0, t_0) + \delta T(P_0, t_0) + \frac{dT}{dP}(P_0)\delta P + \frac{dT}{dt}(t_0)\delta t
\]

\[
T(P_0 + \delta P, t_0 + \delta t) = T_v(P_0, t_0) + \delta T(P_0, t_0) + \frac{dT_v}{dP}(P_0)\delta P + \frac{d\delta T}{dP}(P_0)\delta P + \frac{dT_v}{dt}(t_0)\delta t + \frac{d\delta T}{dt}(t_0)\delta P
\]

Where
- \( \frac{dT_v}{dP}(P_0) \) is the tide gradient with respect to the position. We will consider that the tide variations are insignificant for a small position variation \( \delta P \).
- \( \frac{d\delta T}{dP}(P_0) \) is the local variation of the tide uncertainty versus position. We will assume that tide’s error will be the same in a given small area, so this component is supposed to be zero.
- \( \frac{dT_v}{dt}(t_0) \) is the tide variation versus time. This derivative will not be significant.

Following these assumptions and simplifications, the water level variation can be written by:

\[
T(P_0 + \delta P, t_0 + \delta t) = T_v(P_0, t_0) + \delta T(P_0, t_0)
\]

The term \( \delta T(P_0, t_0) \) may include two types of errors:
- The first one is may be a tidal measurement error, due to instrument and Chart Datum (CD) uncertainties. CD uncertainty may be due to a too short time series used for its estimation.
- The second one may be due to the fact that the tide model used at vessel’s position \( P_0 \) may be defined for another position \( P_1 \). Consequently, the term \( \delta T(P_0, t_0) \) may include the spatial variation of tide due to the use of a model (or tide gauge) at a remote location.

**Other components**

Other component of the UKC uncertainty model do not depend of time (we may consider that heave is a centered random variable) and vessel’s position. But they may be submitted to measurement errors or uncertainties. We will represent these errors by:

\[
d = d_v + \delta d
\]

\[
h = h_v + \delta h
\]
All these components can be seen as centered variables and their uncertainties as constant offsets. We can now propagate the uncertainty due to all component of the UKC equation in a global linearized model:

\[ u(P, t) = u(P_0 + \delta P, t_0 + \delta t) = Z_v(P_0) + T_v(P_0, t_0) + (d_v + h_v) + \delta u \]

Where

- \( \delta u = \delta Z(P_0 + \delta P) + \delta T(P_0 + \delta P, t_0 + \delta t) - (\delta d + \delta h) \)
- \( \delta Z(P) = \delta Z_v(P_0) + \frac{\partial Z_v}{\partial p} (P_0) \delta P \)
- \( \delta T(P, t) = \delta T(P_0, t_0) \)

**Under-keel clearance uncertainty model**

We can now propagate uncertainties through equation (A.9).

\[ \sigma^2_{\text{ukc}} = \left( \frac{\partial Z_v}{\partial E} (E_0) \right)^2 \sigma^2_{\delta E} + \left( \frac{\partial Z_v}{\partial N} (N_0) \right)^2 \sigma^2_{\delta N} + \sigma^2_{Z(P)} + \sigma^2_{\delta T(P)} + \sigma^2_{d} + \sigma^2_{h} \]

Where: \( \sigma^2_{\text{ukc}}(P_t) = \sigma^2_{\text{ukc}(P_0,t_0)} \)

We shall denote by \( \sigma^2_x \) the variance of a random variable \( x \).

From equation (A.10), we see that whenever all source of error follows a normal law, the UKC will also follow a normal law which variance depends on:

- \( \left( \frac{\partial Z_v}{\partial E} \right)^2 \sigma^2_{\delta E} + \left( \frac{\partial Z_v}{\partial N} \right)^2 \sigma^2_{\delta N} \): is a term which depends on the expected or estimated terrain morphology. It should be noticed that this term can only be defined locally, in other words, terrain morphology can’t be extrapolated for significant positional errors.
- \( \sigma^2_{Z(P)} \): sounding uncertainty;
- \( \sigma^2_{\delta T(P_0,t_0)} \): tide uncertainty;
- \( \sigma^2_{d} \): draft uncertainty;
- \( \sigma^2_{h} \): heave uncertainty.

