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Virtual aids to navigation

R. Glenn Wright

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WORLD MARITIME UNIVERSITY
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VIRTUAL AIDS TO NAVIGATION

By

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A dissertation submitted to the World Maritime University in partial fulfillment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY
In
MARITIME AFFAIRS

2016

Declaration

I, **R. Glenn Wright**, certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred to me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University

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Signatures *Date*

Dedication

To my wife, Magdalena
who has persevered through
many years of late nights, early mornings
airport security lines and lost files.
Thank you!
… I've almost finished

Acknowledgements

I would like thank my family, and especially my wife Magdalena for their patience and support throughout my studies. In addition I would very much like to thank:

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I would also like to acknowledge the inspiration of Rowan Atkinson playing the part of Edmund Blackadder who, just prior to departing to sail the Sea of Certain Death, was handed a map prepared by the foremost cartographers of the land of the area he would be traveling. He opened it up and saw it was blank. He was then told, “They’ll be very grateful if you could just fill it in as you go along. Bye-bye.” (Elton and Curtis, 1986).

… it somehow seemed to fit the topic.

Abstract

Title of Dissertation: **Virtual Aids to Navigation**

Degree: **Doctor of Philosophy**

There are many examples of master, bridge crew and pilot errors in navigation causing grounding under adverse circumstances that were known and published in official notices and records. Also dangerous are hazards to navigation resulting from dynamic changes within the marine environment, inadequate surveys and charts. This research attempts to reduce grounding and allision incidents and increase safety of navigation by expanding mariner situational awareness at and below the waterline using new technology and developing methods for the creation, implementation and display of Virtual Aids to Navigation (AtoN) and related navigation information. This approach has widespread significance beyond commonly encountered navigation situations. Increased vessel navigation activity in the Arctic and sub-Arctic regions engenders risk due, in part, to the inability to place navigational aids and buoys in constantly changing ice conditions. Similar conditions exist in tropical regions where sinker placement to moor buoys in sensitive environmental areas with coral reefs is problematic. Underdeveloped regions also lack assets and infrastructure needed to provide adequate navigation services, and infrastructure can also rapidly perish in developed regions during times of war and natural disaster.

This research exploits rapidly developing advances in environmental sensing technology, evolving capabilities and improved methods for reporting real time environmental data that can substantially expand electronic navigation aid availability and improve knowledge of undersea terrain and imminent hazards to navigation that may adversely affect ship operations. This is most needed in areas where physical aids to navigation are scarce or non-existent as well as in areas where vessel traffic is congested. Research to expand related vessel capabilities is accomplished to overcome limitations in existing and planned electronic aids, expanding global capabilities and resources at relatively low-cost. New methods for sensor fusion are also explored to

reduce overall complexity and improve integration with other navigation systems with the goal of simplifying navigation tasks. An additional goal is to supplement training program content by expanding technical resources and capabilities within the confines of existing International Convention on Standards for Training, Certification and Watchkeeping for Seafarers (STCW) requirements, while improving safety by providing new techniques to enhance situational awareness.
Key Words: Aid to Navigation, AtoN, 3-dimensional Forward-looking Sonar, 3D-FLS, Hydrographic Survey, Virtual AtoN

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Paper 2 – Wright R.G., Baldauf M. (2016) 'Correlation of Virtual Aids to Navigation to the Physical Environment'. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, Vol. 10, No. 2, 287-299, DOI: 10.12716/1001.10.02.11

Paper 3 – Wright R.G., Baldauf, M. (2016) 'Hydrographic Survey in Remote Regions: Using Vessels of Opportunity Equipped with 3-dimensional Forward-Looking Sonar'. *Journal of Marine Geodesy*. Vol. 39, No. 6, 439-357. DOI 10.1080/ 01490419.2016.1245266

Paper 4 – Wright R.G., Baldauf, M. (2016) Arctic Environmental Preservation through Grounding Avoidance, *Sustainable Shipping in a Changing Arctic Environment*, L.P. Hildebrand & L.W. Brigham, editors. Springer International Publishing, AG, Cham. London. *Submitted, undergoing peer review.*

Paper 5 – Wright R.G., Baldauf M. (2014) 'Enhanced Situational Awareness through Muli-Sensor Integration', in *Proc. 18th International Navigation Simulator Lecturers' Conference (INSLC 18)*, Buzzards Bay, Massachusetts USA, 40-59. ISBN 978-0-692-29012-5.

List of Abbreviations, Acronyms and Frequently Used Terms

3D-FLS	3-dimensional Forward-Looking Navigation Sonar
AIS	Automatic Identification System
AtoN	Aid(s) to Navigation
bbl	Barrels (e.g., of oil)
BeiDou	name of the Chinese satellite navigation system
CLIA	Cruise Line Industry Association
COLREGS	International Regulations for Preventing Collisions at Sea
CSBWG	Crowd-Sourced Bathymetry Working Group
ECDIS	Electronic Chart Display and Information System
eLORAN	enhanced Long Range (Radio) Aid to Navigation
ENC	Electronic Navigation Chart
EPE	Estimated Positioning Error
Galileo	European GNSS (not an acronym)
GLONASS	Global'naya Navigatsionnaya Sputnikovaya Sistema (Russian Federation)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System (US)
HtoN	Hazard to Navigation
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IEEE	Institute of Electrical and Electronic Engineers
IHO	International Hydrographic Organization
IMO	International Maritime Organization
INS	Integrated Navigation System or Inertial Navigation System
NGO	Non-Governmental Organization
NI	Nautical Institute
NOAA	National Oceanographic and Atmospheric Administration (USA)
PAtoN	Private Aid(s) to Navigation
RADAR	RAdio Detecting and Ranging
S-57	IHO Transfer Standard for Digital Hydrographic Data
S-100	IHO Geospatial Standard for Hydrographic Data
S-102	IHO Bathymetric Surface Product Specification
SOLAS	Safety of Life at Sea (IMO Convention)
SONAR	SOund NAvigation and Ranging
STCW	International Convention on Standards for Training, Certification and Watchkeeping for Seafarers
THU	Total Horizontal Uncertainty (in measuring position)
TVU	Total Vertical Uncertainty (in measuring depth)

VHF	Very High Frequency (30 – 300 MHz)
VOR	VHF Omni-directional Radio Range
WAAS	Wide Area Augmentation System (US)
WGS84	World Geodetic System 1984 (GNSS datum)

Chapter 1 Introduction

This chapter describes Virtual Aids to Navigation (AtoN) that comprise the domain of the research embodied within this dissertation. The subjects of hydrographic survey and the Arctic are also discussed as they form elements essential to the placement of AtoN and their operating environment.

1.1 Background

There exist various landmarks, markers, devices and other natural features, manmade signs and apparatuses to aid travelers in determining their location and direction of travel and to identify routes between destinations, warn of dangers and obstructions to travel, and to assess the rate of progress being made in their transit. In the maritime and aviation communities such features, signs and apparatuses are referred to as aids to navigation that are found both within the physical environment as well as on navigation charts that depict their geographic positions and characteristics by which their purpose and function may be recognized. Long range AtoN include Global Navigation Satellite Systems (GNSS) such as the United States Global Positioning System (GPS), Russia's Global Navigation Satellite System (GLONASS), the European Union's Galileo, China's BeiDou Navigation Satellite System, and the low frequency Long Range Navigation (eLORAN) radio systems. Short range maritime AtoN include various lighted and unlighted beacons and buoys, ranges, lighthouses, leading lights and associated sound signals.

The Virtual AtoN concept of a charted aid to navigation having no physical presence at the charted location is relatively new to maritime use. However, this concept is now becoming more widespread and accepted with the adoption of Automated Identification System (AIS) radio-based technology that can project a virtual AtoN to a specific position for display on AIS monitors and AIS-capable Radar and Electronic Chart Display and Information System (ECDIS) monitors. This is accomplished using a Very High Frequency (VHF) radio transmitter augmented with AIS capabilities located within the line of sight of the specific position at which an AIS virtual AtoN is deployed. A similar approach has been implemented in the aviation community for many decades beginning in the middle of 20^{th} century in the form of VHF Omni-directional Radio Ranges (VOR). Virtual navigation fixes are defined by the intersection of radials from two different VOR stations, and bearings to and from these stations are also provided facilitating navigation along traffic routes and corridors. VOR technology in aviation is gradually being replaced with GNSS enabling direct routing between origins and destinations. Universal adoption of GNSS provides equally useful utility to mariners for navigation.

1.2 Virtual aids to navigation

The results of this research embody a new and unique approach for Virtual AtoN implementation through a modern realization of piloting as a commonly recognized method of marine navigation defined in Bowditch (2002) as, "navigating in restricted waters with frequent determination of position relative to geographic and hydrographic features". The approach recognizes the limitations of modern satellite and radio-based navigation systems due to atmospheric phenomena, spoofing, aliasing and denial of service resulting from natural events and manmade actions and activities. This results in a "ship-centric" orientation providing the watchstander with the tools necessary to perform successful navigation using ship's own resources without overreliance upon external sources and systems such as GNSS and AIS. The described Virtual AtoN may be *static* in terms of their characteristics not changing over long periods of time, or *dynamic* as their characteristics may change in both the time and space domains in accordance with the specifications of the vessel itself by providing a capability to discern hazards to navigation based upon operating requirements in terms of draft, speed and other factors rather than using a static AtoN model. Virtual AtoN may also be *permanent*, *temporary* or *momentary* in duration reflecting the indication of a hazard to navigation detected using 3-dimenstional forward looking navigation sonar (3D-FLS) and displayed on ECDIS in real time having significant relevance to the vessel while making way.

The Virtual AtoN concept resulting from this research is enhanced beyond existing AIS virtual AtoN technology from several perspectives. First, the results reflect a truly Virtual AtoN described by International Association of Marine Aids to Navigation and Lighthouse Authorities - IALA (1081) as,

"A virtual aid to navigation (Virtual AtoN) does not physically exist but is a digital information object promulgated by an authorised service provider that can be presented on navigational systems",

where the described Virtual AtoN is computer-generated and exists entirely as a digital data object with no corresponding presence in the physical environment such as a VHF transmitter, sinkers or piles required for implementation. Virtual AtoN also include expanded functional elements beyond AIS virtual AtoN to support static and dynamic characteristics with permanent, temporary and momentary durations that are only possible using a ship-centric approach on a vessel equipped with modern environmental sensors. The result is a highly versatile Virtual AtoN capable of providing comprehensive and timely information to mariners about hazards to navigation, safe waterways, caution and avoidance areas.

Second, the Virtual AtoN digital information object contains the complete set of functional and operational characteristics in addition to a high resolution 3-dimensional topological model of the physical environment at and adjacent to the position at which the Virtual AtoN is deployed. Such enhancement to the traditional characteristics of an AtoN provides an inherent capability for self-verification that the AtoN is *on station* and *watching properly* defined as, "an aid to navigation on its assigned position exhibiting the advertised characteristics in all respects" and "the state of an aid to navigation on charted position and exhibiting its proper characteristics" (USCG, M16500.7A; Bowditch, 2002a). The act of watching properly is closely related to AtoN availability described by IALA (1035) as, "the probability that an aid to navigation or a system of aids to navigation, as designed by the Competent Authority, is performing its specified function at any randomly chosen time". This concept may also be applied to verification of both traditional, physical and AIS AtoN, and represents advancement in technology that can significantly expand and enhance the capabilities of scarce national resources presently dedicated to perform this task.

The concepts of ship-centricity, dynamic and momentary AtoN and the new capabilities they provide as advanced by this research are contrary to the present static functionalities, methods and procedures used by competent national authorities and authorized service providers in provisioning charting and AtoN services. For example, rather than having to rely on navigation charts that are blank and contain no soundings, a ship-centric approach places the tools necessary to complete a safe passage directly into the hands of the mariner. This is accomplished by using 3D-FLS data to provide soundings information and create Virtual AtoN of momentary duration representing detected hazards to navigation existing within the water column but not attached to the bottom for immediate display using existing symbology on ECDIS. Indeed, the time frames currently required to properly establish such Virtual AtoN using existing practices would nullify many of their benefits.

The approach followed for Virtual AtoN introduction includes examination and approval by responsible authorities of the methods and processes for their creation and to take best advantage of their static and dynamic characteristics. Their initial deployment should only be to areas where existing AtoN services are deficient or non-existent due to environmental and logistical challenges, such as in the Arctic where ice movement can destroy physical AtoN, and in tropical locations where the potential to damage sensitive coral reefs prevents the placement of sinkers for physical AtoN.

1.3 Hydrographic survey

The impetus for initiating research into Virtual AtoN lies in a perceived need for such services in the Arctic and other remote places where existing AtoN services are inadequate or do not exist at all. A key factor is the availability of hydrographic survey results adequate to determine where AtoN are most needed. Existing limitations in the present AtoN system and inadequate resources to perform hydrographic surveys impede expansion to geographic regions experiencing significant growth in marine traffic yet are highly remote and ecologically fragile. This is a problem worldwide, with large gaps along major international shipping routes in the Indian Ocean, South China Sea, Western Pacific and adjacent waters. This problem also exists in the Caribbean, some coastal waters of Africa, Australasia, Oceania and the Antarctic where modern surveys, metrication and datum shift to World Geodetic System 1984 (WGS84) are all urgent requirements in locations which are now frequented by cruise liners (IHO C-55).

In the United States this includes thousands of square miles in the Arctic and sub-Arctic encompassing the northern slope of Alaska, the Aleutian Islands, and tropical regions spanning the Hawaiian Islands to Midway Atoll and other US territories. Many of these areas are poorly charted, if they are charted at all. The US National Oceanographic and Atmospheric Administration (NOAA) states that the Arctic is severely deficient in many capabilities extended to the rest of the Nation and large gaps exist in the information they do have as illustrated by empty white space on navigation charts of the region (NOAA, 2011; 2013).

In areas where surveys have not been conducted to modern standards and charts are blank or contain sparse information, a ship-centric approach involves acquiring live soundings information ahead of the vessel using 3D-FLS and displaying this in real time as soundings on ECDIS and for the creation of Virtual AtoN of momentary duration. This depth information can also be stored for subsequent use by national hydrographic and AtoN authorities for chartmaking and the placement of static and dynamic Virtual AtoN in these areas in the future. Although 3D-FLS is not intended to replace multibeam sonar in performing hydrographic surveys, its use by vessels of opportunity can enhance safety of navigation and supplement national hydrographic authority survey vessel assets by providing an independent source of high-resolution 3D bottom topography data and expanding geographic coverage to new areas.

1.4 Aid to Navigation establishment

The International Maritime Organization (IMO) requires Governments to provide AtoN as the volume of traffic dictates and the degree of risk requires (SOLAS 74/78). According to the U.S. Coast Guard, a situation to be avoided unless specifically warranted by unusual circumstances is the establishment of AtoN in areas not properly charted or where they would invite the inexperienced to attempt a passage which would still be dangerous in spite of the AtoN (USCG, M16500.7A(a)). The increasing traffic in the Arctic region would in itself qualify as unusual circumstances in terms of the establishment of AtoN. Given the inadequacy of Arctic surveys and navigation charting and the increasing level of traffic in the region, the requirements of this research identified a need to accomplish adequate hydrographic surveys and the establishment of AtoN through extraordinary means. Fulfillment of this need was investigated through the examination of potential technological solutions.

1.5 Enabling technologies

An analysis of environmental sensing technologies was performed to determine which, if any, sensors were sufficiently capable, suitable and able to supplement existing sensor suites to aid mariners in safely navigating poorly surveyed and unsurveyed waters. Due to the remoteness of the Arctic the scope of this analysis was limited to vessels that are most likely to be involved in transits of the region and for which the consequences of grounding and other incidents would be most significant. This includes vessels subject to the International Convention for the Safety of Life at Sea (SOLAS) convention and the International Code for Ships Operating in Polar Waters (the Polar Code) but excludes many small vessels whose transits tend to be local using local knowledge, have minimal instrumentation and sensor suites, and generally provide low environmental risk (SOLAS 74/78a; MSC.385(94)). The basic sensor suite presently mandated by the International Maritime Organization (IMO) as carriage requirements on SOLAS vessels includes radar, AIS, ECDIS and echosounder in addition to various communication devices and GNSS. With the exception of the echosounder, all other sensors and equipment are designed for use with respect to the physical environment above the waterline. The single-beam echosounder is the sole sensor capable of providing visibility into the underwater environment, and this is only to the extent of determining water depth directly below the hull and nowhere else. The availability of a more advanced multi-beam echosounder on the bridge would not provide significant advantage over the single-beam echosounder as this would yield depth information along a swath of the bottom athwartships, and nowhere else.

The analysis concluded that the only sensor capable of assisting vessels in safely navigating poorly surveyed and unsurveyed waters by providing insight into the underwater topography ahead of the bow of a vessel making way is an echosounder with 3-dimensional forward-looking capabilities that encompasses 3D-FLS. This dissertation reports results and findings obtained from different experiments performed at diverse geographical locations using various 3D-FLS types and manufacturers' models examined during the course of this research. Its use, along with a single beam echo sounder, in verifying AtoN as watching properly and as a means to perform hydrographic survey in accordance with International Hydrographic Organization (IHO) standards and requirements is also discussed.

1.6 Frames of reference

A comprehensive treatise of Virtual AtoN research must cover a broad range of subject matter spanning multiple areas of responsibility. Five frames of reference have been considered in conducting this research and in the performance of investigations that include:

- Applications – Where the results of this research may be applied,
- Sensors – Environmental sensors needed to accomplish the research objectives,
- Engineering – Resources needed to build the systems resulting from the research,
- Regulatory – Authorities accountable for research adoption and implementation, and
- Training – Instruction on the use of the research results.

A graphic that attempts to depict the scope and nature of these subjects and the frames of reference these represent is illustrated in Figure 1.1.

Efforts have been made to interact with several different maritime communities to explore the implications of Virtual AtoN research. This includes diverse areas of application, technical authorities both in sensor development and in the engineering of AtoN systems, educators involved in the training of mariners, and regulatory authorities at the national and international levels.

Application – Geographic areas where the use of Virtual AtoN is most appropriate include those where existing AtoN systems and their infrastructure are not in place and/or cannot rapidly be put in place to support essential operations. Such areas include the Arctic where ice movement can move or destroy physical AtoN rendering them ineffective and logistical and maintenance support is hampered by the large distances involved, harsh weather conditions and lack of personnel. Virtual AtoN can also benefit tropical regions in which the placement of sinkers to moor physical AtoN or to place

HF transmitters to support AIS AtoN can harm coral reefs or other sensitive environmental features, and to provide guidance to mariners where such services would not otherwise be available. Additional locations include those ravaged by the effects of war or natural disaster where existing infrastructure has been destroyed. The ability to rapidly deploy Virtual AtoN in such locations may assist in providing logistical support for reinforcement of manpower and materiel and the provisioning of food and building materials for relief efforts.

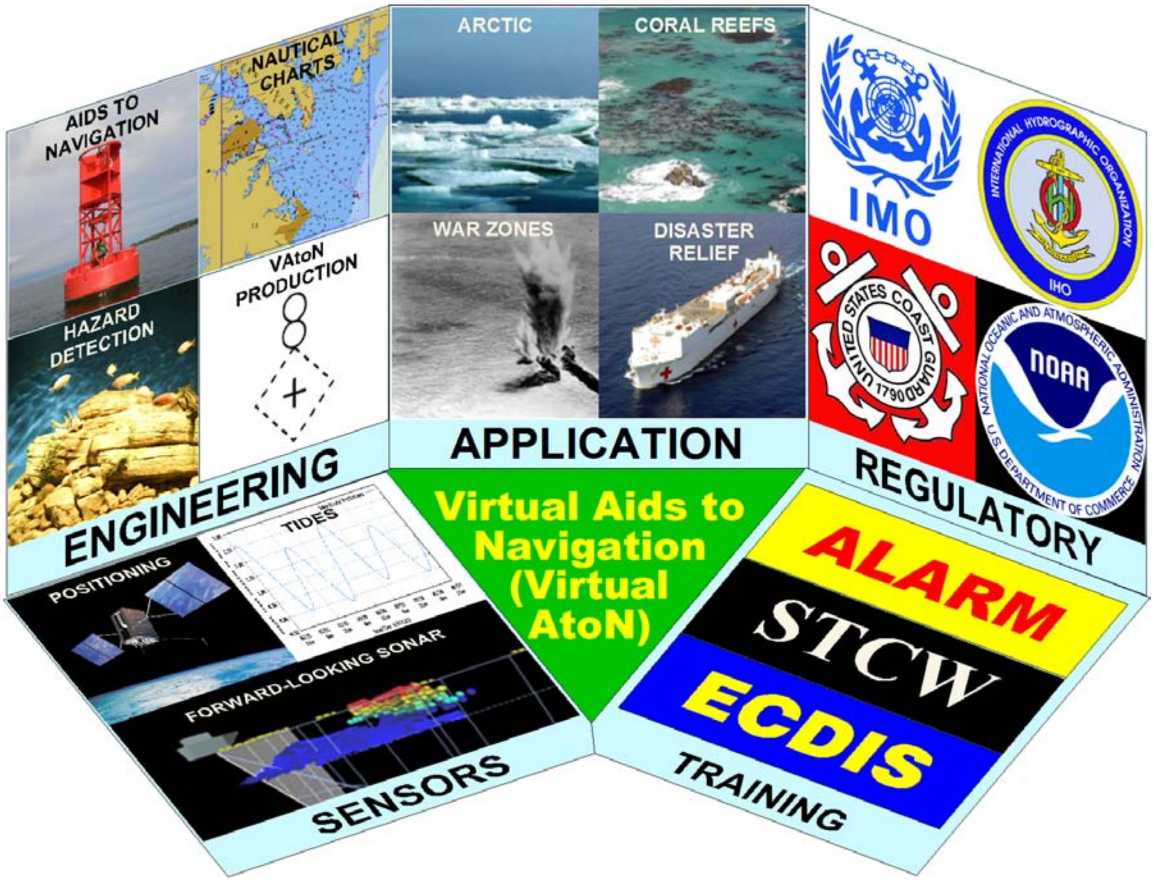


Figure 1.1: Frames of reference for Virtual AtoN research

Sensors – The transit of poorly charted waters where Virtual AtoN have been deployed requires the use of the complete sensor suite on the bridge of a vessel subject to SOLAS requirements. Additional sensor requirements in the form of 3D-FLS are needed in such areas when prior surveys are inadequate resulting in poor charting and Virtual AtoN are not present.

Engineering – Engineering efforts are accomplished in the analysis of 3D-FLS capabilities to assist in detecting hazards to navigation and to acquire information for hydrographic survey and chart making. Multi-sensor integration involving the use of Virtual AtoN combined with 3D-FLS, ECDIS, single beam echo sounder, AIS, radar, GNSS and other sensors is also considered as the basis for automating much of the data acquisition aspects of this research whereby crowd sourcing of hydrographic data and Virtual AtoN system design may be accomplished. However, this scope of this research has presently been limited to the use of 3D-FLS in combination with the single beam echo sounder for the purposes of assisting in the verification of Virtual AtoN as being in the correct position and watching properly.

Human factors and training – Human factors are examined related to the use of 3D-FLS as a means for navigating without having to impose any additional training requirements on watchstanders and other crewmembers. Further consideration of human factors is also accomplished pertaining to the use of 3D-FLS and the technical means for its display on ECDIS as well as the setting of alarms and training issues. The focus of these efforts was to integrate 3D-FLS with ECDIS rather than require the use of another display on the bridge, to adopt standard protocols for the display of electronic symbols, and in determining reaction times for watchstander intervention upon detection of hazards to navigation.

Regulatory environment – The fifth frame of reference has to do with the regulatory environment and the many governmental, inter-governmental and non-governmental organizations in charge of the various areas of responsibility identified in this research. Governmental organizations such as the Coast Guard and NOAA are responsible for implementing IMO, IHO and national guidance in the United States; each of which are represented at the IMO and IHO. At the international level the IMO is cognizant of maritime affairs and the IHO is cognizant for issues pertaining to hydrographic survey and chart making. Non-governmental organizations (NGOs) include many professional and technical organizations such as International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), the Nautical Institute (NI), the Cruise

Line Industry Association (CLIA), and many others that provide industry, cause-specific and other representation at the IMO and IHO.

1.7 Objectives and research questions

The hypothesis investigated by this research is that environmental sensor data can be acquired, managed, adopted and applied to provide real time guidance for vessels to safely transit uncharted waters and/or waters lacking physical aids to navigation. The overall goal is to determine the potential for and to design and evaluate ship-centric Virtual AtoN capable of rapid deployment and adapting to dynamic environmental and situational conditions enabling safe ship's navigation without benefit of physical AtoN in remote and underdeveloped locations, war zones and disaster areas.

The specific objectives of the research are as follows:

1. Facilitating safe vessel transits of uncharted and poorly surveyed waters, as well as waters lacking physical aids to navigation;
2. Creating infrastructure to support navigation system dynamic sensor fusion and integration with vector chart data to enhance watchstander situational awareness;
3. Compatibility with existing and evolving standards and practices for AtoN, AIS, ECDIS, other eNavigation methods and technologies; and satellite services for GNSS positioning and data communications;

To achieve these objectives, the following questions have guided this research:

1. What sources of environmental sensor data can be used to maintain a lookout below the waterline, and are these data of sufficient resolution to safely use in vessel navigation? Additional aspects of this same question include:
   - How may these environmental sensor data be acquired, and with what area of coverage? Also, are the measurements repeatable and able to provide the same data at different times and conditions?
   - Are bottom, submerged and/or floating hazards to navigation (HtoN) detectable, to what degree and accuracy, and under what conditions?
   - How may hazards to navigation be represented to watchstanders as Virtual AtoN in a manner that is intuitive, understandable and correct?

2. Can data necessary to create static and dynamic Virtual AtoN be communicated to responsible AtoN authorities with sufficient resolution to meet evolving AtoN implementation goals and practices?
3. Can 3D-FLS survey data be communicated to national hydrographic authorities with sufficient resolution to meet charting standards?

1.8 Appended papers

In addition to the main body of text, this dissertation is based upon the research results reported and described within the following papers:

Paper 1 – Wright, R.G. and Baldauf, M. (2016) 'Virtual Electronic Aids to Navigation for Remote and Ecologically Sensitive Regions', *Journal of Navigation*, 1–17. DOI: 10.1017/S0373463316000527.

This paper describes the results of research that determines whether Virtual AtoN existing entirely as digital information objects can overcome the practical limitations of physical AtoN and AIS virtual AtoN. Also described are possible methods of deployment based upon similar concepts already in use.

Paper 2 – Wright R.G. and Baldauf M. (2016) Correlation of Virtual Aids to Navigation to the Physical Environment. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, Vol. 10, No. 2, 287-299. DOI: 10.12716/1001.10.02.11

This paper describes the results of research in the ability of Virtual AtoN to fulfill traditional navigation aid functions by considering attributes of the physical environment to help ensure their proper location and to verify the display of correct characteristics.

Paper 3 – Wright R.G. and Baldauf M. (2016). Hydrographic Survey in Remote Regions: Using Vessels of Opportunity Equipped with 3-dimensional Forward-Looking Sonar. *Journal of Marine Geodesy*. Vol. 39, No. 6, 439-357. DOI 10.1080/01490419.2016.1245266

This paper describes research efforts to exploit the capabilities of commercial-off-the-shelf 3D-FLS installed on expeditionary and other vessels of opportunity for hydrographic survey and detecting bottom features to navigate by georeferencing. Also cited are capabilities to provide high-resolution full bottom survey data to supplement the assets of responsible hydrographic survey authorities in exploring and charting these regions.

Paper 4 – Wright R.G. and Baldauf, M. (2016) Arctic Environmental Preservation through Grounding Avoidance, L.P. Hildebrand & L.W. Brigham, editors. Springer International Publishing, AG, Cham. London. *Submitted, undergoing peer review.*

This paper describes the Arctic in terms of transit routes, the challenges of Arctic navigation and increases in vessel groundings that have occurred and may potentially occur as traffic in the region increases. The use of Virtual AtoN and 3D-FLS as means for developing strategies to avoid groundings and preserving the Arctic environment is considered.

Paper 5 – Wright R.G. and Baldauf M. (2014) 'Enhanced Situational Awareness through Muli-Sensor Integration', in *Proc. 18th International Navigation Simulator Lecturers' Conference (INSLC 18)*, Buzzards Bay, Massachusetts USA, 40-59. ISBN 978-0-692-29012-5.

This paper examines the capabilities of 3D-FLS to detect hazards to navigation at cruising speed through an in-depth analysis of the Costa Concordia tragedy. Insight into bridge alerts and alarms that may have been generated had 3D-FLS been installed, operational and observed just prior to the grounding are also provided.

1.9 Other related papers and publications

Additional presentations, papers and publications resulting from this research useful to supplement the five primary papers cited in this dissertation are listed as follows:

- Wright R.G., Baldauf M. "Physical Aspects of Virtual Aids to Navigation", Activities in Navigation – Marine Navigation and Safety of Sea Transportation; ed. Adam Weintrit, 61-68, 2015, CRC Press, London.

- Wright R.G., Zimmerman C. “Vector Data Extraction from Forward-Looking Sonar Imagery for Hydrographic Survey and Hazard to Navigation Detection”, Proc. of *IEEE/MTS Oceans Conference*, Washington D.C., 19-22 October 2015.
- Wright R.G., Baldauf, M. “A Georeferencing Approach to Real-Time Virtual Aid to Navigation Verification”, in Proc. *ION GNSS+ Conference 2015*, Institute of Navigation, Tampa, FL, 14-18 Sep. 2015.
- Wright R.G., Baldauf M. “Improving the Safety of Polar Navigation – Contribution of New Technology and Training”, presented at *6th Arctic Shipping Summit*, Montreal, Canada, 18-19 March 2015.
- Wright R.G.; Baldauf M.: “Collaborative Navigation through the Establishment and Distribution of Electronic Aids to Navigation in Real Time”, in Proc. *Joint Navigation Conference*, Institute of Navigation, 16-19 June 2014, Orlando, FL.
- Mehdi, 2016: Mehdi Raza Ali, Wright R. Glenn and Baldauf Michael. “3-dimensional Forward-looking Sonar: Offshore Wind Farm Applications”, 2016 European Navigation Conference, Helsinki, Finland.
- Patent Application: Number 62218306, “Method of Virtual Aid to Navigation Verification using Georeferencing”, US Patent and Trademark Office. Filing Date: 14 September 2015. Named Inventor: R. Glenn Wright.
- Patent Application: Number 62378691, “Virtual Dynamic Aids to Navigation”, US Patent and Trademark Office. Filing Date: 24 August 2016. Named Inventor: R. Glenn Wright.

1.10 Limitations

This dissertation presents a new approach towards the design, development and implementation of Virtual AtoN systems that can complement and work in conjunction with existing AtoN. The theories and concepts described do not presently conform to nor are in accordance with existing practices of national and international AtoN or hydrographic authorities. Analysis of the integration of the processes and products involved in Virtual AtoN creation with responsible authorities is beyond the scope of this research and must be investigated further with their cooperation.

Discussion is provided on the use of 3D-FLS to perform hydrographic survey of the sea bed ahead of the vessel's path of transit as well as to analyze the features and characteristics of the water column itself to detect potential hazards to navigation. It should be noted that 3D-FLS is presently not mandated for use by the IMO or any national authority under equipment carriage requirements for vessels, nor is its use presently sanctioned for hydrographic survey by the IHO or any national authority.

1.11 Structure of the dissertation

Chapter 1 provides an introduction to the domain of this research. The aims and objectives of the research are described in Chapter 2, followed by a discussion of the theoretical underpinnings of the approach in Chapter 3. Five areas of study examined as part of this research effort are discussed in Chapter 4. In Chapter 5 the materials and methods used in this research are described. Chapter 6 presents the results of this research, followed by a discussion of these results in Chapter 7. In Chapter 8 findings and conclusions are provided.

1.12 Discussion of aid to navigation terminology

During the course of this research it came to light that there are several different terms with similar meanings, and different meanings for similar terms pertaining to aids to navigation. The use of proper terminology in a new discipline requires a learning curve as these concepts mature. The papers appended to this dissertation provide such an example as the terminology has changed in these writings over the several year course of this research. In an attempt to clarify the present use and meaning of terminology within the context of new capabilities identified herein, a summary of the following words, terms and working definitions are offered here for the basis of discussion:

- <u>Aid to Navigation (AtoN)</u> – Any device or system, external to a vessel, which is provided to help a mariner determine position and course, to warn of dangers or of obstructions, or to give advice about the location of a best or preferred route (IALA NAVGUIDE, 2014).

- Physical Aid to Navigation (Physical AtoN) – Reference to visual and other physical (real) aids to navigation in contrast to electronic AIS AtoN (IALA NAVGUIDE, 2014a).
- AIS Aid to Navigation (AIS AtoN) – AIS AtoN that emanate VHF radio transmissions and can vary from the presence of an actual transmitter on a physical AtoN, to the transmission of a 'synthetic' or 'virtual' AtoN as a Message 21 from an AIS base station to a location within the radio transmission range of the AIS base station (IALA 1062).
- Virtual Aid to Navigation (Virtual AtoN) – A Virtual AtoN does not physically exist but is a digital information object promulgated by an authorized service provider that can be presented on navigational systems (IALA 1081). In terms of letter capitalization, the word "Virtual" when associated with "AtoN" is capitalized in IALA 1081. This convention has been adopted throughout this dissertation. However, several variations of this practice may be spotted in the appended papers as usage appears to have changed over time. Two types of Virtual AtoN exist in terms of behavioral characteristics:
    - ***Static***: Characteristics do not change over long periods of time, such as when emulating a physical AtoN.
    - ***Dynamic***: Characteristics may change in both the time and spatial domains in accordance with the specifications of the vessel itself by providing a capability to discern hazards to navigation based upon operating requirements in terms of draft, speed and other factors.

  Both Static and Dynamic Virtual AtoN may be implemented with time durations that are permanent, temporary or momentary in nature.

Other commonly used terms found in discussion on this subject contain variations of the terms described above. These include:

- Electronic Aid to Navigation (eAtoN or e-AtoN) – Reference to AIS AtoN emphasizing their electronic nature in contrast to physical AtoN (USCG 11D, 2014; Lewald, 2015).

- Real AIS Aid to Navigation (Real AIS AtoN) – A ‘real’ AIS AtoN is transmitted as a Message 21 from an AIS Base Station that is physically located on the AtoN (IALA 1062a).
- Synthetic AIS Aid to Navigation (Synthetic AIS AtoN) – A ‘synthetic’ AIS AtoN is transmitted to the location of a physical AtoN as a Message 21 from an AIS Base Station situated in the vicinity of the physical AtoN (IALA 1062b).
- Virtual AIS Aid to Navigation (Virtual AIS AtoN) – A ‘virtual’ AIS AtoN is transmitted as a message 21 for an AtoN that does not physically exist. (IALA 1062c). In terms of punctuation the use of the word “virtual” when associated with “virtual AIS AtoN” is used as an adjective in IALA 1062 to denote its description of a type of AIS AtoN and is therefore not capitalized.

Chapter 2 Aims and Objectives

Aids to Navigation (AtoN) comprise a portion of the set of tools needed to safely plan and execute a voyage from berth to berth. Another such tool is the navigation chart used by mariners to identify the depths needed to formulate a route providing sufficient under keel clearance to allow for safe passage. The navigation chart also shows the positions of AtoN that include buoys, daymarks, lights and ranges used to identify channels and routes of safe passage as well as known hazards to navigation in the area of intended transit. Although they are indispensable to mariners in helping to identify safe routes of passage, navigation charts merely provide a static representation of the results of hydrographic surveys that may have occurred years, decades or even centuries ago. Their depiction of AtoN portrays the locations of where they are supposed to be if they are on station and watching properly, and have not sunk or drifted away. Notices to mariners are issued by the appropriate authorities to update navigation charts with interim changes until the next formal release of an updated chart. However, there is no guarantee that these notices are sufficiently comprehensive or up to date to assure safe passage.

The records abound with incidents where navigation charts and notices to mariners were inadequate or not observed. For example, in 2010 the cruise chip *Clipper Adventurer* grounded in the Northwest Passage on a shoal discovered in 2007, published in Canadian Notices to Shipping but not officially charted until June 2012 (TSB, 2010). The February 2010 grounding on rocks of the sternwheel cruise boat *Willamete Queen* in Oregon was, as explained by the Captain, due to missing buoys that mark the hazard. These buoys were marked as seasonal on NOAA chart 18528 and were scheduled to be installed and watching the location between May and October (USCG vs Chesbrough, 2012).

These are just two incidents that spotlight examples of master and bridge crew errors under circumstances that were well known and published in official notices and records. Many other current examples also exist: *Exxon Valdez, Shen Neng 1*, *Fedra*, *Sea Diamond*, *Costa Concordia*, *USS Guardian*... In each of these cases the vessel did the airplane equivalent of flying into a mountain. Although charting errors may be cited as a contributing factor in some of these incidents, watchstanders on the bridge of vessels generally have had no primary or direct means to gain insight into the underwater environment other than an echo sounder showing the depth immediately below the keel.

The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), International Regulations for Preventing Collisions at Sea (COLREGS), common law and statutory authority of individual nations require ship owners and mariners to operate in a manner that is diligent by maintaining a proper lookout to conduct safe transit and avoid collision and grounding. This has traditionally been interpreted as being what watchkeepers can directly observe with their own eyes as well as using electronic aids such as RADAR and AIS. Other than through the use of navigation charts (a secondary measure) and an echo sounder (a direct measure) showing depth of the water under the keel, there is not and has not ever been an effective means to maintain a lookout below the waterline other than a watchstander examining the area ahead of the bow with a pair of binoculars looking for changes in water color, different wave patterns or other effects to indicate hazards or obstructions might lie ahead in the immediate path of the vessel. Until now, there has been no promise of technology that could assist in accomplishing this task.

2.1 Safe transit of waters lacking physical aids to navigation

The frontiers of the world are those areas that border the furthest extent of settled or inhabited areas beyond which lies wilderness and the unexplored (Oxford, 2016). This definition applies to the Polar Regions where extreme environmental conditions prevail and ship transits are relatively few. Although this definition is historically accurate, world events are fostering ventures into these areas for a variety of reasons that include exploration for energy and minerals, shortened trade routes, the expansion of national territorial claims and increasing military presence, and even tourism. The Arctic in particular is the focus of much of this activity, where figure 2.1 illustrates the primary routes of transit through this region.

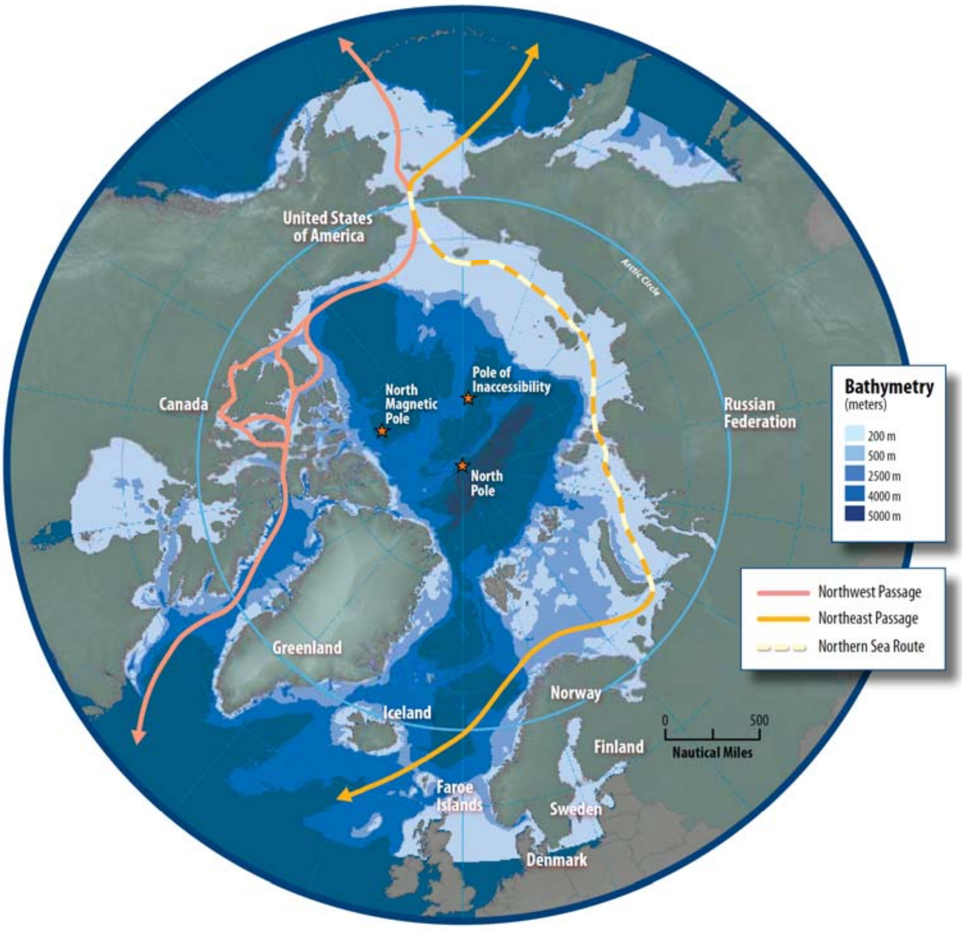


Figure 2.1: Arctic shipping routes (Source: AMSA, 2009)

These routes may be considered coastal and archipelago waters that are relatively shallow and teaming with surface and underwater hazards to navigation. Such routes require the use of piloting methods and procedures to safely prepare for and complete a voyage. In doing so it is vital to be able to obtain and evaluate soundings, identify and use AtoN effectively and to fix a vessel's position throughout the voyage. However, such capabilities are extremely limited in the Arctic.

2.1.1 Issues with Arctic navigation

Arctic waters are for the most part unsurveyed, and many of the existing surveys were completed decades or even centuries ago using antiquated methods. Hydrographic authorities in Russia, Canada and the United States have recently stepped up their efforts using modern techniques with state of the art sensors, but the areas that need to be surveyed are vast and the resources to accomplish them are relatively few. A recent initiative, the IHO Crowd-Sourced Bathymetry Working Group (CSBWG) whose purpose is to acquire useful hydrographic information through unconventional sources, represents an important step towards filling this gap (CSBWG, 2015). In the meantime many navigation charts in the Arctic contain unacceptably large areas without soundings by which mariners are expected to identify routes of safe passage. Many of these charts were created using different geodetic datums, complicating the situation.

Another problem in the Arctic is the lack of short range AtoN by which vessel traffic is guided through channels where masters may generally be confident of safe passage, along preferred routes that minimize distances and transit times as well as avoid ecologically sensitive and wildlife protection areas, and which mark hazards to navigation that must be avoided. AtoN take the form of beacons that are permanently fixed to the earth's surface using piles and other structures, and buoys that require mooring to the sea bed by concrete sinkers and other devices. However, ice movement in the Arctic can destroy beacons and hole and sink buoys or move them to positions where they are no longer useful. Incorrectly positioned AtoN may lure unwary seafarers to grounding and lose their ships to casualty with potentially great cost in human life and loss of cargoes, in addition to detrimental effects to the fragile Arctic environment through fuel and chemical spillage and pollution. Also, since AtoN are scarce or non-existent in the Arctic, the information they provide regarding routes and safe areas for transit are also not available on navigation charts for voyage planning.

Further complicating matters is that precise positioning and timing capabilities provided by GNSS at high Arctic latitudes are less accurate and reliable as a result of the satellite constellations that provide the radio signals used by GNSS receivers being low to the horizon. Additional factors affecting AIS and GNSS performance include the susceptibility of signals to propagation delays and resulting inaccuracy due to aurora activity and the atmospheric effects of the ionosphere and troposphere on radio waves.

To sum it up, ship navigation in the Arctic is challenging due to the widespread lack of knowledge of water depths in the region, charts that are inadequate or blank and with inaccurate equipment to ascertain position. This situation has changed little since the early days of Arctic exploration.

2.1.2 Overcoming Arctic navigation issues

The approach taken in this research acknowledges the limitations of hydrography and buoyage, and the relationships between these two disciplines. Simply put, the placement of beacons and buoys cannot be accomplished in areas that are poorly surveyed or not surveyed at all since the knowledge of where they should be placed is absent. Thus a twofold approach to this research was undertaken. The first challenge was to determine how to safely navigate without knowledge of the bottom topography. The second challenge was to provide a means to place short range AtoN in an area that is hostile to their existence.

This research attempts to exploit modern sensor technology as a tool to increase watchstander awareness of the underwater environment in the vicinity of the vessel, and especially forward of the vessel in the direction of transit. Such increased awareness must be provided at a distance sufficient to promote the effective avoidance of grounding and hazards to navigation, or at least to significantly lessen the effects of allision with such hazards. This is attempted through the use of 3D-FLS that can provide high-resolution imagery forward of the bow out to 1,000 meters at speeds of up to 20 knots or more. Using this technology it appears possible to navigate in such an area in relative safety. The potential of 3D-FLS to perform this function was explored by examining its accuracy in creating a 3-dimensional bathymetric model of the sea bed and in using this information as a means to verify vessel positioning. With detailed, high-resolution knowledge of the sea bed obtained either through conventional hydrographic survey using multibeam sonar or 3D-FLS, sufficient knowledge of the area would be available to place AtoN.

The second challenge was to overcome the physical barriers to the placement of AtoN in the Arctic in a manner that would be useful and intuitive to mariners, supportable within the existing AtoN design lifecycle, and maintainable by responsible AtoN authorities. The concept of Virtual AtoN seemed fully amenable to solving this problem, excepting that the traditional methods of verifying that AtoN are in their proper position and watching properly cannot apply as there is no physical device for which to verify position. Certainly one could match the position of an icon on an Electronic Navigation Chart (ENC) or ECDIS display with the proper position where a Virtual AtoN is supposed to be deployed. However, visibility may be limited precluding the taking of a fix using physical objects or landmarks or GNSS inaccuracies as a result of high latitude or atmospheric effects or a variety of manmade interference due to spoofing, aliasing or a denial of service attack may render any means of electronic positioning subject to significant error, with potentially disastrous results. Thus, the ability to verify Virtual AtoN as being on station and watching properly became a significant aspect of this research.

2.2 Infrastructure creation to support general navigation

The problem of harsh weather and environmental factors destroying and disabling AtoN may be solved with the advent of truly Virtual AtoN that require no physical presence whatsoever in the area of their deployment and are verifiable. Such an approach can dramatically enhance the ability to extend AtoN systems into the Arctic. This may be accomplished in part through an automated approach towards verification of position and watching properly in best waters that can be performed on a continuous basis by suitably equipped vessels of opportunity while passing Virtual AtoN as part of their normal operation without requiring any assistance or action by crewmembers.

The capability to extend nations' navigational infrastructure in terms of short range AtoN for shipping to the furthest and most remote and inhospitable regions is the ultimate goal of these objectives. However, this does not necessarily imply that this should occur with rapidity. Suitable projects for the development of prototype systems must first be established to integrate Virtual AtoN production and deployment into existing methods and procedures used for AtoN systems in general. Further research must still be performed to explore the potential limits in the verification of Virtual AtoN, and how this concept may be extended to physical and AIS AtoN in general, with the potential to produce significant cost savings over present methods.

Finally, no thoughts are entertained towards replacing existing physical or AIS AtoN with Virtual AtoN. Existing AtoN systems are fully capable and excellent at performing their required functions and these must remain the preferred methods of buoyage in all areas where their use is not limited by environmental or logistical factors. At present, Virtual AtoN should only be considered for use in the Arctic and remote areas that feature sensitive coral reefs where sinker placement for attaching buoys to the bottom is limited.

2.3 Compatibility with existing and evolving standards and practices

Early discussions with industry representatives at eNavigation and other conferences and venues produced clear-cut preferences that the use of 3D-FLS and Virtual AtoN should not create any additional workload upon watchstanders on the bridge. The maritime industry has and continues to undergo significant change in terms of crewmember qualifications and training in accordance with STCW, and companies are struggling with keeping in compliance with existing training mandates and requirements. Indeed, widespread assurance was given (rightly so) that any thoughts of imposing additional training requirements based upon the introduction of new technologies would be met with stiff resistance by the maritime community.

Based upon these observations, every opportunity has been taken to introduce new equipment, concepts and methods for use on vessels within the confines of existing requirements and regulations. For example, the display of 3D-FLS information to watchstanders should be accomplished using ECDIS, without imposing any new requirements for additional monitors on the bridge. All of the symbols, with few exceptions, expressed for Virtual AtoN have been prepared in accordance with the requirements for existing ECDIS symbols, with minor variation to depict their virtual nature. The only exceptions are where entirely new capabilities are identified for Virtual AtoN that are not available using physical or AIS AtoN. In terms of hydrography, the data obtained from 3D-FLS residing on vessels of opportunity should be readily compatible with the IHO S-100 and S-102 hydrography standards.

Chapter 3 Theoretical Underpinnings

Virtual AtoN as envisaged in this research are used to enhance the situational awareness of watchstanders on the bridge as to hazards to navigation that exist at and below the waterline, including hazards detected in real time and ahead of the vessel. The availability of such knowledge, especially in poorly surveyed and charted regions such as the Arctic, can facilitate better decision making in ship operation while making way. The goal is to ultimately result in enhanced safety of navigation through a reduction in unintended groundings and allision with hazards to navigation.

The theoretical underpinnings of this research encompass:

- Virtual AtoN contribution to knowledge of the state of the environment,
- 3D-FLS efficacy for hydrographic survey,
- Single beam echo sounder efficacy for validation of Virtual AtoN operation, and
- Assessment of risk based upon the availability of sensors and Virtual AtoN.

This chapter discusses the concepts in the overall approach taken to guide the methodology and examine the results achieved in this research. The focus is on the use of Virtual AtoN and how they contribute to determining the state of the environment in establishing situational awareness to watchstanders on the bridge. Also discussed are the measurements and contributing factors towards measurement error in analyzing the experimental results achieved in determining the efficacy of 3D-FLS as a means to independently source hydrographic survey data, and single beam echo sounders in a georeferencing approach to Virtual AtoN verification. Advantages gained through the use of 3D-FLS and Virtual AtoN from the point of view of risk management and decision theory applied to voyages in areas lacking proper survey and AtoN are also discussed.

3.1 Ship-centric approach

The application of these theories is accomplished through the establishment of a ship-centric approach to enhancing watchstander situational awareness below the waterline when the use of traditional methods of voyage planning and following is not possible.

This is especially appropriate for vessels transiting littoral regions in the Arctic and elsewhere that are not adequately surveyed and nautical charts are blank or otherwise inadequate. This lack of situational awareness in modern times has not been an issue of great significance as shipping routes are generally well surveyed and mariners have the benefit of centuries of previous experience and observations to aid them. However, the recent increase of transits of poorly surveyed areas by vastly larger ships where the consequences of groundings and accidents in terms of loss of life, vessels and cargos along with catastrophic environmental damage attaches much greater significance to this issue.

An approach is taken whereby Virtual AtoN are placed along routes to guide vessels in transit and warn of hazards to navigation where AtoN would not otherwise be available. In areas that feature recent hydrographic surveys and where hazards to navigation are known, static and dynamic Virtual AtoN may be incorporated by responsible authority directly into ENC and displayed to watchstanders on the bridge using ECDIS. Where hydrographic surveys are lacking or not performed to modern standards ENC may include inaccurate or missing soundings and hazard to navigation information, or this information may be entirely absent from the ENC. In such areas 3D-FLS can provide live soundings information and detect hazards in real time to compensate for ENC lacking this data so essential to safe navigation. Also, 3D-FLS can assist in detecting and identifying uncharted hazards that may have occurred since the last survey as well as hazards present in the water column. The creation of Virtual AtoN with momentary duration to represent such hazards may then be accomplished for display to watchstanders using ECDIS.

3.2 Situational awareness

Situational awareness is broadly defined as, “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future” (Endsley & Rodgers, 1998). In the context of maritime operations the U.S. Coast Guard defines this as simply “knowing what’s going on around you” (USCG TCT). The Endsley model of situational awareness is illustrated in figure 3.1.

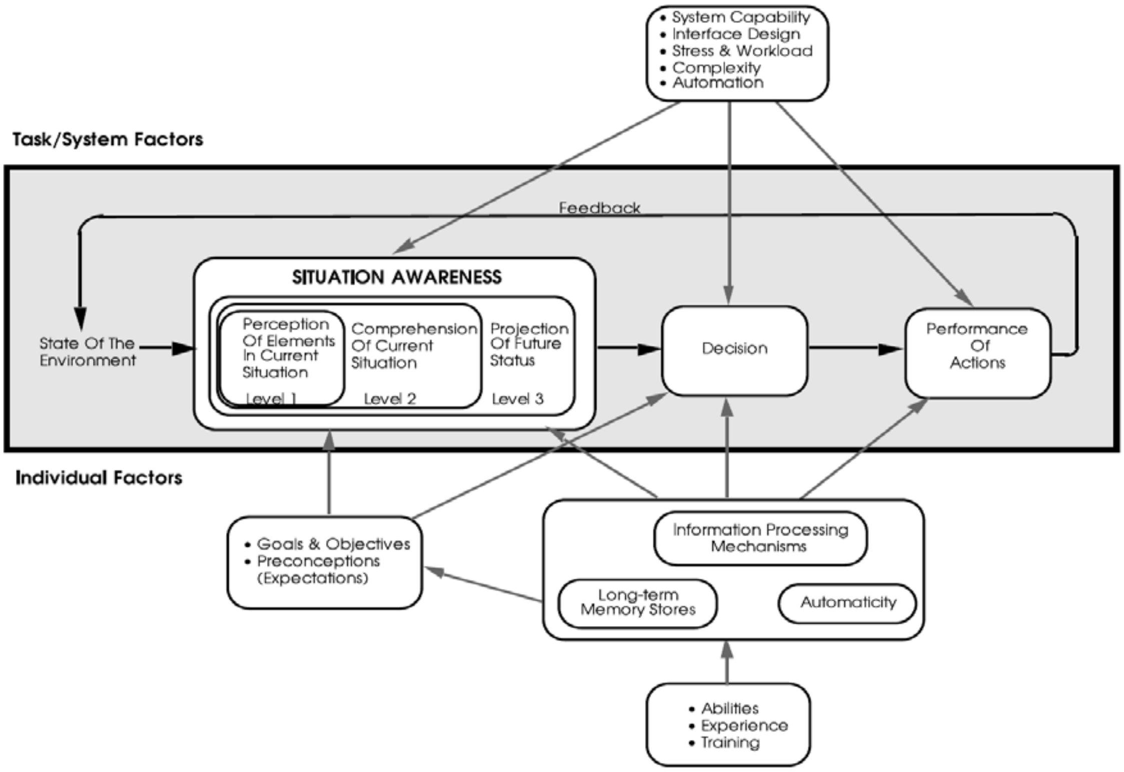


Figure 3.1: Situational awareness in dynamic decision making (from Endsley, 1995)

Ship-centricity, as used in conducting this research, involves enabling mariners to envision their environment using ship's own sensors to gain and maintain situational awareness in conjunction with or in the absence of resources that are normally available for this purpose. This capability is essential to safe navigation when no other direct or indirect method is available on which to base command decisions. Using the Endsley Model, the perception of environmental factors (state of the environment) is made possible through the use of 3D-FLS to acquire information regarding bottom topography ahead of the vessel. Comprehension of the current environmental situation is then achieved through the presentation of 3D-FLS data in the form of soundings and Virtual AtoN on ECDIS using standard symbology, the meanings of which mariners are already trained (ECDIS, 2012). Based upon this comprehension of the situation, a watchstander may then project future events and initiate action appropriate to the level of threat, such as altering speed and/or course to avoid grounding or allision.