In summary, if the sounding, tide, draft, and heave uncertainty follows a normal law, then the UKC also follows a normal law, which is described by its most probable estimate at time \( t \)

\[ u(P, t) = Z_{\text{obs}}(P) + T_{\text{obs}}(P, t) - (d_{\text{obs}} + h_{\text{obs}}(t)) \]

**Appendix B: Weights Estimation**

We will here describe the weights estimation equation.

Let us remind the risk matrix computation:
Examination of Navigation Risk Assessment Methodologies with Particular Relevance to Arctic Regions

\[ r = (X_T \cdot W_T)(X_L \cdot W_L)(X_C \cdot W_C) \]

Where:

- \( X_T, X_L, X_C \) are the matrix marks for Traffic, Likelihood and Consequence sections.
- \( W_T, W_L, W_C \) are the matrix weights for Traffic, Likelihood and Consequence sections.
- \( r \): Risk matrix result

The risk result is a combination of marks and weights. In our case, we will only estimate the likelihood weights and consequently, equation (A.1) becomes linear under constraints.

To estimate likelihood weights, we need to minimize the following difference:

\[ \min \left( \frac{r}{(X_T \cdot W_T) \cdot (X_C \cdot W_C)} - (X_L \cdot W_L) \right)^2 \]

Then, for \( m \) different scenarii:

\[ \min \left( \sum_{j=0}^{m} \left( R_j - \sum_{i=0}^{n} W_i \cdot X_{ij} \right)^2 \right) \]

Where:

- \( m \): Number of scenarii
- \( n \): Number of likelihood criteria

\[ R = \frac{r}{(X_T \cdot W_T) \cdot (X_C \cdot W_C)} \]

Considering that the sum of all weights needs to be equal to one, our estimation will need to meet the following conditions:

\[ \min \left( \sum_{j=0}^{m} \left( r_j - \sum_{i=0}^{n} W_i \cdot X_{ij} \right)^2 \right) \]

\[ \sum_{i=0}^{n} W_i = 1 \]

Problem (A.5) is a optimization problem under equality constraints. Let us introduce the Lagrange multiplier of (A.5):

\[ \mathcal{L}(W, \lambda) = \sum_{j=0}^{m} \left( r_j - \sum_{i=0}^{n} W_i \cdot X_{ij} \right)^2 - \lambda \left( \sum_{i=0}^{n} W_i - 1 \right) \]

By differentiating equation (A.6) with respect to the weight vector \( W_p \), we obtain:
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\[
\frac{\partial \mathcal{L}(W, \lambda)}{\partial W_p} = -2 \sum_{j=0}^{m} \left( r_j - \sum_{i=0}^{n} W_i \* X_{ij} \right) - \lambda
\]

The other necessary condition for optimality of the weight vector is:

\[
\frac{\partial \mathcal{L}(W, \lambda)}{\partial W_i} = 0
\]

Thus we obtain the following system of equations:

\[
\begin{aligned}
\sum_{j=0}^{m} \left( X_{pj} \* \sum_{i=0}^{n} W_i \* X_{ij} \right) - \frac{\lambda}{2} = \sum_{i=0}^{n} \left( W_i \* \sum_{j=0}^{m} X_{pj} \* X_{ij} \right) - \frac{\lambda}{2} = 0 \\
\sum_{i=0}^{n} W_i = 1
\end{aligned}
\]

From which we write the final matrix form of (A.9):

\[
\begin{pmatrix}
\sum_{j} X_{1j}^2 & \ldots & \sum_{j} X_{1j} \* X_{nj} & -\frac{1}{2} & \vdots & \sum_{j} X_{1j} \* r_j \\
\vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\
\sum_{j} X_{nj} \* X_{1j} & \ldots & \sum_{j} X_{nj}^2 & -\frac{1}{2} & \vdots & \sum_{j} X_{nj} \* r_j \\
\frac{1}{2} & \ldots & \frac{1}{2} & 0 & \frac{1}{2} & \frac{1}{2} & \lambda
\end{pmatrix}
\begin{pmatrix}
W_1 \\
\vdots \\
W_n \\
\lambda
\end{pmatrix}
= \begin{pmatrix}
\sum_{j} X_{1j} \* r_j \\
\vdots \\
\sum_{j} X_{nj} \* r_j \\
\frac{1}{2} & \frac{1}{2} & \lambda
\end{pmatrix}
\]

Where:

\(W_i\): The estimate weight \(W_i\)

\(\lambda\): The estimated Lagrangian factor.