The three issues considered primary in the Endsley definition of situational awareness in terms of assessing the state of the environment include:

- Perception of the elements comprising the current situation (Level 1),
- Comprehension of the current situation (Level 2), and
- Projection of future status (Level 3).

The factors pertaining to hydrographic survey and Virtual AtoN at each of these levels are described in the paragraphs that follow.

3.2.1 Level 1 – Perception

A mariner's inherent perception of the state of the environment is limited to their own senses and their capabilities to process the various sensory inputs they receive in a timely and accurate manner to derive cues as to their meaning, with their visual sense being of the greatest significance for ship navigation in preventing accidents. The avoidance of unintentional grounding and allision is accomplished beginning with voyage planning by visually examining the elements of the domain using applicable navigation charts to gain an accurate understanding of the minimum depths of the water along a planned route and to identify and note prominent landmarks, AtoN and any hazards or obstructions that may be encountered. This process continues by monitoring the voyage as it progresses using these same charts along with analyzing live sensor data during the voyage. Also examined are the light lists to ascertain detailed AtoN descriptions and notices to mariners to identify updates and changes to navigation charts and/or light lists that may apply to the voyage. The relationships between voyage planning and monitoring and the use of resources in determining the state of the environment are illustrated in Table 1.

Resources also used but not listed include tide tables and monitoring station data that predict and provide real time height of water information, meteorological and oceanographic forecasts and sensors to determine currents, wind speeds and related information. Given this reliance on navigational publications and forecast information used to determine the state of the environment during voyage planning, it is vital to ensure such routes are adequately surveyed and AtoN systems are in place and maintained in accordance with modern standards for soundings and AtoN information to be included within these publications.

Table 1: Use of resources in determining the state of the environment

		Voyage Planning			Voyage Monitoring					
		Publications			Sensors			Displays		
	Resources / State of the Environment	Navigation Chart / ENC	Light List	Notice to Mariners	3D-FLS	echo sounder	Radar	ECDIS	echo sounder	Radar
Features	Soundings	X		X	X	X		X	X	
	Landmarks	X	X	X			X	X		X
	Hazards to Navigation	X	X	X	X			X		
AtoN	Buoys and Beacons	X	X	X			X	X		X
	AIS radio AtoN	X	X	X				X		
	Virtual	X[1]			X[2]			X		

Notes: 1. Static and Dynamic Virtual AtoN.
2. Virtual AtoN with momentary duration.

In areas where hydrographic survey has been performed to modern standards, soundings information is used by responsible authorities to identify the types of AtoN required and the positions at which they should be situated. Figure 3.2 identifies the two types of existing AtoN as being physical and AIS, and a third type encompassing the proposed Virtual AtoN that is the focus of this research. Also identified are their functions, behavior characteristics, how they are manifest within the maritime domain, how they are observed by the mariner, and the time of their duration in practical use.

Assuming an Arctic environment or tropical location featuring coral reefs where physical or AIS AtoN placement and maintenance is difficult, static and dynamic Virtual AtoN may be used in their stead. The same process currently used for physical and AIS AtoN is appropriate for establishing Virtual AtoN, resulting in their inclusion within navigation charts/ENC and light lists with updates between revisions included in notices to mariners (USCG M16500.7A (a)). This includes the review of criteria having to do with initial justification, system benefit analysis and system type selection. Virtual AtoN may be displayed on ECDIS using symbology appropriate to function in the same manner as for physical and AIS AtoN.

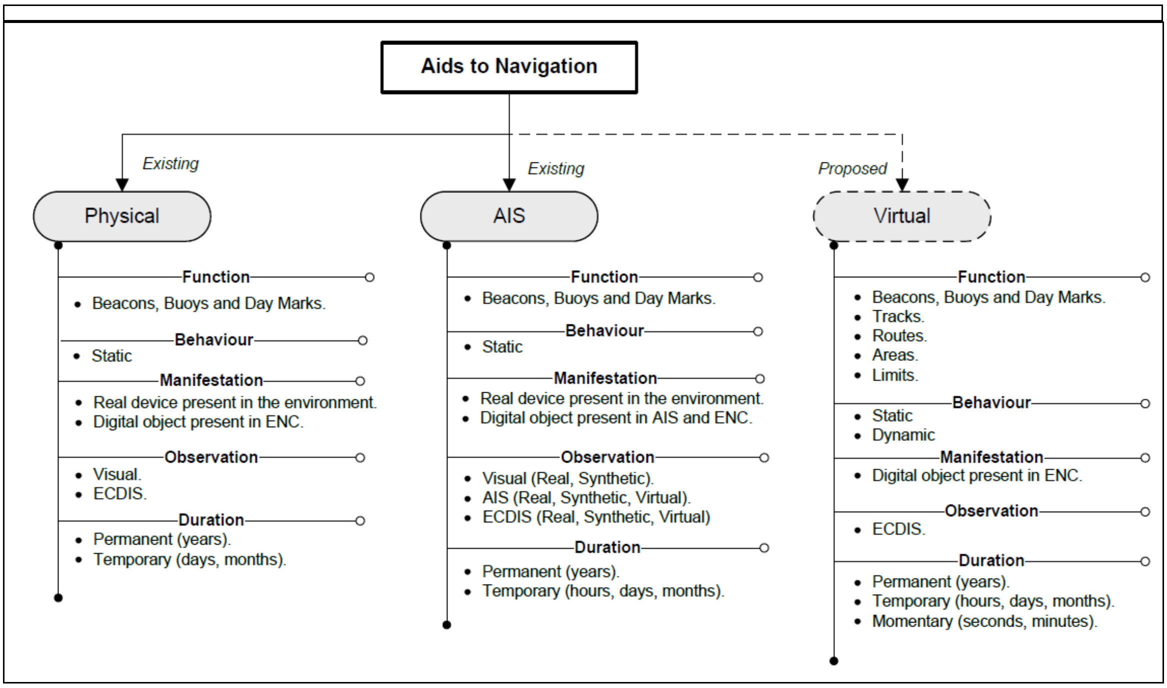


Figure 3.2: Aids to navigation systems

However, in the Arctic it has already been established that this is indeed not the case; and that great portions of the Arctic are not surveyed at all or have been surveyed using obsolete methods and AtoN are few or non-existent. Tide information, accurate forecasts and live environmental sensors are also deficient. Absent adequate information to conduct voyage planning, it is therefore necessary to acquire the needed information regarding bottom topography and hazards to navigation that exist in real time during the voyage itself.

3.2.1.1 Static Virtual AtoN – Virtual AtoN may be implemented featuring characteristics that are static in nature and do not change over time instead of physical AtoN, and may be used in the same manner during voyage planning. This capability can emulate physical AtoN such as marks providing lateral guidance, notice of hazards and obstructions, warnings and information. Their characteristics can change, for example, as a result of responsible authority review determining that repositioning is appropriate to ensure the AtoN is positioned in best waters, replacement by another

AtoN with more appropriate characteristics, or is discontinued entirely due to no longer being needed.

3.2.1.2 Dynamic Virtual AtoN – Virtual AtoN may be implemented featuring characteristics that are dynamic in nature and may change in either or both the time and/or spatial domains as a result of environmental features and/or to accommodate properties unique to a specific vessel such as draft and speed. For example, changes in the time domain may include seasonal adjustments in Virtual AtoN presence due to the establishment of marine animal sanctuaries, fishing and no-fishing zones; and daily or hourly adjustments due to regulatory requirements or special events. Changes in the spatial domain may include modifications to Virtual AtoN position to accommodate the needs of specific vessels, potentially eliminating the need for coaxial waterways with separate markings for deep draft and shallow draft vessels. This may also include the use of dynamic Virtual AtoN for individual vessels and for private aids to navigation that fulfill specific government, military, organizational and/or industrial requirements. Dynamic Virtual AtoN established in an area of planned transit can help to determine optimal routes or facilitate operations based upon changing voyage dynamics such as draft requirements considering different loads during the voyage planning stage.

3.2.2 Level 2 – Comprehension

The comprehension of a mariner regarding their current situation begins with their perception or mental model of the elements of the domain created during voyage planning and continues with the monitoring of events as the voyage progresses. These elements represent large amounts of data that must be combined and interpreted to derive their meaning. The symbols and conventions for presenting the information contained within the various resources used in gaining their perception of the current situation are placed into operational context as a result of their use and display within navigation charts, ECDIS and by sensors providing data in real time. Figure 3.3 illustrates these various sensors available to the watchstander to supplement voyage planning information on SOLAS vessels, plus communications equipment from which other navigationally significant information including forecasts and reports from vessels traveling nearby routes may be available.

Watchstander comprehension of the meaning of these inputs with respect to the current situation involves comparing their perception of expected conditions against apparent conditions through the application of their knowledge within the context of real time events.

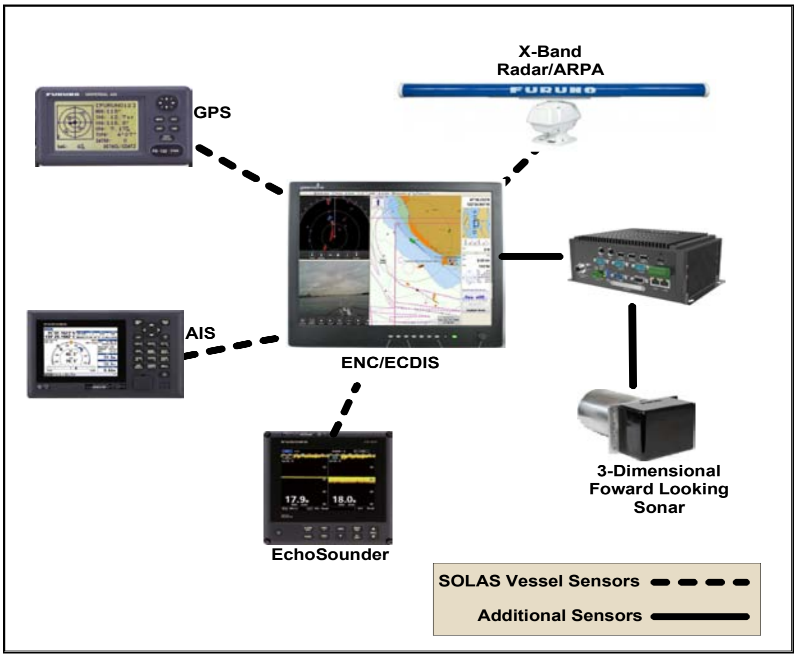


Figure 3.3: SOLAS vessel sensor compliment

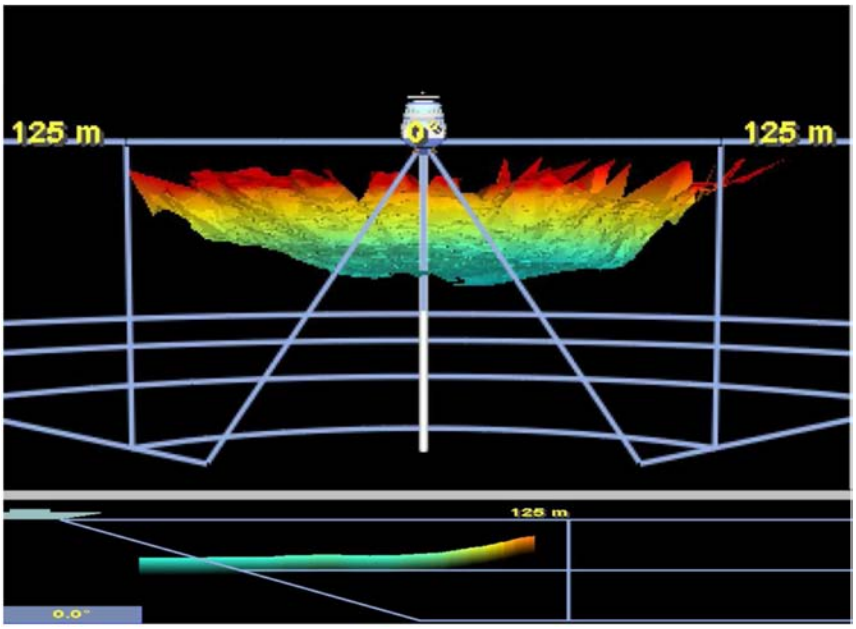
3.2.2.1 Permanent Virtual AtoN – Virtual AtoN with permanent duration in terms of years would be created using the traditional AtoN provisioning process used for physical AtoN whereby traditional multibeam or 3D-FLS survey data obtained from national hydrographic authorities is examined along with direct observations from mariners by national AtoN authorities to identify specific areas where AtoN are needed.

3.2.2.2 Temporary Virtual AtoN – Virtual AtoN with temporary duration in terms of days or months would be created using the AtoN provisioning process for physical and/or AIS AtoN whereby traditional multibeam or 3D-FLS survey data obtained from national hydrographic authorities is examined along with direct observations from mariners by national AtoN authorities. This is to identify specific areas where AtoN are needed such as for marking incident locations and/or special events that may include boat races and air shows being held over the water to mark restricted areas and special anchorage boundaries.

3.2.2.3 Momentary Virtual AtoN – Virtual AtoN with momentary duration of seconds to minutes created in real time from 3D-FLS data further enhances watchstander situational awareness by alerting them to the presence of transitory and short-lived hazards to navigation that exist within the water column, and translating their position and bearing information into ECDIS coordinates and displaying an appropriate symbol at this location. The detection of such in-water hazards are not possible through any hydrographic survey whose origin is through traditional multibeam sonar.

In areas lacking hydrographic survey to modern standards 3D-FLS can provide vessels with a means to determine an awareness of bottom topography ahead of the vessel while making way to help bridge crews to assess minimum depths and ensure safe navigation. This capability is also a necessary precursor to the establishment of Virtual AtoN where they are most needed. This research focuses on the use of 3D-FLS to fulfill this need.

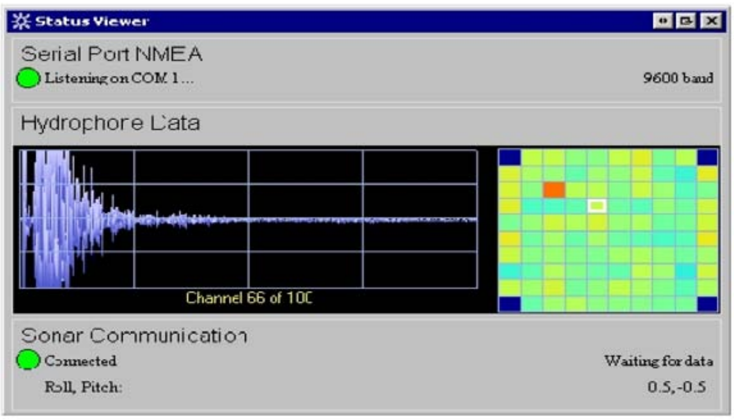
Using the FarSounder 500 meter 3D-FLS system as an example, figure 3.4 illustrates the potential of 3D-FLS to provide real time, high resolution imagery ahead of a vessel while making way (FS-500, 2015). This image illustrates a swath of soundings ahead to 125 meters showing bottom depths ranging from approximately 25 meters just below the vessel sloping upwards to less than 5 meters. This image was created as a result of a series of single pings emitted from the 3D-FLS transmitter, and received by approximately 200 hydrophones. The imagery is updated at a rate of approximately once every 1.5 seconds, refreshing the hydrophone data each time resulting in greater accuracy based upon the repeated measurements of the same area using multiple hydrophones at different angles. A speed of 6 knots results in a new sampling of data along a swath of the bottom approximately every 4.6 meters.



Source: FarSounder, Inc. Used with permission.

Figure 3.4: Environmental perception using 3D-FLS

Data from individual hydrophones may be recorded for subsequent analysis, from which the route of transit of a vessel may be recreated on a ping-by-ping basis. Figure 3.5 illustrates the array of approximately 200 hydrophones showing relative signal strength between hydrophones ranging from blue (no or few echo returns) to red (high strength echo return). The waveforms depicting the actual returned signals are also recorded for each hydrophone, allowing for the determination of horizontal and vertical bearing and target range information. Further examination of target features and properties based upon ping signal characteristics is also possible. These hydrophone



Source: FarSounder, Inc. Used with permission.

Figure 3.5: Hydrophone data display

data provide full-bottom bathymetric coverage that may be used by responsible hydrographic authorities to determine minimum depths over the survey area and to detect critical items such as wrecks, obstructions and hazards to navigation using procedures similar to that used with multibeam echo sounders.

3D-FLS capabilities to detect in-water hazards to navigation such as growlers, logs, shipping containers and other objects that exist within the water column can add immensely to watchstanders' comprehension of situational awareness by making them aware of the presence of these hazards that may otherwise be missed, continuously updating the state of the environment in real time. The positions of such hazards are determined in relation to the route of transit of the vessel and displayed on ECDIS using the appropriate symbology by examining individual hydrophone contact information with respect to nearby hydrophone signal characteristics. An in-water hazard is identified when a contact exists in one or more hydrophone(s) that does not appear to be physically connected to adjoining hydrophone contacts indicating bottom returns.

3.2.3 Level 3 – Projection

The third level of situational awareness involves thinking ahead or projecting into the near future possible situations and events based upon comprehension of the current situation. Within the context of this research this means the ability of the watchstander to assess the potential for his or her vessel to experience an unintended grounding or allision considering their knowledge of the present environmental situation as a result of voyage planning and voyage monitoring using sensor and other data.

The factors associated with projecting risk of grounding and allision have to do with the operational specifications of the vessel as well as the characteristics of the route being taken, sea states and weather conditions (Mazaheri, 2009). The primary factors include the length, breadth and draft of the vessel itself; capabilities in terms of speed, power and environmental sensors; performance characteristics based upon windage, maneuverability, stopping distances and turning radius. Significant route characteristics include the length, depth and width of the waterway; depth uncertainty, traffic volume and the slope of the sea bed.

3.2.3.1 3D-FLS use in situation projection – The rate at which environmental conditions change and the distances in which these changes become apparent during the course of a voyage help to predict the range of possible events and subsequent consequences that may result from these events. One example of the use of 3D-FLS to project a possible future grounding situation is shown using the image provided in figure 3.4. In this case the rising slope of the sea floor ahead of the vessel to shallow depths provides decisive clues regarding imminent potential for grounding. Should the vessel lie adrift without making way, this imagery would not necessarily indicate imminent grounding unless the rise in the sea bed represents a lee shore upon which the vessel is being driven by winds and currents. Alternatively, should the vessel be making way at a speed of 15 knots over a steady bottom when the rise at 125 meters is suddenly detected an alert watchstander could visually project that a dire situation is imminent and alarms to that effect could also be generated. Soundings information may also be displayed directly on ECDIS in areas where charts are blank or incomplete using a suitably integrated system.

3.2.3.2 Virtual AtoN use in situation projection – The use of Virtual AtoN can help watchstanders to determine potential future situations and scenarios by enabling them to determine their actual position and relative positions to any hazards that may exist and to establish a safe course. One means to accomplish this is through the use of either static or dynamic Virtual lateral aids to mark channels that provide safe passage. Dangers and obstructions may be identified using isolated danger marks, while cardinal marks, safe water marks and special marks may also be used as appropriate. Virtual AtoN with momentary duration may be generated in real time using 3D-FLS to display on ECDIS hazards that exist within the water column. In the case of the rising bottom shown in figure 3.4, these may include isolated danger and other marks.

3.3 Theory of Errors

The Theory of Errors provides a foundation from which to base the assessment of experiment results to evaluate the capability of 3D-FLS technology in this role (Sheynin, 1966). This assessment then provides the basis upon which the viability of crowdsourcing for navigation chart development using 3D-FLS data obtained from vessels of opportunity may be judged.

Measurement error is the difference between a measured value and a reference value of a measurand (JCGM 200:2008). Theory of errors is related to Estimation Theory in statistics and states that all measurements contain error and the exact measurement is not known. Tailoring this theory to this research involves evaluating the error associated with spatial data contained within the 3D-FLS and echo sounder measurement results (Fan, 2010; Wu, et al., 2010). There are three general types of errors to be considered when measurements are made: systematic, spurious and random errors.

3.3.1 Systematic errors

Errors that are systematic in nature relate to the accuracy, precision and trueness of measurements. Such errors are generally attributed to the instruments used to perform the measurements, but they can also pertain to the methods and procedures used in the process of making the measurements as well as human errors made in performing this process. Systematic errors tend to follow physical and mathematical rules that can be checked and adjusted through statistical analysis. Increasing the number of measurements will not result in a reduction of errors.

Measurement *accuracy* is defined as the closeness of agreement between a measured quantity value and a true quantity value of a measurand (JCGM 200:2008a). Proper calibration of equipment against known references and using recognized standards are two examples of how equipment may be adjusted to improve accuracy. Measurement *precision* is the closeness of agreement between measured quantity values obtained by repeating measurements on the same or similar measurand, and can represent the repeatability of a measurement (JCGM 200:2008b). The ability of an instrument to make precise measurements is generally a function of the quality of the instrument itself and the methods by which it performs a measurement. Measurement *trueness* is the closeness of agreement between the average of many (through an infinite number) repeated measured values and a reference value, and is inversely related to *systematic* measurement error (JCGM 200:2008c). Systematic errors may be reduced by changing the equipment, altering the measurement performance processes and/or changing human habits that contribute to systematic errors.

3.3.2. Spurious errors

Spurious errors affect measurements in a non-systematic way and may be caused by instrument malfunctions, the use of incorrect measurement methods, and human factors such as gross errors and mistakes caused by errors in reading the measurement results and errors in transcription made while recording the results. It is not possible to evaluate or compensate for spurious errors using statistical methods. Such errors are generally considered as outliers and are discarded.

3.3.3. Random errors

Random errors affect measurements in a non-systematic way which yields results that are unpredictable. They are caused by human factors, instrument malfunctions, characteristics of the physical environment that may alter measurement values and methods of measurement that do not consider all relevant factors which may affect measurement results. Random errors remain after systematic and spurious errors are excluded.

3.3.4 Application to this research

In this research errors apply to the uncertainties encountered in making measurements using 3D-FLS to ascertain bottom depths forward of the bow with accuracy in accordance with navigation charts to ensure safe navigation by detecting shoal depths that approach the draft constraints of the vessel (Wright & Zimmerman, 2015). A second set of different measurements using the data obtained from either multibeam echosounders or 3D-FLS in conjunction with single beam echosounders are also made in verifying Virtual AtoN as watching properly (Wright & Baldauf, 2015).

Uncertainties that pertain to measurement of depth and positioning include (IHO C-13):

- Total Horizontal Uncertainty (THU): The sum of both random and systematic measurement uncertainties in the horizontal plane. The maximum allowable THU for IHO Special Order surveys is 2 meters, and for Order 1a surveys is 5 meters. Factors used in determining THU include geodetic datum, availability of Wide Area Augmentation System (WAAS), and equipment specifications in terms of angular accuracy and roll/pitch error.

- Total Vertical Uncertainty (TVU): Constant and depth-dependent uncertainties that affect depth measurements according to the formula:

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

Where:

a represents that portion of the uncertainty that does not vary with depth,

b is a coefficient which represents that portion of the uncertainty that varies with depth,

d is the depth, and

b x *d* represents that portion of the uncertainty that varies with depth.

The maximum allowable TVU for IHO Special Order surveys is factor *a*, 0.25 meters and factor *b*, 0.0075; and for Order 1a surveys is factor *a*, 0.5 meters and factor *b*, 0.013.

Factors used in determining TVU include:

- Vertical offset between the transducer mounting location and the water's surface determined by measuring the vertical distance between the transducer and the vessel waterline.
- Actual height of tide offset from mean lower low water. Height of tide is determined based upon predicted values using the tide tables for the reporting station nearest to the measurement location, adjusted for local meteorological and oceanographic conditions based upon hourly forecasts.

- 3D-FLS angular accuracy. This value is obtained from the manufacturer specification for the 3D-FLS used in making measurements, and
- Roll-pitch error. This value is obtained from the manufacturer specification for the 3D-FLS used in making measurements.

3.4 Georeferencing

The navigation process encompasses careful route planning and closely monitoring vessel positions while enroute. In areas that lack traditional navigational infrastructure the means to verify position using visual landmarks and references can be severely restricted. This is especially true in the remote Arctic where soundings to indicate depths are often not available on charts, landscapes can be low to the horizon and nondescript, and AtoN rarely exist except in the immediate vicinity of a handful of major ports.

Virtual AtoN may be placed in lieu of physical and AIS AtoN in such areas. An underlying assumption to the correct establishment of AtoN is that they must be verified as being in their correct position as part of a determination of watching properly. However, present verification methods established to determine that AtoN are correctly positioned are deficient under such circumstances. It is therefore necessary to implement a practical means to verify this condition essential to the establishment of Virtual AtoN. In addition, such an approach must be resilient to overcome any single point of failure condition by GNSS as a result of natural events or manmade actions where failure may render Virtual AtoN ineffective and result in an inability to fix vessel position. The consequences of lacking navigation capability to verify proper positioning can be accentuated in the Arctic environment which is often devoid of physical landmarks by which an accurate fix may be made. The theory of navigation by georeferencing, defined as aligning physical and geographical features to an internal coordinate system that can be related to a ground system of geographic coordinates, forms a vital means through which Virtual AtoN verification may be accomplished (USGS, 2016).

The state of an aid to navigation on its assigned position may be expressed as follows:

$$AtoN_{pos} = TRUE$$

where:

$AtoN_{pos}$. The correct position of the AtoN is the location given in latitude and longitude conforming with the precision standards of accuracy classification expressed as the radius of a circle around the assigned position of an aid to navigation within which the aid is considered to be on station (USCG, M16500.1C).

As external references are likely to be minimal or nonexistent other than the AtoN itself, these circumstances presently require reliance upon ship's own sensors in terms of GNSS to establish a fix, and the echo sounder to determine the relevant depth contour and the amount of water below the keel. There are two problems with this scenario. First, a number of natural and manmade problems are associated with GNSS availability, reliability and accuracy in the Arctic, increasing risk as a result of overreliance on this technology. Second, in areas that are unsurveyed and poorly charted echo sounder readings provide little reference as to vessel location based upon depth contours since no such information exists within an ENC nor is displayed on ECDIS.

The approach followed to help verify Virtual AtoN as being in its proper position is based upon theories associated with the georeferencing of physical objects to topological features contained within an ENC, and navigation using georeferencing by virtue of topography following using echo sounder measurements. Virtual AtoN position verification considers the following:

1. given a geographic position of a Virtual AtoN expressed in latitude and longitude:

   Virtual $AtoN_{pos}$ = (XX° YY' ZZ" North/South, XX° YY' ZZ" East/West), and

   a. a geographic area (A) encompassing a circular, rectangular or irregularly shaped area of size (*n*) wherein Virtual $AtoN_{pos}$ lies at the center, and

   b. the geographic area (A) as represented in the ENC contains a high-resolution bathymetry model that meets the standards represented by IHO Order 1a survey, and
   c. all viable routes to and from Virtual $AtoN_{pos}$ are contained within this geographic area (A), then
2. the depths (D_{ES}) recorded by the vessel single beam echo sounder when adjusted for height of tide and vertical offset of transducer to the water's surface, and
   a. the change of depths (dD/dt), and
   b. the rate of change of depths (d^2D/dt^2)
   c. for a locus of points (P) within geographic area (A) along the route (R), will approximate
3. the depths (D_{ENC}) as represented by the ENC bathymetric model when adjusted for height of tide and vertical offset of transducer to the water's surface[1], and
   a. the change of depths (dD/t), and
   b. the rate of change of depths (d^2D/dt^2)
   c. for a locus of points (P) within geographic area (A) along the route (R),
4. within a certain tolerance level.

A Virtual AtoN that meets the above criteria in combination with the use of traditional GNSS and/or navigational fixes to known objects or landmarks may be considered as having a higher probability of being in the correct position than a Virtual AtoN that does not meet these criteria. The exact probability varies and cannot be determined in

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[1] Note: The locus of points (P) approximating depths (D_{ENC}) of step 3 is searched based upon local patterns identified using a contour-tracing algorithm that identifies change of depths (dD/t) of immediately adjacent soundings along a local minima path within the route (R) in the specific AtoN geographic area (A) (Wright R.G., 2005; Seo, J., et al., 2016).

areas that are not well surveyed since the adjacent bottom contours are unknown to any relative degree of accuracy, and nearby similar seascapes may provide false indications of being in the correct position. Therefore, a Virtual AtoN should not be considered as being verified in its proper position using georeferencing criteria alone.

However, the converse of this statement has also true. A Virtual AtoN that does not meet the above criteria, whether or not it is used in combination with traditional GNSS and/or navigational fixes to known objects or landmarks, may be considered as having a higher probability of being incorrectly positioned and not watching in the best waters. This may be due to two reasons. First, GNSS indications may be in error as a result of natural or manmade causes that place the vessel in a position other than the indicated position. Second, even if the correct position is indicated, should bottom contours not match the surveyed bathymetric model it is likely that bottom conditions have changed that may invalidate the Virtual AtoN position as being in best waters. This situation would warrant the sounding of an alarm to alert watchstanders of a possible position discrepancy or other unforeseen circumstances.

This approach provides a positive baseline against which live single beam echo sounder measurements may be compared with ENC values. Including areas outside of normal transit within the soundings bathymetry model may also be useful in positively identifying that a vessel is outside of its intended route, as opposed to inferring this condition as a result of bottom topography not matching the features of the intended route.

3.5 Risk assessment

In assessing risk of Arctic operations it is appropriate to perform an analysis of the complex systems comprising a model of the interrelations between shipboard capabilities and external support services, the vulnerabilities that may be encountered as a result of the loss of these capabilities, and the potential consequences of the loss. Loosely based upon the so-called Swiss Cheese Model developed by Reason (1990), this analysis identifies priorities for navigation risk assessment considering the state of hydrographic survey, the content and recency of navigation charts, environmental sensing capabilities and the availability of aids to navigation.

An analysis of the causal relationships between the spatial and geographical uncertainties existing in the natural environment and technological capabilities for environmental sensing are explored considering sensor availability, resolution and accuracy; the means by which sensor data are communicated, the products created using sensor data, and potential effects of sensor data corruption and interruption due to natural and human causes.

The potential for accident causation arising from interactions between latent failures and a variety of local triggering events considered in this research pertain to:

- Hydrography,
- Navigation Charts,
- Environmental Sensing,
- Aids to Navigation (AtoN), and
- Human Error;

and involves the unlikely and often unforeseeable conjunction of several contributing factors arising from different levels of the system. The use of the Swiss Cheese Model ties in well with the previously described Theory of Errors in terms of the types of errors that may occur and their potential effects on the processes involved at the different levels of the productive plane hierarchy.

In the methodology used, potential hazards are identified in accordance with various scenarios that may result. Cause analysis considers both distal and proximate causes of error, and various options that may potentially reduce or eliminate these causes. Consequence analysis addresses the barriers and defenses erected to help reduce or eliminate the potential outcomes and effects of the errors that may result.

Chapter 4 Materials and Methods

The hypothesis on which this research is based suggests the present state-of-the-art in ship sensors is sufficient to provide real-time guidance for vessels to safely transit uncharted waters and/or waters lacking physical aids to navigation. This premise is supported in that many modern expeditionary vessels are equipped with advanced oceanographic sensors such as forward-looking navigation sonar, enhanced radar, GNSS and satellite communications capabilities complimenting ECDIS to provide them with every available tool to accomplish their mission as safely as possible. Further support is provided in that few, if any, similarly equipped vessels with properly operating sensors and alert watchstanders are known to have been involved in incidents where uninstalled, missing or improperly watching aids to navigation were considered to be significant factors in the cause of the incident.

This research examines whether maritime safety and environmental protection may be enhanced through the automation of sensor data interpretation and display in enhancing watchstander situational awareness below the waterline. A key element is the timely and accurate establishment of Virtual AtoN in real-time hazard to navigation detection, classification and characterization in a form already familiar to watchstanders. Further investigation explores the archiving of sensor data for use by hydrographic/navigation chart and AtoN service providers.

Prioritization of ship sensors is given to 3D-FLS which appears to be the most critical of available modern sensors pertaining to vessel operation in unknown environments. This is due to the unique ability of such sensors to explore the area below the waterline ahead of the bow to seek and identify hazards to navigation that may jeopardize a voyage. However, consideration of other technologies is made in developing a system architecture that will support a full and comprehensive modern vessel sensor suite.

4.1 Overall approach

Specific tasks are formulated within study areas to investigate answers to the research questions identified in this dissertation. The setting within which these studies are performed is described including two research vessels used as test beds for experiments and environmental sensor data collection using 3D-FLS and other instruments along with the various inputs required for their performance; the processes and procedures employed to acquire, manage and evaluate these inputs; the outcomes to be achieved as a result of these processes and procedures; and the metrics used to measure these outcomes in determining whether the results are correct or not. Expectations are provided as to the results along with areas of risk encountered in performing each of the study tasks that may alter expectations or invalidate the premise upon which the question itself was based. Results are recorded throughout the performance of each study task, and comparisons are made with expected results. Conclusions are then drawn as to whether the questions have been answered along with rationale as to why or why not. Finally, lessons learned are documented regarding errors in input, process, product and/or metrics; assumptions made and actual proceedings; and expectations and outcomes.

4.2 Areas of study

Several specific areas of study were followed during the course of this research. Details on these studies are provided in the paragraphs below.

4.2.1 Study area 1: 3-dimensional forward looking sonar data acquisition

The acquisition of 3-dimensional forward-looking sonar (3D-FLS) data has been performed supporting experiments to obtain and extract sensor data of sufficient resolution to accomplish the following:

- Perform hydrographic survey of the sea bottom,
- Detect hazards to navigation present in the water column or attached to the bottom, and
- Create a 3-dimensional surface topography model to be included as a portion of the characteristics of Virtual AtoN.

3D-FLS systems produced by different manufacturers were used in the acquisition of data in an effort to determine whether measurements taken by different systems with varied capabilities using different methods and algorithms can achieve similar results.

The EchoPilot 3D-FLS with a range of 200 meters utilizes two one-dimensional arrays of receiving transducers, with the arrays mounted at a predetermined angle relative to each other so as to receive reflected sound waves from different respective segments of the water in front of the vessel that are separated from each other in a horizontal plane. The transducer arrays emit sound waves into non-overlapping segments of water, reflected by the underwater floor back to the transducer arrays, which convert them to electrical signals. The electrical signals are processed to calculate a three-dimensional position of each point on the underwater floor (EchoPilot, 2012). Positioning of the two transducers is recommended by the manufacturer near the stern of the vessel where three-axis movement may be minimized. This unit provides only raster data from which soundings were extracted using a method previously developed by this researcher (Pendleton & Wright, 2002). Only soundings information was available from this system to analyze potential to perform hydrographic survey, with no capabilities evident for hazard to navigation detection.

Data was also acquired using the FarSounder model 500 3D-FLS with a range of 500 meters. This system utilizes one sonar transducer combined with a roll, tilt and yaw sensor mounted at the bow. A raw data signal is generated and transformed into an image rotated responsively to the sonar sensor's orientation generating a complete image with a single transmission (FarSounder, 2008). In-water target multi ping stabilization was also used to detect hazards to navigation that are not attached to the bottom such as shipping containers floating at or just below the surface, icebergs, large debris and debris fields, and possibly whales and other marine mammals and large fish that may lie in the vessel’s path. A software development kit helped ease the use and analysis of data at sea and post-voyage for Virtual AtoN creation. High-resolution digital data from each of the approximately 200 hydrophones on the single transducer representing both soundings and hazards to navigation were available directly available from this system. This access to the internal data structures containing the vector data from which the raster images are derived is useful for generating the soundings data in a format suitable for use by hydrographic agencies.

In making comparisons between 3D-FLS depth measurements and ENC soundings, specific hydrophone data is examined with respect to the closest location(s) to the corresponding sounding as shown on the ENC. This is accomplished by analyzing ping-by-ping 3D-FLS hydrophone coordinates based upon bearing and distance with ENC sounding positions.

Sensor data resolution for both systems were examined to determine sufficiency for charting near coastal and inland locations to IHO order 1A survey and Virtual AtoN verification requirements as described in appended Paper 3. Issues pertaining to 3D-FLS measurement accuracy, precision and repeatability were examined in both cases considering systematic, spurious and random errors as part of this evaluation. The comparisons made between the two systems were to determine strengths and weaknesses in their data content and representation for study purposes, and not to evaluate each from a product point of view. A key factor in this evaluation is any potential differences in accuracy or induced error as a result of the raster to vector conversion performed on the EchoPilot data, as compared to the direct digital data access without conversion permitted by the FarSounder system. The analysis of sonar data supports work efforts performed under Study Areas 2 and 4.

4.2.2 Study area 2: Virtual AtoN establishment from hazard to navigation data

Hazards to navigation and identifying class definitions are based on examples likely to occur in the Arctic and the tropics, but are also commonly found worldwide. These are obtained from the United States Code of Federal Regulations (33CFR64) where three specific hazard attributes are identified as follows:

- *Hazard to Navigation* means an obstruction, usually sunken, that presents sufficient danger to navigation so as to require expeditious, affirmative action such as marking, removal, or redefinition of a designated waterway to provide for navigational safety.
- *Obstruction* means anything that restricts, endangers, or interferes with navigation.

- *Structures* mean any fixed or floating obstruction, intentionally placed in the water, which may interfere with or restrict marine navigation.

Specific examples of hazards to navigation were identified by examining navigation charts from those portions of the Arctic where detailed surveys have been conducted, followed by tropical coral reef regions, and then other regions where such hazards, obstructions and structures exist. This examination also covers Notices to Mariners where hazards to navigation have been identified but are not yet charted. Attempts were also made to identify specific examples that provide realistic test cases that replicate hazard to navigation attributes and characteristics during actual in-water testing using 3D-FLS. This includes objects and features that are attached to and project from the bottom such as shoals, rocks, ledges, reefs and wrecks. Also included are test cases that represent in-water hazards within the water column, the presence of which is opportunistic in nature and not necessarily abundant or easily found in the natural environment. Similar targets such as buoys were used when available and appropriate.

Differences in precision and accuracy are considered between hazards to navigation attached to the bottom and those drifting within the water column. This is anticipated due to potential differences in resolving targets that lie on a plane where adjoining hydrophone signals may tend to promote averaging of measurements, as opposed to detecting and characterizing a target that exists in free space without reference to adjoining hydrophone signals. Bottom targets are detectable with 3-dimensional characteristics, while depth information for hazards to navigation drifting in the water column may not be readily discerned.

The detection of hazards to navigation is accomplished in real time by the FarSounder system itself directly from the sonar data, eliminating any possible delay that may be incurred as a result of post-processing sonar data. The EchoPilot system has no specific capability for this purpose and detection is dependent upon user interpretation of sonar data presented in the visual display. Post processing of the raster data provided by this system would be required to detect hazards to navigation, which is beyond the scope of this research. Presentation on navigation displays in a form that is easily interpreted considering human factors is discussed under Study Area 5.

The process used in acquiring 3D-FLS data, analyzing the data to detect hazards to navigation, developing ENC and then displaying ENC data on ECDIS is illustrated in Figure 4.1. High resolution data representing a 3-dimensional topological model of the sea floor in areas where the bottom rises to above 50 or 100 meters, depending on make and model of 3D-FLS, is acquired live and displayed to the watchstander on ECDIS in real time while a vessel is making way. Hazards to navigation that are present either attached to the sea floor or suspended in the water column between the surface and the sea floor are detected and also displayed as momentary Virtual AtoN using appropriate symbology in accordance with existing ECDIS protocols, with minor variation to depict the virtual nature of the notification.

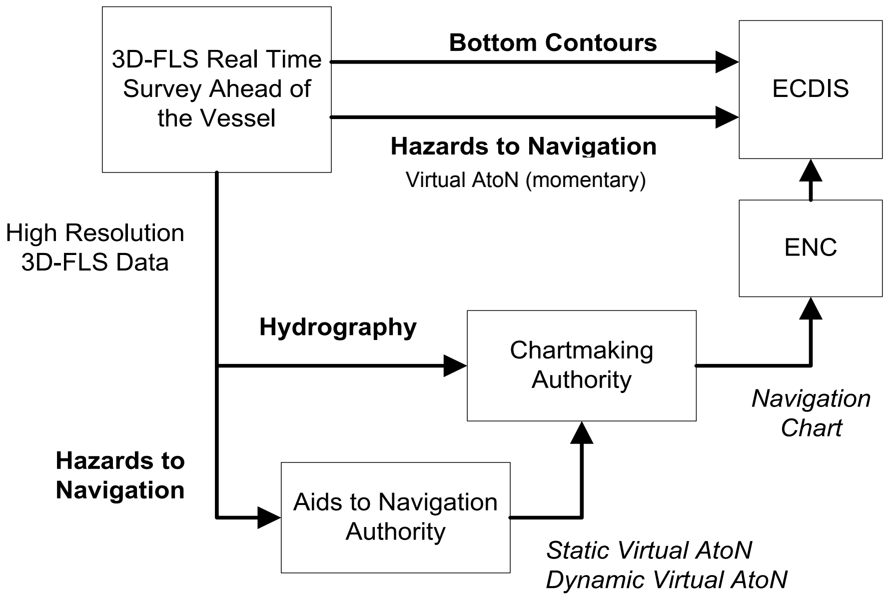

Figure 4.1: Correlation of 3D-FLS data flow with national authorities and Virtual AtoN creation for electronic navigation chart development and display to mariners on ECDIS.

This data is also recorded and subsequently transmitted for use by national hydrographic authority in chart making, and also by national AtoN authority for determining the placement of AtoN, including static and dynamic Virtual AtoN for inclusion in navigation charts. This information is embodied within an ENC for display to mariners on ECDIS.

The methodology used in this research is illustrated in figure 4.2. The objectives to be achieved are defined and boundary conditions and constraints identified as the first step in our analysis. Once completed, the assessment of risk can then be performed. This is accomplished by first identifying potential hazards and development of a scenario by which their causes and consequences may be examined, followed by the identification of options to control risks and to compare benefits of each of the options. Finally, recommendations are provided based upon the hazards identified, the options to reduce or eliminate their occurrence, or the consequences and associated costs and benefits.

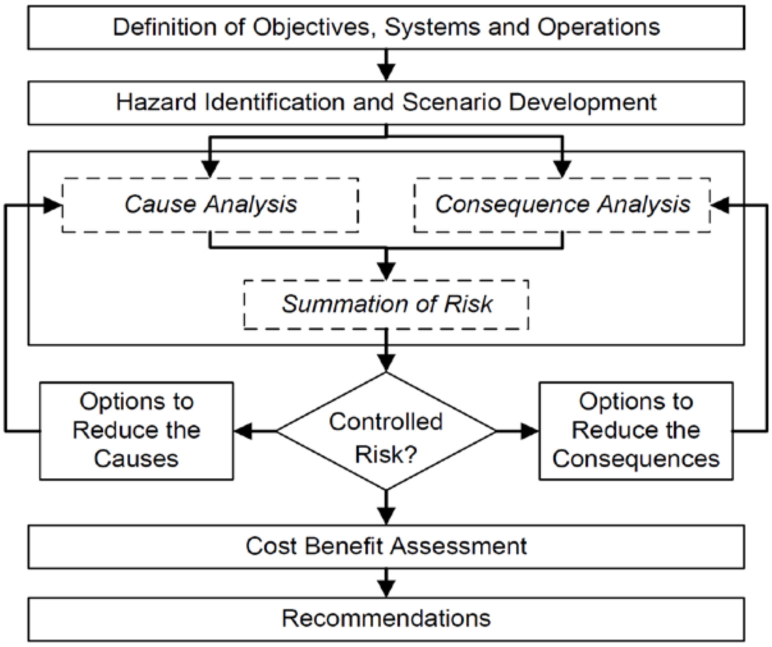

Figure 4.2: Risk assessment methodology

The objective of this research is to identify the various factors and reduce associated risks that may lead to the unintentional grounding of vessels, especially in remote regions where hydrographic surveys to modern standards are rare and navigation charts are incomplete and inaccurate. Also included in this objective is allision with objects that exist either afloat or present in the water column that may cause an accident. A further objective is to examine new sensor technologies and reduce the occurrence of unintentional groundings and how this may be accomplished. This includes results obtained directly through new technology use along with products and capabilities obtained indirectly through the post-processing and secondary use of data. Examples of new technologies include 3D-FLS and Virtual AtoN that do not require the use of AIS radio technology or physical infrastructure of any kind for its use.

This analysis is limited to SOLAS vessels that are likely to operate in the Arctic including those involved in community re-supply, bulk cargo transportation, fishing activities and tourism. Scope is also limited specifically to spatial and geographical uncertainties along transit routes that may lead to unintentional grounding.

Ship systems include those generally considered under the e-Navigation umbrella and communication systems needed for provisioning of meteorological and oceanographic data associated with weather, tides, currents and waves (sea state). This includes ECDIS, AIS, GNSS, Radar, Sonar and communications system components providing maritime safety information broadcasts. Also considered is hydrographic data for creating navigation charts, including ENC, in their present form and also with detailed hydrography data integrated within the International Hydrographic Organization (IHO) S-100 framework standard Universal Hydrographic Data Model. Specific reference is made to the draft S-102 High Definition Gridded Bathymetry standard that supports development of new navigation products not possible under the S-57 and previous hydrographic standards (IHO S-102). New products can include tools for navigation by georeferencing to known features that exist on the bottom to supplement positioning information provided by GNSS and AIS. This same hydrographic data is used for the design, implementation, placement and verification of AtoN in the Arctic to guide vessels along their routes (Wright and Baldauf, 2015 and 2015a).

Limitations include risk to personnel, environmental and property damage. A prototype case is developed to illustrate the factors involved to generalize to other segments of the Arctic fleet. Choice of route illustrates a typical trade for the vessel type and size. There is 100% ENC coverage for this route and ECDIS availability is assumed. However, ENC data content in terms of soundings and other data useful for navigation over many portions of this route is sparse and even non-existent in many areas. Paper charts for these areas are not required when electronic charts are in use, and high speed vessels are not considered.

A generic model characterized by functions and capabilities inherent to ship navigation was defined representing an integrated collection of systems, including the interactions of functions and systems appropriate to unintended grounding.

4.2.3 Study area 3: Value added for hydrographic and AtoN authorities

The focus of this study area included cognizant national authorities in the United States: the National Oceanographic and Atmospheric Administration – NOAA (responsible for hydrography) and the Coast Guard (responsible for AtoN) and elsewhere under appropriate national and international authorities. Research efforts undertaken determined whether geographical references can be established to assess the feasibility of verifying positions of Virtual AtoN as being correct as part of a determination of their watching properly. The study focused on accomplishing this using several measures of a vessel's apparent position to determine if it is different from the expected position. Additional research includes the assessment of the capability to verify Virtual AtoN that can also be extended to the verification of physical AtoN and AIS radio-based AtoN to spawn the creation of more robust verification methods.

Methods used in analyzing the value added for hydrographic authorities are specified in terms of soundings and features deliverables required of commercial contractors performing hydrographic services and include specifications that gridded data must meet, survey coverage and resolution and quality control (NOS, 2015). These methods include adjustment for errors that may be encountered during survey including corrections to echo soundings and uncertainty assessment that include instrument error corrections (draft, speed of sound, attitude, error budget analysis for depths and uncertainty budget analysis for depths) and quality control (multibeam sonar calibration and positioning system confidence checks). Although 3D-FLS data is currently not included as part of the investigations currently being performed by the IHO CSBWG, consideration is also being given to conformance with basic system and sensor descriptions, metadata and data formats relevant to the working group's functions.

Methods used in analyzing the value added for AtoN authorities reflect those promulgated for use by the U.S. Coast Guard involve processes governing the establishment of an AtoN system, review and modification of AtoN systems, survey requirements, marking systems and system design and configuration, and correction of AtoN discrepancies as pertains to federal and private AtoN (USCG M16500.7A). The ability to automate such processes was considered, enhancing the ability of present AtoN authority personnel members dedicated to perform this task. Second, consideration was also made regarding the integration of algorithms to perform these automated verification tasks into ECDIS installations whereby every passing ECDIS-equipped vessel can routinely and without human assistance perform AtoN verification of position and watching in best water while making way on a continuous basis. Such algorithms would track the position of each Virtual AtoN in relation to the vessel route of transit and correlate the single beam echo sounder measurements with the bathymetric model contained within the ENC. When there is little or no correlation between these two data sources alarms may be generated to alert the watchstander of a possible condition that either the vessel is not in the correct position or the bottom conditions relative to the Virtual AtoN has changed. Statistics of Virtual AtoN position verification results may be maintained for each one encountered.

4.2.4 Study Area 4: Virtual AtoN data object verification

The concept of Virtual AtoN verification arose out of a critical need to ensure their suitability and correctness in cyberspace without having the luxury of a physical presence for comparison. With the susceptibility of AIS and GNSS to spoofing, jamming and outages, it is essential this issue be adequately addressed to ensure safety of navigation (AIS, 2015).

The approach followed to verify Virtual AtoN as watching properly in terms of positively identifying the aid, determining it is displaying the proper characteristics and is in its proper position was conceived during this research based upon georeferencing of physical objects to topological features contained within an ENC, and navigation using georeferencing by virtue of topography following using echo sounder measurements. This approach may be described as follows:

A Virtual AtoN that is watching properly ($AtoN_{wp}$) is "on its assigned position ($AtoN_{pos}$) exhibiting the advertised characteristics $\{AtoN_{char(1\text{-}n)}\}^{*}$ in all respects" (USCG, M16500.7A).

$$AtoN_{wp} = AtoN_{pos} + \{AtoN_{char(1 \rightarrow n)}\}$$

where: $AtoN_{pos}$ = TRUE

and: $\{AtoN_{char1} + AtoN_{char2} + AtoN_{char\,3} + \ldots + AtoN_{char\,(n-1)} + AtoN_{char\,n}\}$ = TRUE

given:

$AtoN_{pos}$ The correct position of the AtoN is the location given in latitude and longitude conforming with the precision standards of accuracy classification expressed as the radius of a circle around the assigned position of an aid to navigation within which the aid is considered to be on station (USCG, M16500.1C).

$Characteristic_1$: Light List number.

$Characteristic_2$: Name of the aid to navigation.

$Characteristic_3$: AtoN geographic position in latitude and longitude.

$Characteristic_4$: Not applicable to Virtual AtoN.

$Characteristic_5$: Not applicable to Virtual AtoN.

$Characteristic_6$: Not applicable to Virtual AtoN.

$Characteristic_7$: Not applicable to Virtual AtoN.

$Characteristic_8$: Aid remarks, seasonal remarks, and Private AtoN identification.

$Characteristic_9$: Symbol for aid to navigation included on navigation charts and ENC.

$Characteristic_{10}$: Latitude and longitude coordinates comprising the boundaries of the AtoN geographic area used for georeferencing.

Virtual AtoN verification is therefore represented by the following assertions:

<u>Assertion A (name verification)</u>

1. The Virtual AtoN name contained within the navigation chart/ENC as displayed on ECDIS is the same name as that contained within the Light List.

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* Note: Characteristics are numbered in accordance with U.S. Coast Guard Light List format.

Assertion B (Light List number verification)

1. The Virtual AtoN number contained within the navigation chart/ENC as displayed on ECDIS is the same number as that contained within the Light List.

Assertion C (symbol verification)

1. The Virtual AtoN symbol contained within the navigation chart/ENC as displayed on ECDIS is the same symbol as that contained within the Light List.

Assertion D (position verification)

The method of Virtual AtoN position verification involves the comparison of live echo sounder data to bathymetric data over the vessel's track using three factors, including:

1. Depth (D) after adjustment for height of tide and vertical offset of transducer to the water's surface,
2. the change of depths (dD/dt),
3. and the rate of change of depths (d^2D/dt^2)

for a locus of points (P) within geographic area (A) along the route (R) as recorded by the vessel single beam echo sounder.

Research in this study area encompasses how the use of environmental, physical and electronic characteristics; performance requirements, and database representations for Virtual AtoN can help to determine whether they are watching properly and performing their proper function. Also included were experiments simulating the verification of a Virtual AtoN obstruction mark for a wreck that exists in a well-charted area and the second experiment involves verification of Virtual AtoN lateral marks in an area lacking adequate hydrographic survey.

In experiments related to verifying Virtual AtoN as watching properly, 3D-FLS data was compared to single beam echo sounder measurements along the same tracks representing nominal GNSS operating conditions and performance, and different tracks that represent compromised GNSS operation and performance as a result of natural effects of the Ionosphere and tropospheric ducting and due to intentional interference resulting from denial of service attacks, spoofing and aliasing. Throughout these experiments the obtaining and recording of positions of the data collection platforms, 3D-FLS sensors, and bench marks using a GPS receiver were performed in accordance with US National Ocean Service specifications (NOS, 2015a).

Additional experiments focused on demonstrating the use of these same methods to verify physical AtoN. These results are described using a representative sampling of the thousands of data points shown in reduced form for clarity. A significant focus of this study area included assessing the ability to verify Virtual AtoN are watching properly despite the unavailability of precise positioning information normally obtained using GNSS, AIS and other sources due to a variety of manmade and natural events.

Virtual, physical as well as AIS AtoN characteristics associated with position are generally ascertained using GNSS to compare the measured position with the charted position. In the case of physical AtoN and synthetic AIS AtoN there is a physical AtoN present at the location as well as an AIS/ECDIS representation to corroborate the GNSS fix. For AIS virtual AtoN and Virtual AtoN the problem becomes more complicated since there is no physical AtoN presence at all. A fix developed based upon bearings taken to physical landmarks and features would be a suitable method for determining location only in the case where such features were visible and not obscured or out of visual or radar range.

However, there is another means to take such a fix through reference to ground. This may be accomplished, again using modern technology, by ground referencing to obtain position verification using known surface landmarks through sonar bearings. This can include bottom features obtained through bathymetric ENC models compared to live echo sounder measurements made during the transit of a vessel over time intervals using running averages and derivative trend information. An ENC containing high resolution hydrographic data is required to implement this approach using the concepts illustrated in figure 4.3 where depths associated with the correct Virtual AtoN position can be readily determined at high resolution. This is envisioned using the IHO S-100 Universal Hydrographic Data Model that that supports a wider variety of hydrographic-related digital data sources and products than the S-57 IHO Transfer Standard for Digital Hydrographic Data. Specific reference is made to new spatial models to support imagery and gridded data, 3-D and time-varying data, and new applications beyond those of traditional hydrography. Such ENC can be integrated with ECDIS with the proper resolution and correlation to determine bearings, produce the necessary fixes and generate warnings.

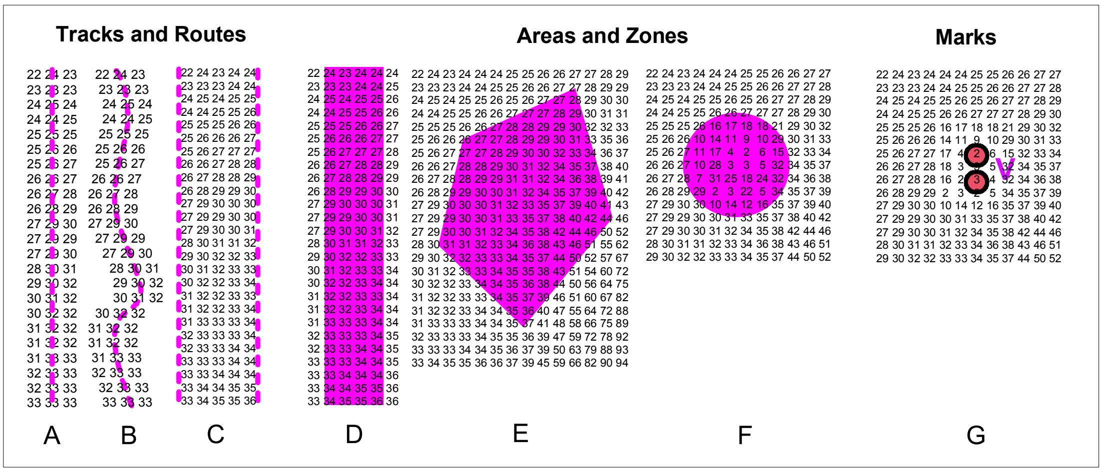


Figure 4.3: Georeferencing characteristics showing correlation between Virtual AtoN and surrounding depths

Integral to each Virtual AtoN digital data object as <characteristic$_{10}$> is high resolution hydrographic data associated with the ENC. For example, tracks A and B in figure 4.3 represent non-regulated, recommended tracks not based on fixed marks associated with depths along the track centerline at a span of predetermined width. The routes C and D fairways are associated with depths along the route between the fairway boundaries such as may be the case in areas where only channels are properly surveyed to modern standards and adjacent waters may be poorly surveyed or not surveyed at all. Areas E and F may represent restricted or exclusion zones through which vessel passage is regulated while mark G may be positioned at any appropriate location where the waters are properly surveyed.

Fix and bearing information to known physical environmental features such as soundings for each Virtual AtoN can be taken during initial installation and encoded as part of its characteristics. These characteristics can then be used anytime thereafter to verify position accuracy during normal use and subsequent verification. Encryption of position characteristics data can ensure their security and validity. Such methods can also detect the effects of AIS and GNSS jamming and spoofing since the presumed location based upon GNSS would not coincide with environmental features of the actual route of transit. Used with inertial navigation system backup, it would also be possible to verify position in the event of GNSS outage.

An example of this approach is shown in figure 4.4 under conditions of nominal GNSS operation and during GNSS spoofing activities are underway such as attempting to highjack a vessel into hostile or restricted waters or to intentionally ground a vessel by making watchstanders believe they are in one location when in fact they may be miles away at a location unbeknownst to them.

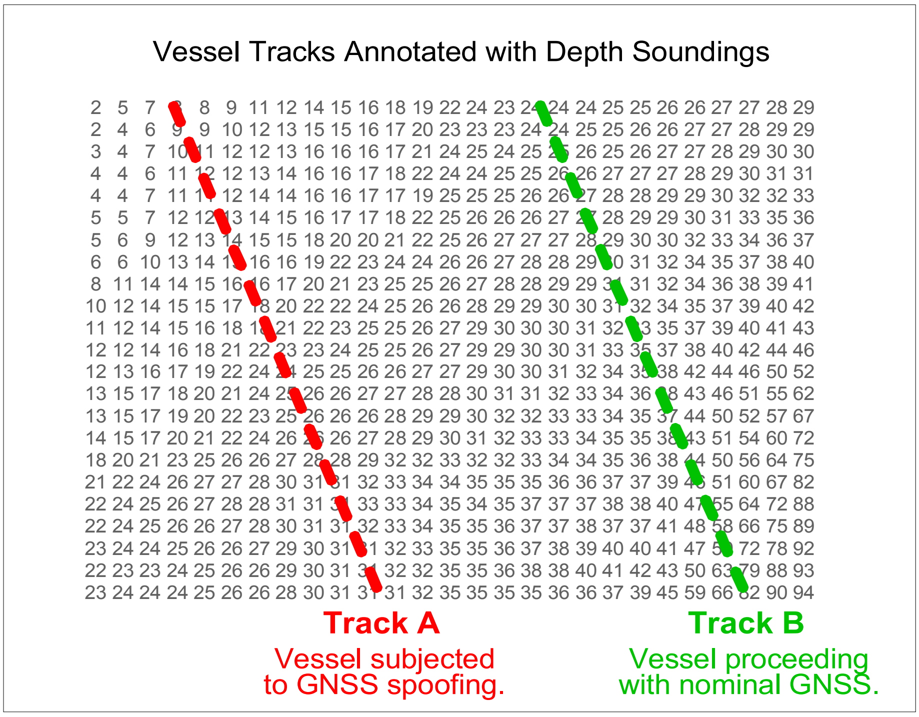
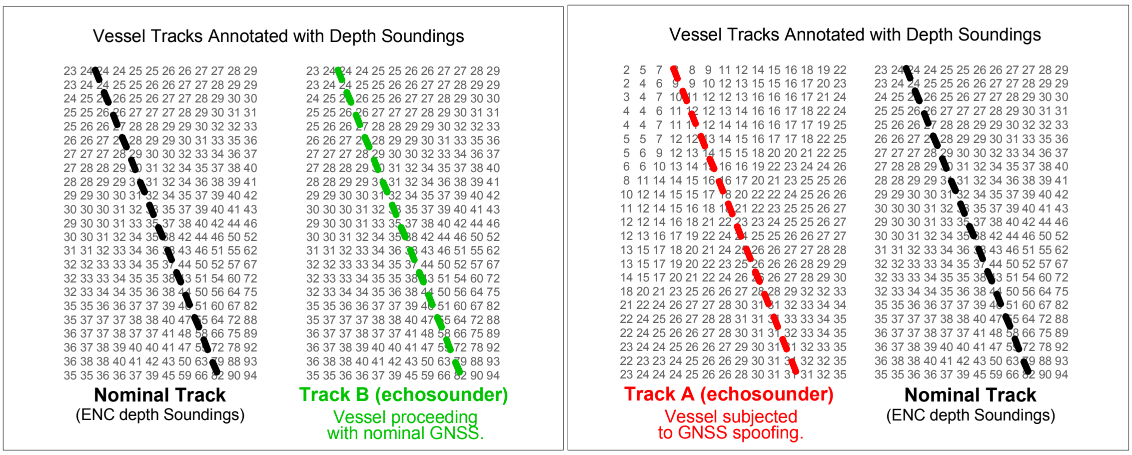


Figure 4.4: Tracks of Vessels Illustrating the Effects of GNSS Spoofing

In the above situation Track B (in green) illustrates the path of transit of a vessel when GNSS equipment is operating correctly and accurately depicts vessel position. Track A (in red) illustrates a potential path of transit of a vessel while making way during a GNSS spoofing attack. Even though in both cases the GNSS and ECDIS will show the vessel is adhering to the same track (Track B), during the spoofing event the vessel is actually transiting a different course as illustrated by Track A. This is the same scenario followed by a vessel in 2013 where scientists from the University of Texas successfully spoofed the GPS on a yacht, directing it on a parallel path hundreds of meters off course while the chart display showed only a straight line (Divis, 2013). Examination of the vessel tracks illustrated in figure 4.5 show differences between ECDIS and echo sounder indications under nominal and spoofed GNSS conditions.

Figure 4.5a shows that a close correlation exists between vessel's echo sounder measurements and the ENC depths displayed on ECDIS when both the GNSS and echo sounder equipment are operating under normal conditions. However, there may be poor correlation between the ECDIS representation of position and route and echo sounder measurements depicting the actual terrain over which the transit is made when GNSS spoofing activity is underway as shown in figure 4.5b. In this case the echo sounder accurately depicts the physical environment below the waterline at the vessel's actual position while ECDIS indications are displaying an inaccurate position showing depths that are very different than that which exists below the hull. Indeed, a vessel transiting Track A is in jeopardy of grounding in the shallows depicted on this line of transit.



a. Close correlation between ENC and echo sounder depth measurements.

b. Poor correlation between ENC and echo sounder depth measurements.

Figure 4.5: Correlation of ENC to echo sounder measurements during nominal GNSS operation and during GNSS spoofing.

Watchstanders would be notified via alarms and other indicators that a discrepancy exists between ENC and ECDIS indications of position as compared to echo sounder sensor measurements of the actual physical environment. These indications would not necessarily help the watchstander to directly determine actual position since navigation by georeferencing is much more computationally complex than determining navigational discrepancies by georeferencing. However, notification of the navigational discrepancy would alert the watchstander of a condition in which caution is justified and action should be taken to determine actual vessel position before proceeding further on course.

4.2.5 Study Area 5: Virtual AtoN representation on navigation display systems

This study area analyzed the depiction of hazards to navigation using standard AtoN symbology on IMO-compliant ECDIS. Although this effort is tailored to the specific scope of this research, it was accomplished within the boundaries established by existing AtoN initiatives of the U.S. Coast Guard where the physical characteristics of AIS AtoN include the symbols for real, synthetic and virtual; and non-AIS Virtual (NOAA AIS). NOAA also provides ENC depiction of the physical characteristics for AIS AtoN that are also available for Virtual AtoN on ECDIS and includes symbols for cardinal marks (N/E/S/W), lateral marks (IALA A/B port and starboard), isolated danger, safe water, special purpose and emergency wreck marking (NOAA 2013). This includes compliance with the fourth attribute of marking a hazard to navigation, where:

> *Markings* mean the lights and other signals placed on or near structures, sunken vessels, and other obstructions for the protection of navigation.

One of the primary references used in the performance of this task is IHO Publication S-52, Specifications for Chart Content and Display aspects of ECDIS (IHO S-52). Within the United States NOAA Chart No. 1 also provides guidance for ECDIS symbols (NOAA, 2013a). Virtual AtoN are intended to exist only in ENC using very similar symbols as presently existing for physical and AIS radio-based AtoN, and display only on ECDIS.

Chapter 5 Results

The ultimate outcome of this research includes a comprehensive definition of a Virtual AtoN that requires no presence in the physical environment whatsoever, along with definitions of constituent characteristics that comprise this aid. A detailed description of a Virtual AtoN is provided in paragraph 5.1 of this chapter.

A significant impediment to achieving this outcome is a lack of adequate hydrographic survey to modern standards in remote Arctic and tropical regions necessary to determine where AtoN are most needed and to place them with precision sufficient to verify they are on station and watching properly. To overcome this impediment the results of experiments exploring the capability and utility of 3D-FLS are described. For properly equipped vessels it will be possible to also safely transit uncharted and poorly charted waters with an increased level of safety that is not possible under existing IMO carriage requirements for vessel equipment.

Two significant outcomes resulted from the use of this technology. First, the capability of 3D-FLS to detect hazards to navigation directly in the path of a vessel in real time resulted in the creation of a new type of Virtual AtoN with momentary duration capable of detecting imminent hazards to navigation in real time that has not previously been possible. Second, 3D-FLS can provide high resolution swaths of hydrographic data that appear to be comparable with multi-beam sonar used for hydrographic survey. Such independently sourced data can supplement national authority survey efforts through the crowd sourcing.

The research leading up to this outcome has been documented in the form of the results of studies and experiments described in peer-reviewed papers published in academic journals and in conference proceedings, presentations made at industry and academic forums, and previously unpublished findings that are included within this dissertation. Of these papers, five that best describe the various aspects of this research have been selected and appended to this dissertation.

Paper 1 provides a general description of what constitutes a Virtual AtoN, followed by a presentation of findings regarding potential Virtual AtoN implementations, their capabilities and limitations, and their use. This discussion is described in paragraph 5.2.

Results are discussed in paragraph 5.3 and provided in Paper 2 that can be used to verify that Virtual AtoN are deployed in the correct position and watching properly by displaying the appropriate characteristics while in use. Further elaboration is provided on verifying proper implementation of requirements and validating intermediate and final results throughout the entire development lifecycle.

Paragraph 5.4 describes Paper 3 wherein is presented the results and findings of field studies using different 3D-FLS systems that pertain to accuracy in terms of their potential to provide topography data to support hydrographic survey in regions that are poorly surveyed or not surveyed at all. This paper also presents findings on the use of topography data obtained using 3D-FLS to help verify Virtual AtoN are in their correct position and watching properly.

In paragraph 5.5 results are presented regarding vulnerability and risk assessment for Arctic voyages as a result of the combination of poorly surveyed waters and limitations of environmental sensing capabilities in modern vessels. The potential advantages of expanding these sensing capabilities using 3D-FLS and resulting risk control options are also discussed.

Paragraph 5.6 discusses the contents of Paper 4 that describes the potential use of Virtual Aids to Navigation and 3D-FLS as a means for developing strategies to avoid groundings and preserving the Arctic environment.

Paragraph 5.7 discusses the results of the initial investigation described in Paper 5 of the capabilities of 3D-FLS to detect hazards to navigation at cruising speed through an in-depth analysis of the Costa Concordia tragedy. Insight into bridge alerts and alarms that may have been generated had 3D-FLS been installed, operational and observed just prior to the grounding are also provided.

5.1 Description of a Virtual Aid to Navigation

The technical definition of a Virtual AtoN as pertains to this research is:

> **Apparatuses comprising one or more digital information object(s), systems and methods that can improve situational awareness by providing guidance pertaining to characteristics of the physical environment external to a vessel to help a mariner determine position and course, to warn of dangers or of obstructions, or to give advice about ship routing without requiring a presence in the physical environment external to a vessel.**

The implementation and realization of a Virtual AtoN may be static in nature where its characteristics do not change such as when emulating a physical AtoN, may be dynamic where its characteristics may change in either or both the time and/or spatial domains as a result of changing environmental features and/or to accommodate properties unique to a specific vessel such as draft and speed. It may also reflect characteristics that exist momentarily or for only short periods of time. Such invention is essential to enhance safety of navigation as vessel traffic in areas such as the Arctic that is expanding in vessel traffic volume both within and transiting the region, yet the necessary physical infrastructure in terms of buoys, beacons and other physical and radio-based devices can be difficult or impossible to place and maintain in this hostile environment that stretches across vast distances. This also applies in tropical regions where sensitive environmental features such as coral reefs prevent the placement of sinkers to affix physical AtoN. Virtual AtoN may also be used to designate positions of tactical significance in planning and executing military, search and rescue and emergency relief operations.

This concept was defined as a consequence of examining responsible national authority practices identified in Study Area 2 and implementation requirements identified in Study Area 3 through elaboration as to the apparatus, systems and methods establishing the embodiment of Virtual AtoN and descriptions of various means of implementation.

5.1.1 Embodiment

The embodiment of a Virtual AtoN may include:

- Apparatus designated as short range aids to navigation traditionally represented as beacons, buoys, lighthouses, lightvessels, lines, daymarks and traffic signals,

- Apparatus designated as positions, routes, tracks, areas, zones and other regions that are safe for navigation or transit,
- Apparatus designated as positions, routes, tracks, areas, zones and other regions from which navigation or transit may be restricted or excluded,
- The above apparatuses that encompass a high resolution three-dimensional digital terrain model data of the sea bottom at and in the vicinity of the position wherein the apparatuses are located and designated for use,
- Systems of one or more apparatuses that together comprise a Virtual AtoN,
- Methods that enable the use of virtual aids to navigation to enhance the safety of vessel navigation, and/or
- Methods to verify that virtual aids to navigation are in their proper geographical position (on station) and exhibiting their correct characteristics (watching properly).

These apparatuses, systems and methods may be employed where freedom of movement of shipping is inhibited by restricted sea-room and where there is the existence of hazards and obstructions to navigation, limited depths, critical depths or unfavorable oceanographic conditions. They may be used to implement routes organizing safe traffic flow to stay clear of fishing grounds, wildlife preservation areas or the organization of traffic through these areas; and to implement routes preventing or reducing the risk of pollution or other damage to the marine environment caused by ships through allision or grounding in or near environmentally sensitive areas. They also may be used to implement tracks along which previous experience has shown, so far as possible, these tracks are free of dangers and along which ships are advised to navigate.

Guidance to mariners may be provided pertaining to characteristics of the physical environment external to a vessel that are relatively static in nature and do not change over relatively long periods of time, where these characteristics are dynamic in nature and subject to change over relatively short periods of time or are in effect for designated periods of time, and/or are provided in real-time and exist only momentarily or for very short periods of time. Guidance to mariners may also be provided to determine position and course, to warn of dangers or of obstructions, or to give advice about the location of a best or preferred route.

Characteristics of the physical environment external to a vessel that are relatively static in nature and do not change over relatively long periods of time include information regarding rocks, sea mounts, ledges, reefs, wrecks, drilling platforms and other natural and manmade static hazards to navigation that may persist within a geographically defined area in the environment over months, years, decades and centuries. Characteristics of the physical environment may also be dynamic in nature, subject to change over relatively short periods of time or in effect for designated periods of time may pertain to shoals, wrecks, construction sites and other natural and manmade dynamic hazards to navigation that may persist within changing geographically defined areas in the environment over days, months and years. Characteristics of the environment may also be determined in real-time that are momentary in duration and exist only for very short periods of time that may pertain to ice bergs, growlers, flotsam, jetsam, buoys that are adrift, marine mammals and other natural and manmade hazards to navigation. These hazards may persist within changing geographically defined areas in the environment over seconds or minutes.

Virtual AtoN apparatuses, systems and methods may be considered to be of primary navigational significance (Category 1), of navigational significance (Category 2), or less navigational significance (Category 3) than Category 1 or 2.

Virtual AtoN characteristics may be realized in physical form and media such as navigation charts and maps and/or may be realized in electronic form and media integral to human-machine interfaces such as analog and digital electronic monitors and signage. Their characteristics may be stored in electronic, optical and other media, form(s) and format(s) such as databases, data depositories and data archives; may be integrated into electronic navigation charts (ENC), electronic chart navigation and display systems (ECDIS) and other software, systems and apparatuses used to contain and present navigationally significant information to mariners using a human-machine interface; and may be accessed, retrieved, sorted, manipulate, arranged, classified and/or operated upon by a computer or computational device.

5.1.2 Essential Elements

In assessing modern AtoN system requirements three primary elements must be considered in terms of system functions, capabilities and the duration of the services provided by AtoN: functions, capabilities and durations.

Functions. Functions traditionally accorded to mariners by AtoN have been manifest as physical beacons and buoys whose functions based upon color, shape, topmarks and other characteristics have explicit meaning in the context of their use. Their placement within an overall AtoN system is used to denote tracks, routes, areas and limits implemented across the entire waterway using a systematic approach. Emulation of these same functions can be accomplished using Virtual AtoN to supplement physical AtoN. They may also be used when the deployment of physical AtoN or AIS AtoN is difficult or impossible. Virtual AtoN can provide additional capability to facilitate the electronic display of lines and symbols that represent areas, routes, tracks and limits directly on ECDIS or other system(s) by emulating the physical or AIS AtoN that are typically used to denote these functions or exhibiting new capabilities that are not possible with physical or AIS AtoN.

Capabilities. Capabilities for implementing AtoN functions have historically been viewed from a static point of view where, upon completion of a waterway design, physical AtoN are deployed to required locations. The ability to provide dynamic AtoN capabilities where their characteristics can change based upon a function of time and other factors has only recently been accomplished using AIS AtoN broadcasting area special messages. Virtual AtoN can be used to display in real time the detection of underwater hazards to navigation detected using 3D-FLS.

Duration. The use of physical beacons, marks, ranges and other apparatus including AIS AtoN continues to be the preferred method of deployment for channels, routes and other locations. Changes are made primarily resulting from experience and maintenance issues as they arise and not based upon new design and implementation methods.

Virtual AtoN can also perform these same functions designed for use over long periods of time, the temporary marking of wrecks and other features as well as marking features with very short or momentary significance like a shipping container that is adrift, growler or whale directly in the vessel's path.

5.1.3 Symbology

Traditional short range AtoN include marks in the form of beacons and buoys, ranges and other apparatus. A primary reference used in developing symbols representing these apparatuses is IHO Publication S-52, Specifications for Chart Content and Display aspects of ECDIS (IHO S-52). Within the United States NOAA (2013a) Chart No. 1 also provides guidance for ECDIS symbols.

A small sample of possible Virtual AtoN symbols similar to existing Cardinal, Lateral and Special Purpose marks in ENC and display on ECDIS are shown in figure 5.1:

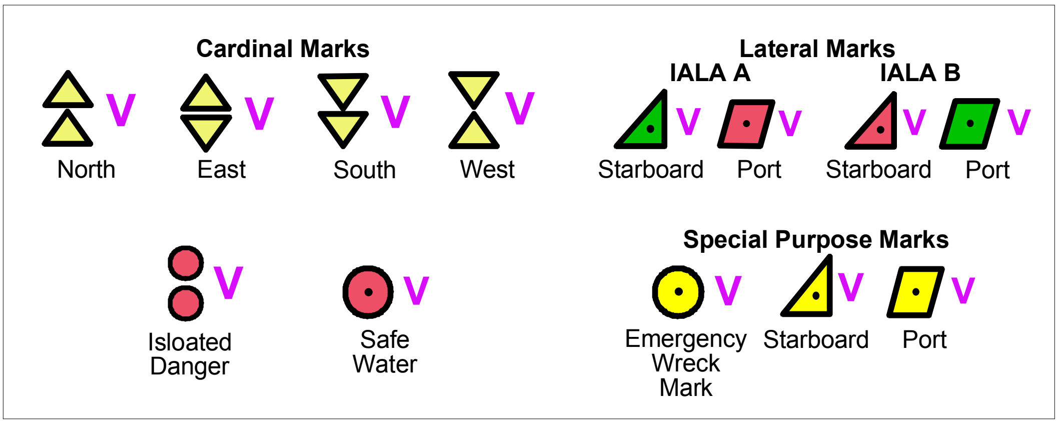


Figure 5.1: Symbols for marks.

These Virtual AtoN symbols are alike to and differ from physical AtoN and AIS AtoN as shown in Figure 5.2 in the following manner:

1. The basic mark symbol is identical in all cases. This is an existing symbol that is in use and presently found in ENC and displayed on many ECDIS;

2. AIS AtoN utilize the basic mark symbol surrounded by a magenta circle denoting a radio AtoN. The letters "V-AIS" are also posted alongside the AIS AtoN mark to designate it as a virtual mark created by an AIS transmitter. This is an existing symbol that is in use and presently found in ENC and displayed on many ECDIS;

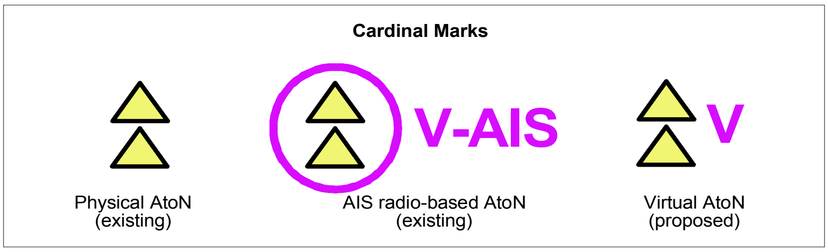


Figure 5.2: Comparison between physical AtoN, AIS AtoN and Virtual AtoN Symbols for marks.

3. Virtual AtoN utilize the basic mark symbol followed by the letter "V" posted alongside the mark to designate it as a Virtual AtoN. This is a proposed mark for Virtual AtoN that is experimental in nature and presently not in use. It is not found in ENC and presently cannot be displayed on ECDIS.

Not all ECDIS are presently equipped to display many of the symbols currently identified for use. Introduction of an extended symbol set into new ECDIS systems will begin in 2017 and continue after this date for older systems.

The capability of Virtual AtoN to emulate physical AtoN can also support new functionality that is not possible with physical AtoN. For example, some additional short range AtoN symbols that exist to represent tracks, areas and zones are illustrated in Figure 5.3.

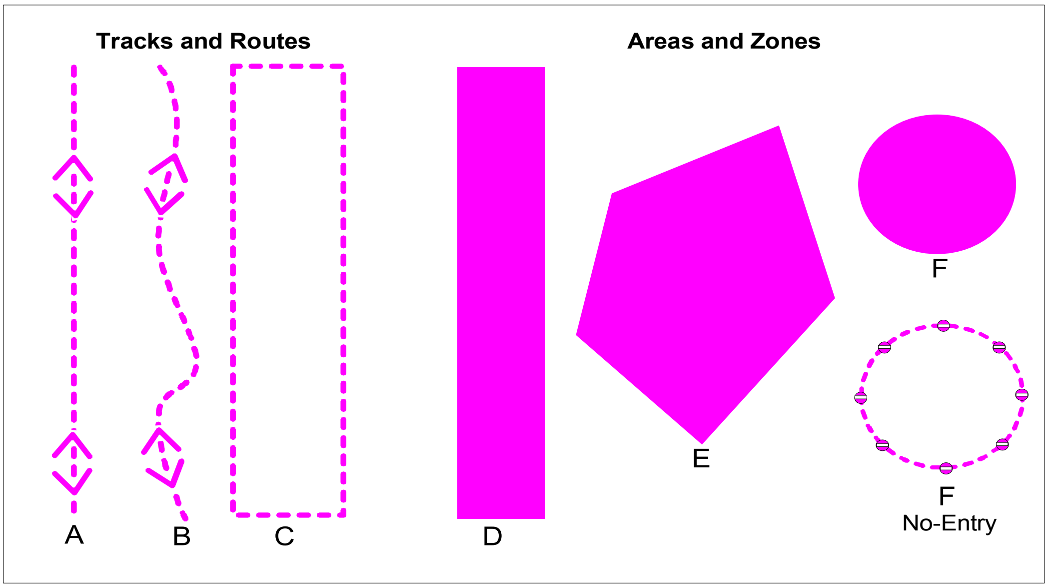


Figure 5.3: Experimental Virtual AtoN symbols for tracks, areas and zones.

These symbols may all be implemented as Virtual AtoN. Tracks A and B represent non-regulated, recommended tracks with two way vessel traffic not based on fixed marks. Route C represents a fairway designated by regulatory authority with minimum depth or maximum authorized draft. The width of the fairway, along with traffic separation zone D, is indicative of the span through which vessel traffic may safely pass. Area E represents an intuitive approach to designating a geographic area with irregular boundaries to supplement the present “–“, “┬“ and “< ” symbols found on ECDIS that require interpretation. Area F represents a geographic area whose boundaries expand a specified radius from the center, one implementation of which could be represented as shown using well understood “no-entry” symbols.

The tracks, routes, areas and zones illustrated here reflect only a small portion of symbols presently available, and soon to be available using ECDIS. There exists opportunities for further expansion of ECDIS symbols to include characteristics and capabilities that are not yet implemented, and possibly those not yet even conceived as the potential for Virtual AtoN technology becomes more fully realized.

5.1.4 Characteristics for Georeferencing

Virtual, physical as well as AIS AtoN characteristics associated with position are generally ascertained using GNSS to compare the measured position with the charted position. In the case of physical AtoN and synthetic AIS AtoN there is a physical AtoN present at the location as well as an AIS/ECDIS representation to corroborate the GNSS fix. For AIS virtual AtoN and Virtual AtoN the problem becomes more complicated since there is no physical AtoN presence at all. A fix developed based upon bearings taken to physical landmarks and features would be a suitable method for determining location only in the case where such features were visible and not obscured or out of visual or radar range.

5.2 Virtual Electronic Aids to Navigation for Remote and Ecologically Sensitive Regions

Paper 1 provides a comprehensive discussion regarding the overall Virtual AtoN concept as envisioned by this research and several of the possible implementations thereof. The results described were defined in part as a consequence of experiments and findings as part of Study Area 1 that relate to the acquisition, use and analysis of 3D-FLS data in identifying environmental conditions below the waterline relevant to AtoN creation and placement. This encompasses requirements definition pertinent to the establishment of AtoN and the examination of traditional physical AtoN and AIS AtoN characteristics. Early in this research it became evident that robust and high resolution 3D-FLS sensors could provide new capabilities in terms of performance resiliency that could detect and possibly overcome many disadvantages inherent in overreliance on GNSS and AIS technologies for vessel navigation. Also resulting from these studies is the identification of momentary objects and events representing potential hazards to navigation such as cargo containers, marine mammals, ice bergs, growlers and other phenomena for which the provisioning of existing AtoN is not possible. This resulted in the creation of Virtual AtoN with momentary duration concept described in this paper. Significant elements that comprise Virtual AtoN are placed into perspective with physical AtoN and AIS AtoN in figure 5.4.

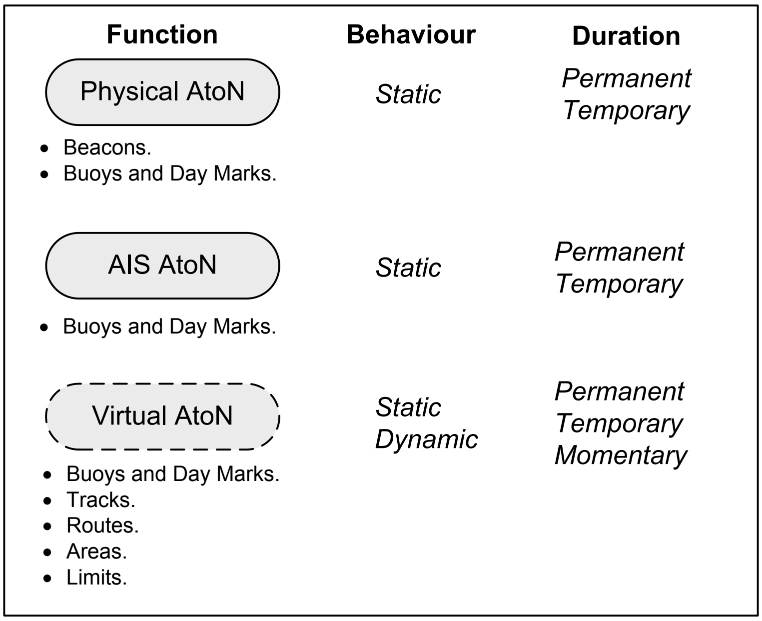


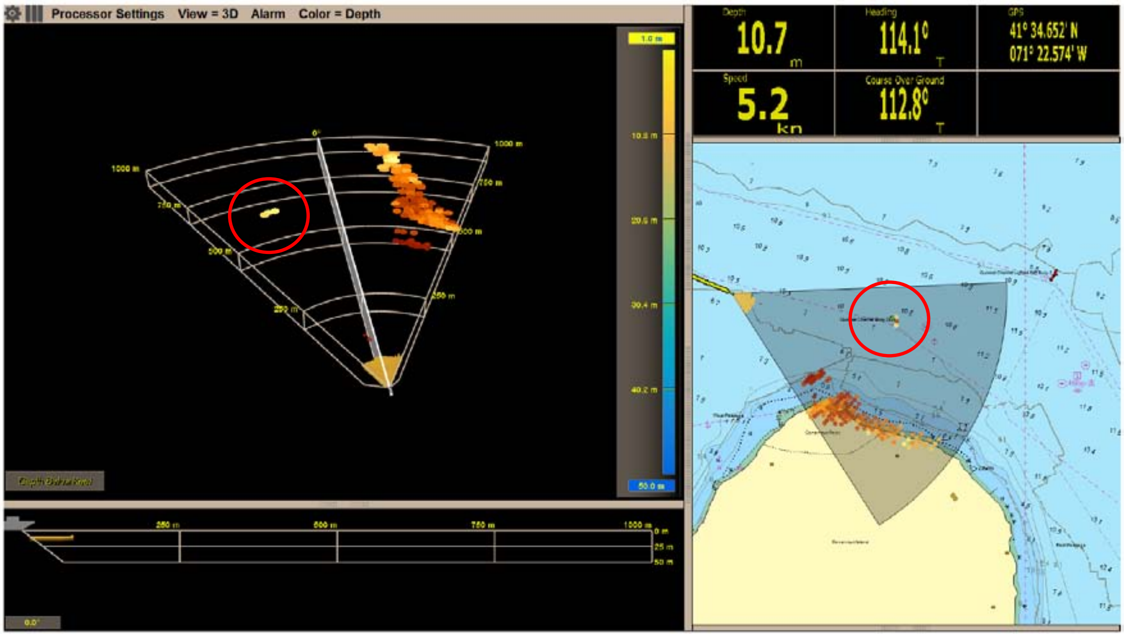
Figure 5.4: Essential Aids to Navigation (AtoN) elements.

Additional results were obtained as a consequence of examining responsible national authority practices pertaining to AtoN creation, provisioning and maintenance identified in Study Area 2. The concepts associated with Virtual AtoN can generally work in harmony with existing AtoN practices that result in their establishment by responsible national authority. An exception is the creation in real time of momentary Virtual AtoN outside of the purview of competent national authority due to their requirement for quick and timely implementation.

Results obtained as a consequence of Study Area 3 were realized in terms of new capabilities for providing AtoN services using Virtual AtoN in areas where these services are presently not possible such as in remote Arctic regions where the harsh weather prevents AtoN placement due to ice movement. This also applies in both the Arctic and tropical regions where the great distances involved and the lack of infrastructure, vessels and staffing capabilities prohibit proper AtoN use and maintenance.

Human factor issues investigated as part of Study Area 5 resulted in the determination that the display of Virtual AtoN should be wholly integrated into ECDIS displays presently mandated by IMO for SOLAS vessels and with which mariners are required to be trained in its operation. Technical issues pertaining to this topic were addressed and examples provided as to how such issues may be resolved using existing ECDIS capabilities. Further analysis of notification and alarms that are possible to be issued as a consequence of hazard to navigation detection and resulting notifications are also discussed separately within Paper 5 as described in paragraph 5.7.

Additional research results are shown below where a buoy with a floating presence within the water column just below the waterline was detected using 3FD-FLS as shown in Figure 5.5.a. The position of this buoy was placed within an ENC as shown in figure 5.5.b.



a. Buoy detected using 3D-FLS b. Sonar contact placed over ENC buoy

Figure 5.5: Momentary Virtual AtoN detected using 3D-FLS.

5.3 Correlation of virtual aids to navigation to the physical environment

In Paper 2 a method is described to verify the performance of Virtual AtoN to help ensure they are watching properly through the use of georeferencing to bottom features and characteristics obtained through electronic nautical chart (ENC) models and/or live sonar data compared to live echosounder readings using running averages and derivative trend information. This approach also utilizes IHO S-102 ENC capabilities to attach tangible physical attributes and characteristics to a virtual data object that has no other physical presence (IHO S-102). This is especially important in an era when both AIS and GNSS on which precise positioning is based are subject to spoofing, aliasing, jamming and denial of service attacks that threaten to render AtoN useless or even pose a hazard to navigation.

Two results emerged from Study Area 3 that are highly significant in terms of value added to national AtoN authorities. First, the ability to verify Virtual AtoN can also be extended to the verification of physical AtoN and AIS AtoN. This capability can spawn the creation of more robust verification methods that may be automated to a great extent, thereby enhancing the efficiency of present AtoN authority staff members dedicated to this task. Second, the algorithms to perform these automated verification tasks can be integrated into ECDIS installations such that every passing vessel can routinely and without human assistance perform AtoN verification of position and watching in best waters while making way on a continuous basis.

Results from Study Area 4 are provided illustrating how environmental, physical and electronic characteristics; performance requirements, and database representations for Virtual AtoN can determine they are watching properly and performing their proper function. There are presently no other methods identified within industry or Government for the verification of Virtual AtoN. This includes the results of experiments performed simulating the verification of a Virtual obstruction mark for a wreck that exists in a well-charted area and the second experiment involves verification of virtual lateral marks in an area lacking adequate hydrographic survey. Results from additional experiments are also provided to demonstrate the use of these same methods to verify physical AtoN using a representative sampling of the thousands of data points available in the high resolution geospatial model of the sea floor obtained through hydrographic survey.

A significant outcome of these experiments is confirmation of the ability to help verify Virtual AtoN are watching properly despite the unavailability of precise positioning information normally obtained using GNSS, AIS and other sources due to a variety of manmade and natural events.

5.4 Hydrographic Survey in Remote Regions: Using Vessels of Opportunity Equipped with 3-dimensional Forward-Looking Sonar

Paper 3 describes the results of two different sets of experiments designed to explore the usefulness and versatility of commercial off-the-shelf 3D-FLS to carry out different tasks. The first set of experiments focused on determining its accuracy in representing the physical environment in which it operates, and the second set involved determining its capability to provide data of sufficient resolution to assist in verifying position using geographical features of the bottom.

The data sources for Paper 3 include two conference papers that are not appended to this dissertation but are included under Other Related Papers and Publications in paragraph 1.7 and listed under References. The first paper describes detailed results obtained under Study Area 1 that represent initial efforts to extract vector data from 3D-FLS measurements to determine their accuracy when compared to the nautical chart that is the legal standard for vessel navigation (Wright and Zimmerman, 2015). The second paper describes results obtained under Study Area 4 from experiments further expanding upon previous efforts involving verification through georeferencing (Wright and Baldauf, 2015). These previous efforts are reported under the discussion in Paper 2. Differences between different vessel transit track data sets positively indicate the detection of GNSS and/or bottom topography anomalies.

The results of these two sets of experiments are examined to arrive at a conclusion as to whether a high quality 3D-FLS with suitable range, regardless of manufacturer, is capable of providing high resolution data necessary to accomplish the stated objectives of these two sets of experiments. Results pertaining to value added for national hydrographic authorities as a consequence of Study Area 3 research indicates 3D-FLS resolution is in accordance with hydrographic survey requirements of less than IHO Orders of Survey 1a resolution with full sea floor coverage over a predetermined swath of the bottom (IHO S-44). This result indicates a hybrid data product somewhere between those provided by IHO Orders of Survey 1a, and 1b surveys that do not require full sea floor search.

5.5 Cooperative use of 3-dimensional forward looking sonar and Virtual Aids to Navigation in reducing risk for Arctic voyages

Results described include the identification of hazards using a scenario by which their causes and consequences were examined. Options to reduce risks and/or their consequences were also identified, followed by the recognition of options to control risks and to compare benefits of each of the options. Recommendations are provided considering the hazards identified, the options to reduce or eliminate their occurrence and/or their consequences and associated costs and benefits.

5.5.1 Identification of Hazards

Groundings can occur through a wide variety of indirect and direct causes. A list of system capabilities associated with voyage planning and execution, hazards that may result from the loss or compromise of these capabilities and the potential consequences of these hazards is shown in Table 2. Lack of hydrographic survey is an indirect cause for grounding due to a lack of available information of the undersea environment fundamental to the development of comprehensive, complete and accurate navigation charts. This results in the creation of a navigation chart that contains large areas of blank space lacking soundings and other information normally available to mariners.

Table 2: Factors pertaining to unintentional groundings and allision.

Capability Loss or Compromise	Hazard due to Effect of Loss or Compromise	Potential Consequences
Hydrography		
- Lack of Assets to Perform Surveys	Poor Navigation Charts	Improperly plan/monitor voyage.
Navigation Charts		
- Lack of Soundings	Unknown depths along route	Grounding
- Uncharted Hazards to Navigation	Danger posed to surface vessels	Grounding, Allision
- Different Datum	Different positions using the same coordinates	Grounding
- ECDIS	Warnings and alarms may be inoperable	Grounding
Environmental Sensing		
- Automated Identification System (AIS)	Identification and location of vessels and AtoN	Grounding, Allision
- Precision Positioning and Timing (GNSS)	Loss of electronic position and time acquisition	Grounding, Allision
- Tides and Currents	Inaccurate depths along route	Grounding, Allision
- Weather	Unknown or inaccurate atmospheric conditions	Grounding, Allision
- Sonar (Echo sounder, 3D-FLS)	Inaccurate or unknown depths along route	Grounding, Allision
- Radar	identification/location of vessels, AtoN, land	Collision, Grounding, Allision
Aids to Navigation (AtoN)		
- Virtual (Permanent/Temporary duration)	Unmarked hazards, reefs, ledges, shoals, etc.	Grounding, Allision
- Virtual (*Momentary* duration)	Unmarked hazards floating in the water column	Allision
Human Error		
- Inaction	Lack of knowledge, situational awareness	Grounding, Allision
- Action too little/too much	Inattention	Grounding, Allision
- Incorrect action	Procedural deficiencies, poor learning	Grounding, Allision
- Action too soon/too late	Poor communication	Grounding, Allision
- Misdirected action	Miscalculation	Grounding, Allision

A direct cause of grounding is illustrated by the navigator of a vessel relying upon a poor chart that may be lacking soundings information while attempting to transit an area where bottom characteristics are unknown and any hazards to navigation that may exist are as yet undiscovered. Another problem in the Arctic is the use of charts where surveys were performed using a datum other than World Geodetic System 1984, requiring a datum shift correction before a position can be plotted on a chart (WGS84, Pub. 180). This also requires that GNSS are set to the same datum as the ENC. The various alarms integral to ECDIS that are intended to alert the watchstander of insufficient water depth ahead along the transit route to prevent groundings will not operate when the ENC does not contain this information.

Environmental sensing capability discrepancies are a potential cause of grounding due to system failure and/or lack of situational awareness on the part of the watchstander. With the sole exception of the echo sounder that provides water depth directly below the hull, all navigational sensor coverage including AIS, GNSS and radar is limited to the environment as it exists above the waterline and is capable of detecting only secondary, indirect references that may indicate shoal waters or hazards to navigation significant to grounding. Such references may include a rock or pinnacle that extends above the surface of the water, or a physical AtoN or AIS AtoN that depicts a hazard or obstruction.

The use of 3D-FLS to supplement the echo sounder in sensing the features and characteristics of the underwater environment should be considered when transiting unsurveyed and poorly charted waters. Such systems can be used at depths to 50 meters or more at speeds to over 20 knots to detect hazards to navigation up to 1,000 meters ahead of the bow. This has been shown to provide up to 1.7 minutes advance notice of a hazard while cruising at speeds of 15 knots (Wright and Baldauf, 2015b). Human error is also a significant contributor to factors relevant to hazard assessment.

The list of capabilities and resulting hazards in table 2 has been examined to determine priorities for risk assessment, resulting in the creation of table 3. Hydrography and the subsequent navigation chart capabilities are considered high priority as these are essential tools for navigation. Direct environmental sensing and aids to navigation, although essential to navigation, are given medium priority as some degree of alternative capability is possible through human intervention if one or more of these sensors are unavailable. Indirect environmental sensing of weather, tides and

Capability	Priority
Hydrography	HIGH
Navigation Charts	HIGH
Environmental Sensing (Direct)	
- Precision Positioning and Timing (GNSS)	MEDIUM
- Sonar (Echosounder, 3D-FLS)	MEDIUM
- Radar	MEDIUM
- Automated Identification System (AIS)	MEDIUM
Aids to Navigation	MEDIUM

Table 3. Capability prioritization.

currents is not considered as these capabilities do not originate on the vessel itself but originate elsewhere, and are provided through communications links. Human factor issues are important considerations in a formal risk assessment and have not been thoroughly investigated in this preliminary assessment.

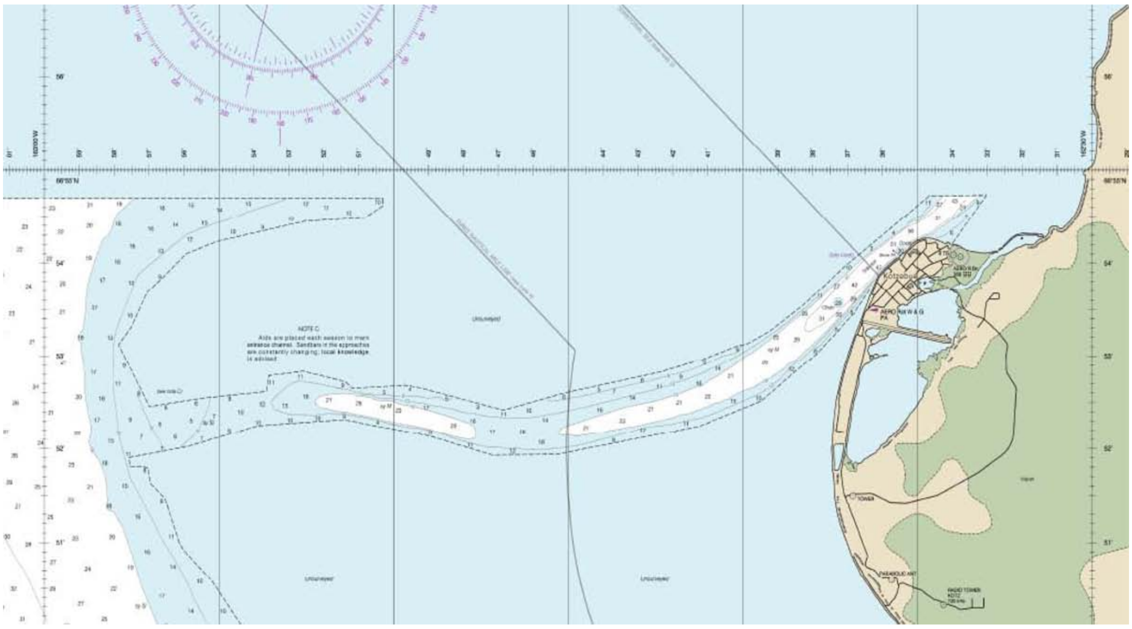
5.5.2 Risk analysis

The following vessel and barge combination was chosen as a reference case for risk modeling and as baseline for risk analysis from which generalizations may be made to other segments of the fleet:

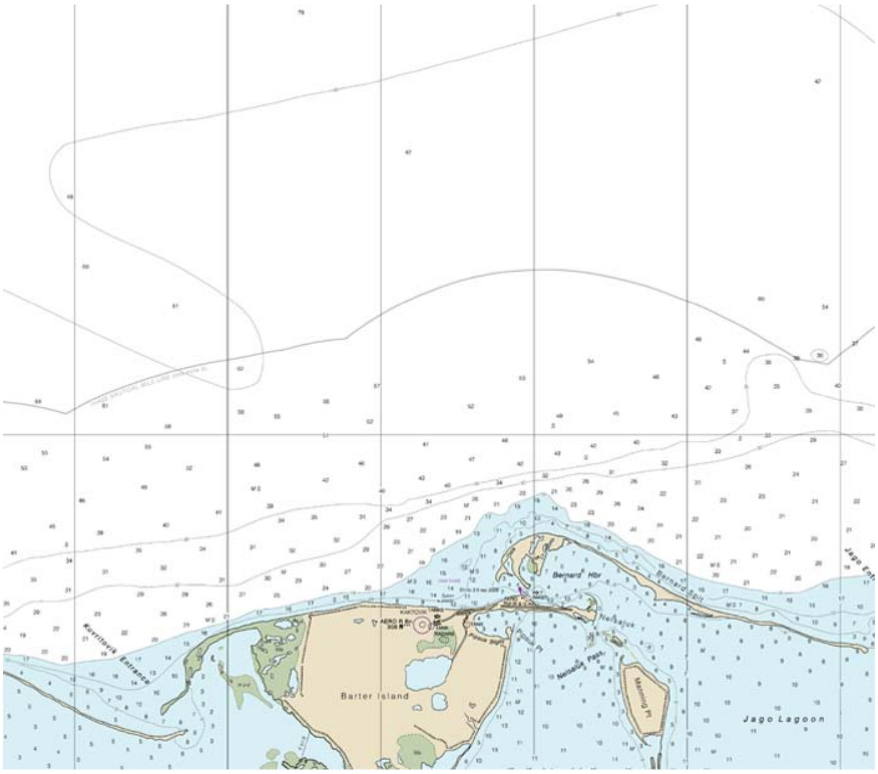
> Barge for oil: L 180ft (55m), W 52ft (15m), D 14.5ft (4.4m); 2,400 DWT LT, 1100 GRT with 12,000 bbl. capacity trading between Anchorage, Kotzebue and Kaktovik, Alaska. Push tug with engines rated at 1,350 HP total.

Vessels of this type provide home heating and diesel oil supplies to rural Alaska communities along the western and northern coasts in the spring and autumn each year (NSREP 2015). Supplies are transferred to shallow draft literage barges for local delivery.

Although the area nearby the city of Anchorage is well surveyed and charted, the areas to the north along the west coast and further around and to the east along the northern slope of Alaska are poorly surveyed, if at all, and navigation charts are poor. Proceeding north to Kotzebue only the five mile channel from clear water to the harbor is surveyed with adjacent waters shown in blue without soundings in figure 5.6. Aids to navigation are not charted at all, and are subject to being moved based upon constantly changing bottom conditions. A portion of the route between Kotzebue and Kaktovik is shown in figure 5.6a where spot and track line soundings predominate except directly along the shoreline. Such navigation chart coverage is common along the entire route. The immediate area around Kaktovik and the harbor shown in figure 5.6b is well charted, however most soundings disappear after leaving the shoreline.



(a) Channel to Kotzebue Harbor, AK (NOAA Chart 16161)



(b) Kaktovik, AK (NOAA Chart 16043)

Figure 5.6: Approaches and Harbor Charts for Kotzebue and Kaktovik, Alaska, USA.

Risk assessment using existing technology – A process for risk assessment using present technology is shown in table 4. Assessment of hydrography is made based upon the recency of survey and the coverage of the survey along the route. Where hydrographic surveys have recently been performed and absent significant storm activity, is it likely that the surveyed bottom configuration still accurately represents the present bottom configuration. As the time since the last survey becomes greater the probability of changes in the bottom increases. However, when surveys are more than 30 years old another factor comes into play in terms of the lower resolution of older sensors and technologies used to perform the survey. Multibeam sonars that provide full bottom coverage at high resolution have only come into use since the 1990's (NOS, HHS). Prior to that single-beam echo sounders were used from the 1940's to the 1980's. Earlier technologies included the wire drag survey introduced in 1904 and the leaded line survey before then.

Coverage of survey refers to comprehensiveness in the area along the route of transit. Full bottom coverage with soundings, depth contours and other topography and hydrography features are given a lower risk factor than areas where only partial full bottom exists in some areas and is absent in others. Likewise, track and spot soundings and lack of depth contours and other features warrant a higher risk factor. A navigation chart exhibiting a complete lack of soundings is given a high risk score. It is entirely possible for a navigation chart to be of the most recent version and current to the latest Notice to Mariners, yet still be entirely devoid of hydrographic information since no survey may have ever been performed in the area covered by the chart.

Table 4. Risk factors.

Capability	Risk Factor Score									
Hydrography		0		2		4		6		10
- Recency of oldest survey along route	< 1 year	☐	1-5 years	☐	6-30 years	☐	> 30 Years	☐	Never	☐
- Coverage of survey along route	Full	☐			Partial	☐	Track or Spot	☐	None	☐
Navigation Charts	Most recent, corrected to Notice to Mariners	☐							Not recent	☐
Environmental Sensing (Direct)										
- Precision Positioning and Timing (GNSS)	Operational	☐							Not Operational	☐
- Sonar (Echosounder)	Operational	☐							Not Operational	☐
- Radar	Operational	☐							Not Operational	☐
- Automated Identification System (AIS)	Operational	☐							Not Operational	☐
Aids to Navigation	Physical	☐	AIS	☐					None	☐
Total Score 0 - 7: LOW RISK			**Total Score 8 - 9: MEDIUM RISK**				**Total Score > 9: HIGH RISK**			

The assessment of environmental sensors is made on the basis of whether they are operational or not operational. As these sensors are required carriage on SOLAS vessels the only consideration given is to the increase of risk to conduct a voyage without them.

Assessment of AtoN is made on the basis of their presence along the route of transit to guide the vessel. Although physical AtoN are generally plentiful in well surveyed and well traveled areas, the Arctic has neither of these characteristics. Few physical AtoN and fewer AIS AtoN exist in and around the Arctic except possibly in the immediate vicinity of harbors during the warmer months.

Risk is evaluated by assessing each of the individual capabilities according to the criteria listed and assigning a score corresponding to these capabilities. A total score within the boundaries of low risk indicate that hydrography, navigational charts and sensor capabilities are at or near their optimal state and a voyage under these circumstances may be appropriate if all other criteria for getting underway are met. A total score in the medium risk range indicates deficiencies exist in the recency of hydrographic survey or the presence of AIS AtoN along the route. Neither of these factors may indicate that a problem exists. However, caution should be exercised during transit. A total score greater than 9 indicates a high risk voyage is possible and additional planning and preparation is needed before attempting the voyage.

Risk assessment using emerging technologies – A process for risk assessment using new technology to supplement existing technology is shown in table 5. Specific reference is made to 3D-FLS to enhance situational awareness into the environment below the waterline by providing a live rendering of the sea bottom and potential hazards to navigation that exist either afloat or within the water column. This system can provide an additional margin of safety when risk associated with a lack of current and comprehensive hydrographic survey is high, and can also provide similar data and functionality as an echo sounder, if necessary.

Further reference is made to the use of Virtual AtoN to replicate physical AtoN and AIS AtoN functions on ECDIS and provide new capabilities for displaying hazards to navigation detected by 3D-FLS that are afloat or in the water column. Capability is provided to lessen the impact of GNSS and AIS service interruptions, spoofing and denial of service attacks, and AIS aliasing resulting in misleading position information. This is accomplished through georeferencing to known bottom features and characteristics as depicted in ENC created in accordance with the IHO S-102 standard.

Table 5. Alternative risk factors with inclusion of 3D-FLS and virtual aids to navigation.

Capability	Risk Factor Score				
Hydrography	0	2	4	6	10
- Recency of oldest survey along route	< 1 year ☐	1-5 years ☐	6-30 years ☐	> 30 Years ☐	Never ☐
- Coverage of survey along route	Full ☐		Partial ☐	Track or Spot ☐	None ☐
Navigation Charts	Most recent, corrected to Notice to Mariners ☐				Not recent ☐
Environmental Sensing (Direct)					
- Precision Positioning and Timing (GNSS)	Operational ☐				Not Operational ☐
- Sonar (3D-FLS)	Operational ☐				Not Operational ☐
- Radar	Operational ☐				Not Operational ☐
- Sonar (Echosounder)	Operational ☐	Not Operational ☐			
- Automated Identification System (AIS)	Operational ☐			Not Operational ☐	
Aids to Navigation	Physical ☐	AIS or Virtual ☐	None ☐		
Total Score 0 - 7: LOW RISK	**Total Score 8 - 9: MEDIUM RISK**		**Total Score > 9: HIGH RISK**		

Risk is evaluated in the same way by assessing each of the individual capabilities according to the criteria listed and assigning a score corresponding to these capabilities. However, there is a difference in the determination of a total score by which risk assessment is made, especially as pertains to hydrography since a live rendition of the bottom configuration can now be viewed in real-time.

The modeled results indicate risk reduction as a consequence of including 3D-FLS to gain insight into the underwater environment and to overcome the limitations of hydrographic survey in areas where no or partial survey was performed, and also using obsolete technologies that provide lower resolution and coverage than modern survey methods. Redundancy in sonar equipment through the use of both an echo sounder and 3D-FLS can also serve to cross-check the performance of each individual system, providing a means to detect sub-nominal performance in either and eliminating a single point of failure that could otherwise go undetected. Further potential risk reduction is possible when an echo sounder is used for navigation through georeferencing to known bottom features and characteristics in conjunction with upgraded ENC developed in accordance with the IHO S-102 standard that supports high resolution environmental models.

5.5.3 Cost benefit assessment

Reliable statistics for grounding in poorly surveyed and inadequately charted waters are limited at best, and it would be premature to provide definitive cost-benefits analysis. However, empirical observations can serve as a starting point for discussions. Using the model barge-tugboat combination (Anchorage, Kotzebue and Kaktovik, Alaska) the cost for 3D-FLS system acquisition and installation would be approximately $200,000 U.S. Cost avoidance resulting from the prevention of one significant grounding accident in the Arctic may be on the order of several million dollars in terms of lives lost, damage to hull and equipment, loss of cargo, search and rescue, pollution remediation, salvage cost and the payment of fines and penalties. A valid comparison is the approximately $2 billion US cost for salvage of *Costa Concordia* that grounded under the exact conditions that 3D-FLS is designed to overcome.

The use of vessels of opportunity equipped with 3D-FLS to acquire high-resolution, full bottom coverage hydrography as externally sourced data for navigation chart development can be accomplished at very little relative cost on the order of hundreds of thousands of dollars US. This can be compared to the multi-million dollar cost of acquiring and operating a fleet of hydrographic survey vessels in the vast expanses of the Arctic.

Accurate costs and benefits associated with the development, implementation and deployment of Virtual AtoN are not yet available. It can be presumed that the cost of a viable virtual AtoN program for vast remote areas where physical AtoN and AIS AtoN are not practical would be far less than the alternatives of implementing existing aids strategies or having no AtoN that may result in a significant accident in the region.

5.6 Arctic Environment Preservation through Grounding Avoidance

Paper 4 describes research exploring technological innovation to contribute to substantially reducing pollution resulting from ship groundings and collisions that are often caused by human factors. The goal of this research is to significantly increase watchstander situational awareness of environmental conditions below the waterline. This goal is especially relevant to ship navigation in the Arctic which poses unique challenges requiring transit through shallow, draft-constrained coastal and archipelago waters that are relatively uncharted, lacking aids to navigation, without adequate search and rescue facilities, and teaming with surface and underwater hazards to navigation.

Under Study Area 1 the contributions of 3D-FLS were examined with regard to its capability to survey the sea bottom and to detect hazards to navigation attached to the bottom and floating in the water column to aid in Arctic navigation. Study Area 3 results considering contributions of Virtual AtoN in the Arctic are described as a means to extend AtoN services in the area. The significance of Virtual AtoN characteristics used to verify these aids are in proper position and watching properly were also examined in the context of the lack of surveys in this poorly charted environment. Human factors in terms of the potential effects of terrorism were also considered under Study Area 5. Factors relevant to the development of grounding avoidance strategies were identified and the results of human reaction times to alarms and indicators relevant to groundings using several case studies were provided.

5.7 Enhanced Situational Awareness through Multi-Sensor Integration

The development of the concept and basic functional and technological structure to support enhanced situational awareness is explained and discussed in Paper 5 from the perspective of the grounding of M/V *Costa Concordia*. Under Study Area 1 the potential contributions of 3D-FLS in alerting watchstanders of the potential for groundings are provided in a detailed examination of the final moments of the voyage just prior to grounding. Human factors considerations under Study Area 5 are also provided in terms of bridge alerts and alarm generation. Results of this study include the identification of factors where the use of simulation to accomplish testing, verification and validation to assimilate 3D-FLS into the integrated navigation system (INS) environment. This is vital to ensure systems are properly integrated and mariners are adequately trained prior to the introduction of the technology into widespread use and as IMO carriage requirements.

Chapter 6 Summary and Discussion

The aims and objectives of this dissertation as stated in chapter 2 are:

1. to investigate how safety of navigation may be enhanced in areas deficient in aids to navigation,
2. to determine the means by which infrastructure may be created to deal with these deficiencies, and
3. to establish how the implementation of this infrastructure may be accomplished in a manner that is compatible with existing and evolving standards and practices.

This chapter summarizes and discusses the results of the research performed to accomplish these aims and objectives highlighting the various outcomes achieved as well as discussing their broader implications to enhancing maritime safety.

6.1 Navigation enhancements to Arctic, tropical, under developed regions, disaster areas and war zones

The common denominator between the Arctic, tropical regions dominated by coral reefs and sensitive ecosystems, under developed regions, disaster areas and war zones is that all of these areas are or can be deficient in AtoN infrastructure in terms of beacons and buoys that are traditionally used to aid mariners in navigating their vessels. The reasons for this vary from environmental and economic conditions that prevent their adequate installation, use and maintenance; to infrastructure having been damaged or destroyed through natural and manmade occurrence. Also generally lacking in these same areas is the high-resolution bathymetry that is needed to survey the sea bottom to help determine where AtoN should be placed.

An approach was taken to enhance the safety of navigation in two steps by:

1. exploiting the capabilities of modern sensor systems that are currently available in the commercial marketplace but are not necessarily mandated as part of IMO carriage requirements for vessels under SOLAS or other regulatory accord, and
2. extending the existing IALA Virtual AtoN concept to create an entirely new type of Virtual AtoN that requires no physical infrastructure whatsoever and possesses

new characteristics and capabilities not available through any other means. These Virtual AtoN may be verified as being on station and watching properly through automated means, and can be implemented and maintained in extreme remote areas regardless of weather conditions or access limitations.

A detailed Virtual AtoN implementation framework was established that includes a definition specific to the use of this term in the context of this research, drawing distinctions between both physical AtoN and the several variations of AIS AtoN. The embodiments and essential elements comprising a Virtual AtoN are made in terms of digital apparatus and characteristics, the system(s) of Virtual AtoN that may be created, the methods to use and to verify their proper operation; and the functions, capabilities and duration of services provided. This includes the introduction of new dynamic and transient characteristics to supplement presently existing static AtoN characteristics, as well as georeferencing as a characteristic that is entirely new to AtoN.

The definition of basic symbology and a range of suggested symbols capable of being used with Virtual AtoN show great similarities in comparisons to existing AIS virtual AtoN symbols. Sample implementations of static and dynamic Virtual AtoN featuring different settings and functions in real world applications are provided for future consideration in AtoN system design. Examples illustrate the creation and functionality of solely Virtual AtoN implementations as well as possible hybrid AtoN systems consisting of the integration of a mix of physical AtoN, AIS AtoN and/or Virtual AtoN marking the same waterways.

Vessels of opportunity can transit remote areas with greater safety when equipped with 3D-FLS to acquire high-resolution hydrographic survey data that corresponds with the legal standard for coastal vessel navigation in the form of ENC data in areas that are considered to be well surveyed and charted. Information derived from detailed analysis of experimental data make the case that 3D-FLS appears capable of providing the equivalent of a hybrid of IHO Orders of Survey 1a and 1b resolution with full sea floor coverage over a predetermined swath (Wright and Zimmerman, 2015).

Discussion points include the following:

- The Virtual AtoN framework includes a small subset of possible AtoN configurations that are suitable to a limited number of real world applications. This subset may serve as a basis for future expansion into a comprehensive suite of Virtual AtoN suitable for widespread use across broad application areas.
- Evidence is provided of measurement accuracy and repeatability to acceptable tolerances when compared to ENC soundings. Systematic errors were considered in terms of horizontal and vertical uncertainty and other factors such as vertical offset between the sonar transducer and the water's surface, roll/pitch error, track error, tide adjustments, effect of GPS Wide Area Augmentation System (WAAS) and estimated positioning error (EPE) in determining adjusted 3D-FLS depths. No evidence was detected of spurious errors or random errors introduced through human or other causes.
- Evidence is provided of measurement accuracy and repeatability to acceptable tolerances for use in georeferencing direct to ENC data originating from 3D-FLS. Differences in depth values caused by tide variation between predicted and actual as well as between actual and mean lower low water as depicted in ENC were considered a systematic error represented as a constant in direct measurements, and are not present in derivative measurements for change in bottom slope and rate of change in bottom slope. No evidence was detected of spurious errors or random errors introduced through human or other causes.
- In all cases of 3D-FLS and single beam echo sounder measurements the speed of sound through the water were not measured, further contributing towards systematic error. One attempt to overcome this limitation is through the use of a normalized sound velocity of 1500 m/s recommended to the CSBWG for consideration at the second meeting of this group (Olex, 2016).

6.2 Innovation and invention in ship operations

There are two areas of innovation and invention in ship operations that pertain to the research results described in this dissertation. The first has to do with expanding watchstander situational awareness by providing direct insight in real time into the environment below the waterline and ahead of the vessel to enhance the ability to detect hazards to navigation and respond accordingly to avert these hazards. The second involves the introduction of new concepts in navigation through the introduction of the Virtual AtoN and the additional capabilities they are able to provide. This also includes the ability of ships to serve as vessels of opportunity to acquire and disseminate to competent national authorities both hydrography data and Virtual AtoN verification results.

Voyages by vessels of all tonnages are presently conducted with an appalling lack of situational awareness regarding the physical configuration of the sea bed forward of the bow. Indeed, the only direct knowledge of water depth available to the watchstander is typically in the form of a two or three digit number provided by an echo sounder measuring the distance between the keel and the bottom at some point that is likely amidships or astern, oftentimes hundreds of meters aft of the bow. The irony of this situation is that the bow may be firmly grounded on a ledge while the echo sounder may still be reporting hundreds of meters depth below the keel. All other information sources by which a watchstander may ascertain water depths are through indirect means by the use of a navigation chart created at some time in the past based upon an even earlier hydrographic survey that may have been performed years or even centuries before. Another source of relatively recent data that can be used for voyage planning and execution is the Notice to Mariners. However, this source also suffers the same latency problem as all other indirect sources.

Historically, AtoN are the means by which this problem has been solved. Their placement along the boundaries of channels and routes known to be safe for navigation, and their marking of hazards to navigation to warn mariners of peril have for centuries greatly contributed to enhance the safety of navigation. However, AtoN do not exist in the Arctic and other remote regions, and are not likely to be introduced anytime in the near future due to lack of hydrographic surveys, the harsh environment, budgetary constraints and numerous other reasons.

One approach has been demonstrated in assessing potential vulnerabilities and risk through the identification of hazards likely to be encountered in vessel operations in the Arctic based upon existing SOLAS equipment carriage requirements. This can prompt a reduction of potential vulnerabilities and the lowering of risk that may occur through the introduction and proper use of the environmental sensing capabilities of 3D-FLS onto the bridge are also described.

New capabilities have been created to assess vulnerabilities in Arctic transits through the examination of risk, providing tools for voyage planning. The ability to determine the amount of time provided to crewmembers to accomplish avoidance procedures has been demonstrated in response from the detection of hazards to navigation on the sea floor using 3D-FLS and the generation of Virtual AtoN with transient characteristics. Further definition of these capabilities was accomplished through the performance of several vessel grounding scenarios as a follow-up to the detailed analysis of the grounding of Costa Concordia.

Discussion points include the following:

- The potential to achieve "ship centricity" has been demonstrated by providing watchstanders on the bridge with direct visibility into the underwater environment using 3D-FLS. This new capability supplements the direct method of assessing the sea bottom by identifying depth contours using an echo sounder, and indirect methods of assessing the sea bottom through existing means such as navigation charts and Notice to Mariners. Integration into existing navigation systems is possible through ECDIS.
- Further demonstrated is the ability of 3D-FLS to detect the presence of hazards to navigation both affixed to the bottom and suspended in the water column. Detection of such hazards can spur the generation of Virtual AtoN with static or dynamic characteristics for display on ECDIS upon examination and direction by competent national authority. Also, in-water hazards likely to exist for a relatively short period of time such as may be caused by buoys adrift, growlers, large timber or other objects can spur the creation of Virtual AtoN with characteristics that are

momentary in nature for display on ECDIS. Such capabilities can provide mariners with the capability to be proactive in their approach to navigation in reducing groundings by providing specific guidance as to the actual bottom configuration rather than what is believed to be the bottom configuration based upon navigation chart data. The degree to which capability is effective to guide mariners in avoiding groundings is yet to be studied.

- Assessment of risk has been accomplished from the perspective of having the advantages of new 3D-FLS capabilities for the bridge watch in providing an additional margin of safety as opposed to not having such capabilities as is currently the case in vessel navigation in poorly surveyed and charted waters. This approach can form the foundation for future statistical analysis to assist in predicting accidents based upon extrapolating vessel traffic and accident statistics of the region. However, there does not yet exist a database of significance related to vessel traffic due to the occasional and infrequent passage of vessels through such areas. Moreover, the application of accident statistics obtained from sources world-wide is not appropriate as the data is derived from a wide variety of vessels under varying circumstances that cannot readily be extended to Arctic traffic and navigation conditions.
- The concept of using shipboard equipment assets to capture large volumes of hydrographic data obtained using 3D-FLS was introduced. However, it is emphasized that any such innovation in ship operations must be accomplished without interference with existing crew responsibilities or adding to crew workload.
- Initial checklists created to assist in assessing vulnerabilities in overall capabilities required for planning Arctic voyages and resulting risk can provide a basis for considering 3D-FLS as an IMO carriage requirement.

6.3 Verification of Virtual AtoN watching properly

Determining that AtoN are on station in their correct position, and watching properly in best waters and showing proper characteristics is an essential part of the overall AtoN verification process. This is accomplished through comparison between AtoN position and characteristics on navigation charts, AtoN description as represented in the Light List and supplemental information contained in Notices to Mariners.

The capability for hydrographic data provided by 3D-FLS when compared with single beam echo sounder data to detect differences in the sea floor has been demonstrated that are indicative of Virtual AtoN being on station and watching properly based upon matching topography signatures between actual course taken and charted course. This confirms georeferencing capabilities to detect Virtual AtoN improperly watching or not watching in best waters as a result of differences in topography signatures between actual course taken and charted course.

Virtual AtoN verification has also been demonstrated to automatically, and in real time, correlate vessel positioning information to the physical environment in helping to verify Virtual AtoN as being on station and watching properly. This is a new capability not previously available to vessels. The only existing scenario that is similar is a AIS virtual AtoN that may be broadcasting to a geographic position. However, in this case it is incumbent upon the watchstander to determine whether the AIS virtual AtoN is incorrect. 3D-FLS use in hydrographic survey as independently sourced data illustrates the potential use of vessels of opportunity to perform this role.

A new process for deployed Virtual AtoN as well as the validation process throughout the entire Virtual AtoN life cycle considers the integrity of Virtual AtoN data as may be represented in complementary databases residing at both hydrographic and AtoN authorities. It also includes automation of much of this part of the verification process.

Discussion points include the following:

- The methods and processes identified for Virtual AtoN verification are based upon existing AtoN verification methods and are intended to work cohesively with physical and AIS AtoN verification.
- The automation of Virtual AtoN verification may also be accomplished with physical and AIS AtoN with the adoption of IHO S-102 Bathymetric Surface Product Specification.

6.4 Contributions to environmental protection and preservation

One of the essential outcomes of this research is the protection and preservation of fragile ecosystems as exist in the Arctic and tropical regions in areas of coral reefs and other critical habitat. The dynamic characteristics of Virtual AtoN may now be applied to rapidly designate no-entry and restricted entry zones around wildlife protection areas and refuges. This same concept can be applied to no-fishing and other areas on a daily to seasonal basis. The potential for reduction in unintentional groundings has also been demonstrated with potential benefits in significant reductions in loss of life, vessel and cargos; and pollution with the subsequent fouling of the environment and loss of wildlife. This includes Virtual AtoN verification providing a means to help ensure Virtual AtoN are on station and watching properly and to reduce the chance of accident resulting from AtoN failure. Sensor fusion technologies also illustrate additional aspects of grounding avoidance and possibly the detection of other hazards to navigation for which Virtual AtoN with momentary duration may be created to alert watchstanders to their presence.

Discussion points include the following:

- Analysis of groundings accidents resulted in the identification of critical elements in the timing and unfolding of events. One of the factors considered, Watchstander Response Time (to a grounding alarm), was selected at 5 seconds after initiation of warning. Even with the quadrupling of response time to 20 seconds and a resulting reduction in time to grounding of approximately 10% from 2.1 minutes to 1.9 minutes, significant time remained to effect corrective action to avert or lessen the consequences of grounding

- Vulnerability assessment and risk analysis was performed at three levels:
    - Organizational level (e.g., cognizant national authority, shipping company)
    - Workplace level (on the vessel itself), and
    - Personal level (e.g., captain, watchstander)

  Analyzing causal factors between these levels revealed the sequential relationships that may potentially result in accident. A key element was indicated to be the lack of primary shipboard capabilities including sensors and other resources available to thwart mishap when lacking outside, secondary resources such as accurate navigation charts in well-surveyed environments and Notices to Mariners.

6.5 Virtual AtoN implications on human factors and training

Extensive measures have been taken to ensure Virtual AtoN conform to existing standards and training conventions whenever possible. The use of existing ECDIS symbology with minor modification may be accomplished to indicate the virtual nature of the AtoN. The only exceptions are in cases of new dynamic capabilities and momentary duration not available with existing AtoN. Likewise, the use of standard ECDIS symbology has been stressed in depicting hazards to navigation detected while making way.

Discussion points include the following:

- Analysis of fatigue risks in the shipping industry often point to workload redistribution as a means to reduce errors and incidents as part of a fatigue risk management system (TNO, 2008). However, redistributing additional workload on an already overburdened crew is not a satisfactory solution especially in light of ever-increasing STCW requirements. The approach taken in this research focuses on the display of 3D-FLS information and resulting Virtual AtoN targets using existing ECDIS display requirements and symbology. This eliminates the need for an additional display monitor dedicated to 3D-FLS on the bridge, as well as the need for additional crewmember training in its use.

6.6 Regulatory contributions to Virtual AtoN establishment

The focus of this research has been primarily aimed at national authorities cognizant of AtoN and hydrography, although authorities that pertain to environmental protection, fish and wildlife preservation and other related jurisdictions are also appropriate. It is these national authorities that comprise the membership of the larger, international organizations that establish industry standards and practices in these related disciplines.

An example is the Coast Guard who is responsible for AtoN within the United States, and who is the U.S. representative to the International Maritime Organization.

Likewise, the National Oceanic and Atmospheric Administration is responsible for hydrography and chartmaking, and is the U.S. representative to the International Hydrographic Organization. There are in addition, many non-Governmental and industry organizations that are relevant to these issues. All such national organizations are instrumental to setting the agenda at the various general and committee meetings of the umbrella international organizations at which issues of vital concern are discussed and decisions are made as to their disposition and solution.

Discussed throughout this research is the importance of working within the confines of existing standards and recommendations that are established by these organizations, a short summary of those referenced within this dissertation include:

- International Convention for the Safety of Life at Sea - SOLAS. (IMO)
- International Code for Ships Operating in Polar Waters - the Polar Code. (IMO)
- S-44. Standards for Hydrographic Surveys. (IHO)
- S-52. Specifications for Chart Content and Display Aspects of ECDIS. (IHO)
- S-100. Universal Hydrographic data Model. (IHO)
- S-102. Geospatial Standard for Hydrographic Data. (IHO)
- Aids to Navigation Manual - Administration. (USCG)
- NOS Hydrographic Surveys Specifications and Deliverables. (NOAA)
- United States Chart No. 1; Symbols, Abbreviations and Terms used on Paper and Electronic Navigational Charts. (NOAA)
- Guideline 1062, On the Establishment of AIS as an Aid to Navigation. (IALA)
- Guideline 1081, On Virtual Aids to Navigation. (IALA)
- Aids to Navigation Manual. (IALA)

The concepts of 3D-FLS and Virtual AtoN are not addressed in any of these documents other than IALA 1081 that defines the concept of a Virtual AtoN but provides no guidance regarding implementation. The initiative to address such issues must originate from the national organizations which rely upon and take action based on the inputs, advice and needs of their constituents. Coalitions between member states must act together to effect changes to carriage requirements, equipment standards and to make meaningful changes in these areas.

6.7 Broader implications of these research results

Several of the key outcomes of this research are discussed in the following paragraphs.

6.7.1 Virtual aids to navigation

Virtual Aids to Navigation are conceptually foreign to the mariner, who traditionally have relied on physical AtoN to provide much of the guidance needed for safe navigation. The potential configurations of Virtual AtoN and AtoN systems, alone and in combination with physical and AIS AtoN discussed in this dissertation provide a glimpse as to the possibilities associated with their adoption and use. However, these are just a small sampling of the true capabilities such aids may possess and of the services they will be able to provide in the future. These services include those provided directly to the mariner in terms of navigational guidance, as well as data feeds associated with the autonomous verification of Virtual AtoN communicated from the vessels to national AtoN authorities.

6.7.2 Greater automation in shipping

An obvious application for which Virtual AtoN are well suited includes providing navigational guidance to the operators of present day vessels to vessels using increasing levels of automation in the future. Being that the operators themselves are providing virtual control and direction to the vessel in an artificial reality setting, it stands to reason that there is no reason or requirement for physical AtoN associated with the operation of highly automated or even autonomous vessels. Such vessels are expected to transit amongst physical and AIS AtoN in coastal and harbor areas that are used for navigation by all vessels. However, the concept of Virtual Private AtoN (PAtoN) can come into play for proprietary use by only the shipping companies involved. Processes similar to those currently used by national authorities for PAtoN provisioning and deployment can be adapted for Virtual PAtoN. The advantages of such an approach include the ability to provision literally hundreds to thousands of Virtual PAtoN systems worldwide tailored to the needs of individual vessels and shipping companies, and to which only those vessels and companies have access. This approach alleviates the crowding of harbors and waterways with multiple beacons and buoys, yet fulfills the exact requirements of large numbers of vessels and company, government and tactical military operations.

6.7.3 3-dimensional forward looking navigation sonar

The use of 3D-FLS should not be limited to remote and unsurveyed locations, but should be encouraged for use by vessels of all sizes for routine operations worldwide. The capability to provide increased situational awareness below the waterline ahead of the vessel should not be overlooked, and it is incumbent upon the masters of all such vessels to be knowledgeable of all aspects of the environment through which they pass throughout voyage planning and execution. The examples are legion of vessel groundings resulting from physical changes that occur due to storms and the natural movement of sand and sediment due to currents in well dredged and charted inlets, channels and passes. One notable example is the shoreline of New Jersey and the entire New York metropolitan region in the U.S. where, as a result of Hurricane Sandy in October 2012, a new inlet was created by storm action and wind and waves altered the shoreline and sea floor (NOAA, 2014). By November 2012 NOAA's rapid response teams had many survey assets on the water in response to this storm (NCS, 2014). NOAA was funded in 2013 to begin the task of redoing the coastal elevation models for the entire area. During the interim period, many vessels passed along the coast with little direct knowledge of the sea floor topography and the hazards to navigation that included buildings, vehicles and debris washed into the sea that existed in their path other than the two or three-digit depth indication provided by the echo sounder.

6.7.4 Crowd sourcing of hydrographic data

Rear Admiral G. S. Ritchie, the President of the Directing Committee of the International Hydrographic Bureau, in his paper noted three possible technical revolutions in hydrography with the introduction of these advances (Ritchie, 1982):

1. Echo-sounding after World War I,
2. Electronic positioning after World War II, and
3. Multibeam swath sounding in the 1960s

The fourth possible technical revolution may very well entail the introduction of crowd-sourcing techniques involving the use of many hundreds to thousands of vessels of opportunity equipped with a variety of equipment ranging from simple echo sounders, multibeam echo sounders and 3D-FLS in an unprecedented attempt to document the vast expanses of the world's oceans, seas and littoral waters. Such an approach may bear the greatest fruit in the Arctic. Vessel traffic is increasing in the region in synchronization with the introduction of 3D-FLS to aid vessels in safely navigating poorly charted waters. The establishment of crowd-sourcing initiatives such as the IHO CSBWG also has the potential to capture and make use of this high-resolution data to supplement official hydrographic surveys and aid in chart making. The future availability of broadband Internet access worldwide, including the Arctic using terrestrial and satellite services will accelerate the transfer of terabytes of data for use in this effort.

There are three challenges that must be addressed in the future to devise an effective solution to this issue:

- Equipping a fleet of vessels of opportunity with sufficient size and range to provide significant and useful data collections. This may be accomplished through joint industry, government and IMO initiatives to enhance safety of navigation by encouraging the installation and use of 3D-FLS navigation sonars in remote and poorly charted regions.
- The distribution of extremely large volumes of data from remote data gathering sources to crowd sourced data processing destinations. Several commercial firms that include Google (Mountain View, CA, USA) OneWeb (Arlington, VA USA) SpaceX (Hawthorne, CA USA) and Societe Europeenne des Satellites (SES, Luxemborg) have initiated projects dedicated to providing worldwide broadband Internet access within the next several years.
- Data reliability and validity checking to ensure correctness. Large scale and big data analytics utilizing trusted source criteria in conjunction with IHO data quality monitoring functions will be needed to ensure data quality assurance. Issues

pertaining to the user of tide and sound speed uncertainties in determining TVU must still be addressed.

Chapter 7 Conclusions

7.1 Findings

The findings of this research indicate the following:

- A means to provision Virtual AtoN without requiring any corresponding physical presence to remote locations and hostile environments has been created that can overcome the limitations of physical AtoN, and is verifiable as being in a state of "watching properly" as determined by being in its assigned position and exhibiting the correct characteristics. This is a new navigational capability which presently does not exist in the maritime domain that can provide greatly needed infrastructure in the Arctic as well as in remote tropical regions where the placement of sinkers to moor physical AtoN is hampered by live coral reefs. Furthermore, the method created to verify Virtual AtoN provides resilience to GNSS and AIS spoofing and denial of service attacks to which existing physical and AIS virtual AtoN are susceptible.
- The initial version of a Virtual AtoN resulting from this research provides a foundation for experimental implementations in a suitable environment that may be developed, tested and evaluated for mariner use.
- Further findings indicate that, given proper hydrographic survey, the provisioning of Virtual AtoN may be accomplished alone, or in combination with physical AtoN and/or AIS AtoN to mark waterways and increase the safety of navigation where AtoN do not presently exist.
- 3D-FLS can accurately, repeatedly and at high resolution perform measurements over the sea floor that approximate soundings as represented in ENC data that is the legal standard for coastal vessel navigation.
- The hydrographic information provided by 3D-FLS appears to be of sufficient resolution and accuracy to facilitate Virtual AtoN verification of position and watching in best waters determination. This finding makes it possible to accomplish this on an automated basis by all vessels using ENC and equipped with an echo sounder during the normal course of operation. Such a capability has

significant implications in terms of the design of integrated navigation systems in terms of the implementation of new alarms, the criteria by which these alarms are activated and the training of crewmembers in how to react and what procedures are to be followed in the event of alarm activation.

A means to report such information to competent national authority responsible for action in resolving deficiencies in Virtual AtoN deployment must be developed.

- A method to assess the viability of large-scale 3D-FLS data collection from vessels of opportunity as a means to supplement responsible authority resources in the crowdsourcing of hydrographic data for survey and the development of navigation charts was created.
- Capabilities to detect hazards to navigation suspended within the water column that are not attached to the bottom were evidenced by 3D-FLS detection of buoys in open water.
- Virtual AtoN can provide new capabilities to actively, rapidly and dynamically designate areas and zones to protect specific environmental habitat and wildlife populations and that can be displayed to mariners on ECDIS.
- The capability to passively utilize Virtual AtoN capabilities and automated processes without requiring crewmember intervention or increasing crew workload can further enhance environmental protection and preservation.
- Coordination between national authorities for fish and wildlife preservation, park services, hydrography and AtoN are essential to secure the greatest benefit from Virtual AtoN capabilities described.
- The reduction of risk in the world's frontier is greatly enhanced through introduction of new technologies to pioneer innovative approaches towards enhancing Arctic infrastructure. The use of 3D-FLS and Virtual AtoN are two technologies for which the Arctic is perfectly suited as a laboratory and testbed.

7.2 Recommendations to stakeholders

- The concept of truly virtual aids to navigation that require no physical infrastructure is unique and unorthodox in many respects. National authorities must retain cognizance over AtoN system design and provisioning processes, yet the real-time nature of Virtual AtoN of momentary duration is not amenable to the long timeframes that presently exist in the AtoN development life cycle. Further research and prototype implementations are required to adequately test and ensure all aspects of Virtual AtoN in their described implementations are verifiable and supportable. Additional research is required to integrate Virtual AtoN into existing AtoN development and provisioning systems.

- The International Code for Ships Operating in Polar Waters (the Polar Code) should reconsider their rejection of mandating use of forward-looking sonar and amend to specify 3D-FLS as a mandatory carriage requirement for vessels while sailing in Arctic waters (IMO SDC 1). Absent this, acknowledgment of 3D-FLS as the preferred implementation of the requirement for a second echo sounder as currently specified in the Code (MSC.385(94)).

- Further research is required to conclusively determine the usefulness, effectiveness and limitations of 3D-FLS as an independent source of hydrographic data as compared to multibeam sonar.

- Coordination must exist between national hydrographic and AtoN authorities. Post-processing of data to enhance 3D-FLS measurement accuracy by integrating speed of sound and other factors need to be thoroughly investigated, along with new sensor designs for sound speed measurement that may be integrated with 3D-FLS systems. The timing and evolution of new hydrographic standards by which ENC are created is well aligned with innovation in georeferencing techniques by which navigation may be accomplished, and the performance of navigation systems may be verified. Finally, the development of new tools by which mariners can determine the depths of water ahead of the bow to fulfill requirements to maintain an effective watch can also serve to improve self-reliance in this demanding environment.

- The IMO eNavigation initiative, and any follow-on initiatives, should provide for a means to integrate new technologies beyond those currently pursued for consideration as part of their inquiries.

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Appendix 1: Appended Papers

Paper 1 – Wright, R.G. and Baldauf, M. (2016) 'Virtual Electronic Aids to Navigation for Remote and Ecologically Sensitive Regions', *Journal of Navigation*, 1–17. DOI: 10.1017/S0373463316000527.

Paper 2 – Wright R.G., Baldauf M. (2016) 'Correlation of Virtual Aids to Navigation to the Physical Environment'. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, Vol. 10, No. 2, 287-299, DOI: 10.12716/1001.10.02.11

Paper 3 – Wright R.G., Baldauf, M. (2016) 'Hydrographic Survey in Remote Regions: Using Vessels of Opportunity Equipped with 3-dimensional Forward-Looking Sonar'. *Journal of Marine Geodesy*. Vol. 39, No. 6, 439-357. DOI 10.1080/ 01490419.2016.1245266

Paper 4 – Wright R.G., Baldauf, M. (2016) Arctic Environmental Preservation through Grounding Avoidance, *Sustainable Shipping in a Changing Arctic Environment*, L.P. Hildebrand & L.W. Brigham, editors. Springer International Publishing, AG, Cham. London. *Submitted, undergoing peer review.*

Paper 5 – Wright R.G., Baldauf M. (2014) 'Enhanced Situational Awareness through Muli-Sensor Integration', in *Proc. 18th International Navigation Simulator Lecturers' Conference (INSLC 18)*, Buzzards Bay, Massachusetts USA, 40-59. ISBN 978-0-692-29012-5.

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Virtual Electronic Aids to Navigation for Remote and Ecologically Sensitive Regions

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Vessel traffic in the Arctic is expanding in volume both within and transiting the region, yet the infrastructure necessary to support modern ship navigation is lacking. This includes aids to navigation such as buoys and beacons that can be difficult to place and maintain in this hostile environment that stretches across vast distances. The results of research are described which determine whether virtual electronic Aids to Navigation (eAtoN) existing entirely as digital information objects can overcome the practical limitations of physical aids to navigation (AtoN) and Automatic Identification System (AIS) radio eAtoN. Capabilities unique to virtual eAtoN that are not available using either physical or AIS radio technologies are also examined including dynamic and real time properties and immunity to Global Navigation Satellite System (GNSS) and AIS spoofing, aliasing, denial of service attacks and service outages. Conclusions are provided describing potential methods of deployment based upon similar concepts already in use.

KEYWORDS

1. Charting. 2. ECDIS. 3. Navigation. 4. Ship. 5. SONAR.

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1. INTRODUCTION. The seascape is changing in terms of beacons used as short range Aids to Navigation (AtoN) to provide regulatory guidance and information to vessels. Their traditional role to help navigators determine their position, follow a safe course and avoid dangers and obstructions remains unchanged. However, the methods used for implementation and presentation to navigators and watchstanders on the bridges of vessels are evolving and expanding using new technologies. The results are a wider range of more capable AtoN that can now be deployed in more locations to supplement existing AtoN, as well as to regions where environmental factors and remoteness have in the past prevented AtoN use. Instrumental to this change is the concept of virtual electronic AtoN (eAtoN) presently implemented using Automatic Identification System (AIS) radio technology viewable on the bridge where eAtoN can be projected to locations where no physical AtoN exists. These may also be

included within Electronic Navigation Charts (ENC) and displayed using Electronic Chart Display and Information Systems (ECDIS).

The nature and outcome of new research is described focusing on the creation of truly virtual eAtoN that require no physical infrastructure whatsoever and are intended for use where physical AtoN and AIS eAtoN are impractical. This includes the Arctic where ice can hole and sweep away buoys from their intended locations, the tropics where sinkers cannot be placed on ecologically sensitive coral reefs, and other areas where navigational infrastructure does not exist or has been destroyed due to war or natural disaster. This concept is more than simply placing a symbol on a chart as it includes high-resolution hydrographic and geospatial data correlation of the physical environment to virtual eAtoN characteristics essential to their operation. This physical data is also used to verify eAtoN are watching properly, defined by the US Coast Guard as, "an aid to navigation on its assigned position exhibiting the advertised characteristics in all respects" (USCG, 2005a). The described implementation can overcome many vulnerabilities of Global Navigation Satellite Systems (GNSS) and AIS, technologies essential to modern vessel navigation.

2. JUSTIFICATION FOR VIRTUAL eAtoN.

A marine AtoN is a device or system external to vessels that is designed and operated to enhance the safe and efficient navigation of vessels and/or vessel traffic (IALA, 2014a). There are limitations to the present AtoN system that impede expansion to geographic regions which are experiencing significant growth in marine traffic yet are highly remote and ecologically fragile. In the United States this includes thousands of square miles in the Arctic encompassing the northern slope of Alaska, the Aleutian Islands, tropical regions spanning the Hawaiian Islands to Midway Atoll and other US territories. Figure 1 (a) illustrates the volume and transit patterns of vessel traffic along a portion of Alaska's northern slope based upon ships using AIS to transmit their position and other information (NOAA, 2015). These same areas are poorly charted, if they are charted at all. According to the US National Oceanographic and Atmospheric Administration (NOAA), the Arctic is severely deficient in many capabilities extended to the rest of the nation and large gaps exist in the information it does have illustrated by empty white space on nautical charts of the region (NOAA, 2011; 2013). This is shown in Figure 1(b) where empty white space is interrupted occasionally by track lines and spot soundings that are often many miles apart.

The scale of these charts is 1:700,000, therefore the soundings appear inordinately large compared to the actual geographic areas represented. According to the U.S. Coast Guard, a situation to be avoided unless specifically warranted by unusual circumstances is the establishment of AtoN in areas not properly charted or where they would invite the inexperienced to attempt a passage which would still be dangerous in spite of the AtoN (USCG, 2005b). The phrase "unusual circumstances" can be applied directly to the Arctic, where vessel traffic is increasing and traditional AtoN systems are inadequate and not practical. Virtual eAtoN can overcome many limitations that afflict physical AtoN and AIS eAtoN in these remote and harsh locations. A significant need can be fulfilled using eAtoN for vessels to transit safely and efficiently and avoid unintentional groundings, obstructions and hazards to navigation. The problem of hydrographic survey insufficiency in much of the region can be solved using 3-Dimensional Forward Looking Sonar (3D-FLS) to assist vessels of

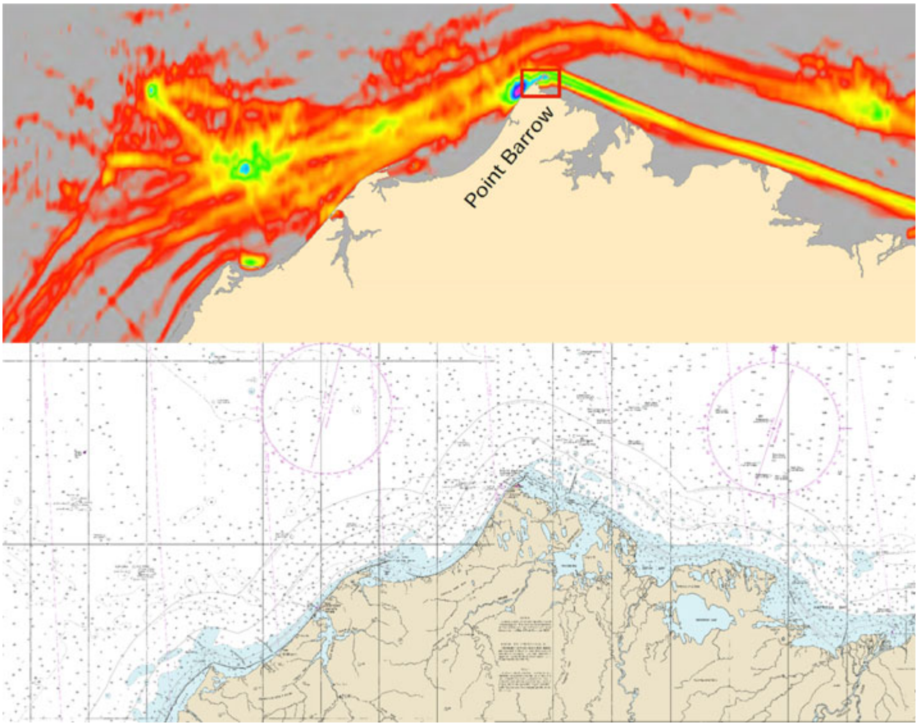

Figure 1. Comparison of AIS tracking of vessel volume and transit routes to official nautical charts of the northern slope of Alaska, US.(a) (top) AIS vessel tracking across the Chuckchi and Beaufort Seas. (source: NOAA, 2015). (b) (bottom) Mosaic of NOAA nautical charts 16004 and 16005 illustrating large areas of unsurveyed bottom.

opportunity to safely navigate uncharted waters while simultaneously capturing high-resolution, full bottom coverage swaths of sonar data that can assist in the development of nautical charts.

3. AIDS TO NAVIGATION: AN OVERVIEW.

AtoN systems are intended to facilitate safe and efficient movement of vessels through a waterway. Their responsible provisioning requires that systems be designed to meet the minimum requirements for safe and expeditious navigation through special waters in accordance with the type and volume of traffic and the degree of risk. Requirements will change due to revised circumstances, the introduction of new technologies and increased demands by crews, vessels and operations. The means to fulfill new requirements must also change through the use of modern techniques, new tools and implementation methodologies in the analysis of sites, needs, simulation, and operations. In assessing modern AtoN system requirements, three primary elements illustrated in Figure 2 must be considered in terms of system functions, capabilities and the duration of the services provided by AtoN.

3.1. *Functions.* The traditional functions accorded to mariners by AtoN have been manifest as physical beacons and buoys whose functions based upon colour,

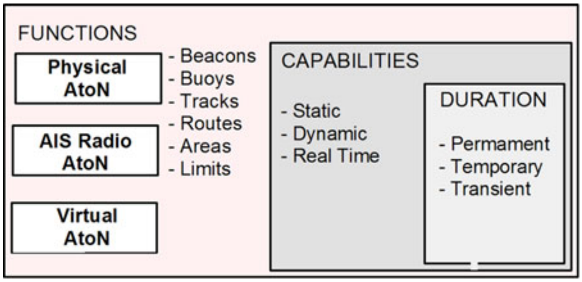

Figure 2. Aids to Navigation (AtoN) elements pertinent to safety of navigation.

shape, topmarks and other characteristics have explicit meaning in the context of their use. Their placement within an overall AtoN system is used to denote tracks, routes, areas and limits implemented across the entire waterway using a systematic approach. Emulation of these same functions can be accomplished using AIS radio-based eAtoN and virtual eAtoN to supplement physical AtoN. They may also be used in their stead when the deployment of physical AtoN or AIS eAtoN is difficult or impossible. However, both AIS and virtual eAtoN can provide additional capability to facilitate the electronic display of lines and symbols that represent areas, routes, tracks and limits directly on ECDIS without having to emulate the physical AtoN that are typically used to denote these functions.

3.2. *Capabilities.* Historically the capabilities for implementing AtoN functions have been viewed from a static point of view where, upon completion of a waterway design, physical AtoN are deployed to required locations. The ability to provide dynamic AtoN capabilities where their characteristics can change based upon a function of time and other factors has only recently been accomplished using AIS radio-based eAtoN broadcasting area special messages. One example is their use to broadcast race boundary lines that appear on spectators' electronic charts marking a safety zone during the 2013 America's Cup races in San Francisco (Queeney, 2013). Exploration of AIS dynamic operational information from both ship and shore installations can lead to further enhancement of AIS eAtoN capabilities. Real time reporting capabilities are inherent in the design of physical AtoN by virtue of their presence in the environment at the time they are viewed. Similar capabilities can exist using AIS eAtoN to report the position of sensor arrays and other tows. Virtual eAtoN can also be used to display in real time underwater hazards to navigation detected using 3D-FLS.

3.3. *Duration.* The use of physical beacons and marks continues to be the preferred method of physical AtoN deployment for channels, routes and other locations. Changes are made primarily resulting from experience and maintenance issues as they arise and not based upon new design and implementation methods. AIS eAtoN can also be used to permanently mark features that are difficult to mark using physical AtoN such as the Isolated Danger mark located on Tarapunga Rock in Doubtful Sound near the South Island of New Zealand (Marinetraffic VIRT, 2016). Virtual eAtoN can also perform the temporary marking of wrecks and other features in addition to marking transient features that have very short or momentary significance such as a shipping container that is adrift, growler or whale directly in the path of the vessel.

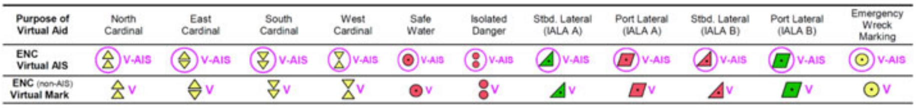

Figure 3. Present AIS virtual eAtoN symbols with suggested non-AIS virtual eAtoN symbols.

4. eAtoN IMPLEMENTATIONS. A beacon is defined by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) as "a fixed artificial navigation mark" that can be recognised by its shape, colour, pattern, topmark or light character, or a combination of these (IALA, 2014b). Beacons are realised in the IALA Maritime Buoyage System (MBS) using piles or buoys as Lateral Marks, Cardinal Marks, Isolated Danger Marks, Safe Water Marks, Emergency Wreck Marking Buoys and Other Marks (IALA, 2014c). They are used to mark a landfall position, obstruction, danger or area; indicate lateral limits of a channel and navigable waterway and turning points or junctions, bearings or lines of position. The methods described using the IALA Region B MBS applicable to the Americas, Japan, Korea and the Philippines also apply to the IALA Region A MBS (IALA, 2014d).

4.1. *AIS eAtoN.* The eAtoN concept has recently been introduced using AIS radio technology to emulate the characteristics of physical AtoN using their electronic equivalents. Their capabilities for rapid deployment and update have proved very useful in operational situations. AIS eAtoN may or may not be present at the deployed location, depending upon their method of implementation which includes the following (IALA, 2008):

- Real: AIS signal broadcasts originate from a physical AtoN,
- Synthetic: AIS signals originate from a remote AIS base station and are broadcast to a location where a physical AtoN exists, and
- Virtual: AIS signals originate from a remote AIS base station and are broadcast to a location where no physical AtoN exists.

Infrastructure to support Very High Frequency (VHF) transmitters, receivers, power and health monitoring must be present at a suitable location in the local environment within line-of-sight to the AIS eAtoN deployment location due to radio range limitations. This requirement for physical infrastructure limits their deployment to accessible regions where personnel and vessels to support the installation and maintenance of these aids are available. Hundreds of locations exist worldwide where AIS eAtoN are currently deployed, with the vast majority being Real and Synthetic aids. Their capability to emulate physical AtoN can support new functionality that is not possible with physical AtoN. Using the symbols shown in Figure 3 charts currently produced by NOAA with AIS eAtoN present within ENC are displayed on ECDIS (NOAA, 2013b). A second line in this table has been added to suggest possible symbols for (non-AIS) virtual AtoN display on ECDIS omitting the magenta radio station circle and text for AIS. Not all systems are presently equipped to display many of the symbols currently identified for ECDIS use. Introduction of an extended symbol set into new ECDIS systems will begin in 2017 and continue after this date for older

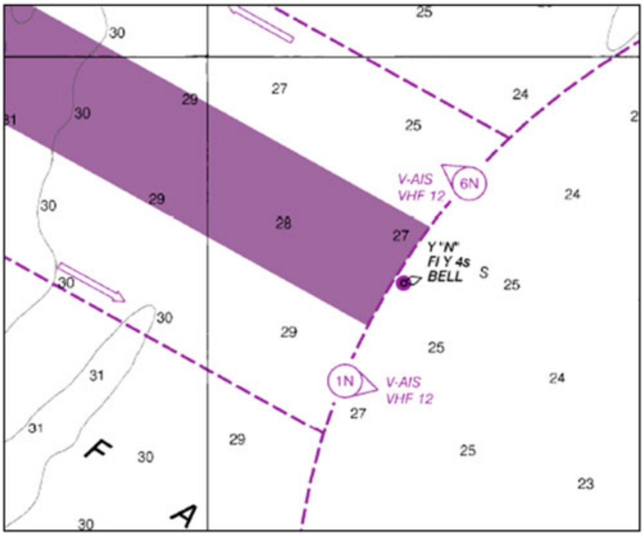

Figure 4. AIS AtoN Marking the Entrance and Exit from the San Francisco Traffic Separation Scheme. Source: NOAA Chart 18645

systems. Symbols similar to those shown in Figure 3 are also contained in raster and printed charts to depict virtual AtoN.

AIS eAtoN have been tested to mark the entrance to a Traffic Separation Scheme (TSS), provide emergency wreck and obstruction markings, identify waypoints and turning points, supplement existing physical AtoN, mark bridge abutments and offshore structures alone and in groups to make them more visible. Examples of wreck marking include a sunken former Russian Whiskey class submarine off Denmark in February 2007 and the cargo vessel Omar N that capsized in the Baltic Sea in October 2007 (FRV, 2009).

In 2008 AIS eAtoN were used to aid vessels on the approaches to the southern end of Drogden Channel between Denmark and Sweden. In 2014 the US Coast Guard began testing synthetic and virtual AIS eAtoN to mark reporting points in the offshore TSS approaches to San Francisco as shown in Figure 4. They are also used to mark the bridge towers to better alert mariners of their presence on the western span of the San Francisco-Oakland Bay Bridge as shown in Figure 5 (USCG, 2014). Many additional AIS eAtoN have been deployed along both coasts, in the Great Lakes and in the interior along portions of the western rivers within the US (Lewald, 2015).

4.2. *Virtual eAtoN.* The virtual eAtoN concept is enhanced beyond AIS eAtoN technology as computer-generated and existing entirely as a digital data object with no corresponding presence in the physical environment required for implementation. Virtual eAtoN also include expanded functional elements beyond AIS eAtoN to support static, dynamic and real time elements with permanent, temporary and transient durations. The basic definition of a virtual aid to navigation is (IALA, 2010):

> "A virtual aid to navigation (Virtual AtoN) does not physically exist but is a digital information object promulgated by an authorised service provider that can be presented on navigational systems",

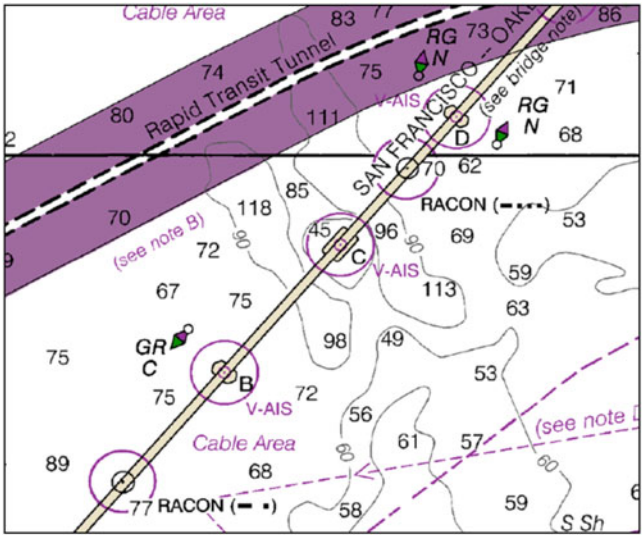

Figure 5. AIS AtoN Marking Bridge Towers on the San Francisco-Oakland Bridge.
Source: NOAA Chart 18645

where a digital information object is further defined as:

> "An item or group of items, regardless of type or format that a computer can address or manipulate as a single object that will inform the user as to the characteristic of a Virtual AtoN".

This definition is further amplified to describe Virtual AtoN use in informing mariners about dangers to navigation, safe waterways, caution and avoidance areas as may be represented by a line, area, position or other form displayed graphically without providing specific implementation mechanisms. Recommendations provided for the provisioning of Virtual AtoN and their deployment under the International Maritime Organization (IMO) e-Navigation initiative have thus far been limited to AIS eAtoN that use VHF radio technology (IALA, 2011; NCSR, 2014).

The characteristics and benefits of virtual eAtoN have been explored by Wright and Baldauf (2014) in research designed to enhance the safety of navigation for vessels in regions that are uncharted or poorly charted. Each of these types of AtoN has their unique functions, characteristics and associated advantages and disadvantages that determine how and where they may be deployed and how they are used by mariners.

4.2.1. *Functions.* Virtual eAtoN can provide the same beacon functions as AIS eAtoN along with additional functionalities pertaining to areas and limits, and tracks and routes that are not possible with either physical AtoN or AIS eAtoN.

4.2.1.1. *Beacons and Buoys.* Figure 6 illustrates the placement of virtual eAtoN lateral marks at the entrance to and along a channel that is particularly difficult to mark with physical AtoN in Kotzebue, Alaska, US.

Located 26 miles inside the Arctic Circle, much of the area is not surveyed and there are constantly changing sandbars along the approaches. A note to this effect is posted on the nautical chart along with advice to seek local knowledge when using this route

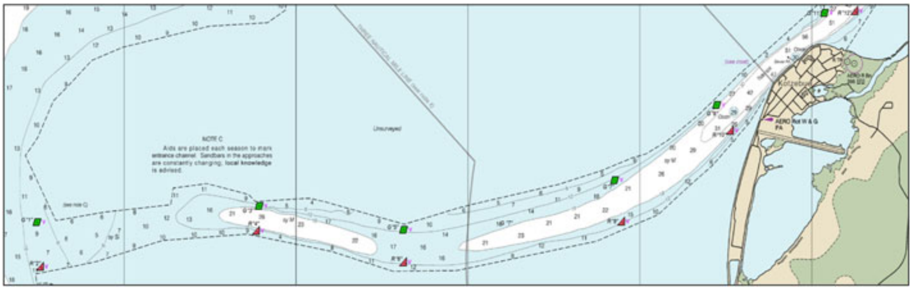

Figure 6. Portion of NOAA Chart 16161 for Kotzebue Harbour, Alaska, US depicting the placement of non-AIS virtual eAtoN where physical AtoN are normally not shown.

that spans several miles from clear water to Kotzebue Harbor. Physical AtoN are placed each season along this route but are not marked on charts due to their varying positions. This location provides circumstances advantageous to determining the viability of virtual eAtoN as it represents a transitional point where VHF radio coverage is also suitable for AIS eAtoN operation. This makes it useful to evaluate the integration and performance of AIS eAtoN and virtual eAtoN. The route is also sufficiently travelled to offer useful experience and feedback in their operation from numerous vessels.

A prime location for the use of virtual eAtoN is remote and not easily accessible for AtoN installation and maintenance and exhibits one or more hazards to navigation that, if left unmarked, may result in significant risk to life, property and the environment. One such example is shown in Figure 7 along a possible Bering Strait TSS providing northbound and southbound traffic lanes through the narrow passage around Big Diomede Island in Russia and Little Diomede Island in Alaska, US (MarEx, 2015). A hazard to navigation exists as Fairway Rock to the south and east of Little Diomede Island.

Virtual eAtoN placed at entrance and exit positions along the TSS and along the transit path centreline or at lateral positions would define the route. These could be mixed with AIS eAtoN along the lanes of the TSS using VHF transmitters located on Big Diomede and Little Diomede Islands respectively, with one additional AIS eAtoN transmitting from Fairway Rock also possible. This figure depicts the use of virtual eAtoN in combination with AIS eAtoN special purpose TSS buoys marking the port and starboard sides of the traffic lanes separated by the two islands along with radio reporting points at the ends of each lane.

Marking of hazards to navigation that heretofore has been difficult or impossible due to the harsh environment and lack of accessibility may now be accomplished. This includes sites such as the previously discovered but uncharted ledge in Resolute Bay, Canada upon which *MV Clipper Adventurer* grounded in 2006 (TSB, 2012). In this respect it might be reasonable to further integrate and investigate the potential of virtual eAtoN for enhanced route, position or direct grounding warnings or alarms.

4.2.1.2. *Tracks and Routes.* In addition to virtual eAtoN temporarily marking beacons, areas and limits, their use can be advantageous to mark tracks and routes in cases where knowledge of previous recent transits can directly contribute to increasing the safety of navigation. One such example is the track of an icebreaker where the

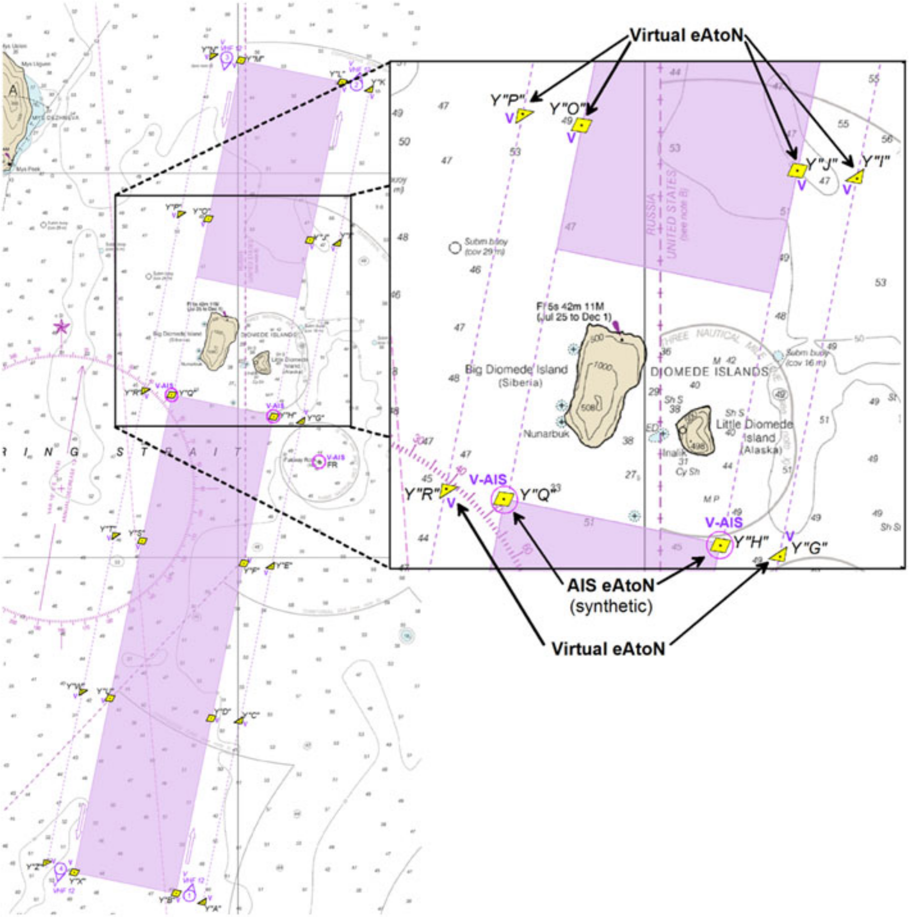

Figure 7. Portion of NOAA Chart 16220 showing a possible Bering Strait TSS and placement of both AIS and virtual eAtoN.

route of transit may provide guidance to where ice may be substantially thinner and more suitable for navigation. In this case it is likely the best representation would take the form of a non-regulated recommended track not based on fixed or virtual marks. Virtual eAtoN encoded characteristics represented by this track should include vessel name and time of most recent transit, an expiration date and time when the virtual eAtoN is no longer valid, heading information and possibly the shoalest depth value along a track as illustrated in Figure 8. Should previous hydrographic survey data exist along the route of transit this information would already be included in the ENC. However, when depths in the track are not known due to lack of survey a reported shoalest depth using single-beam echo sounder measurements from the icebreaker may be encoded but identified as being unreliable.

4.2.1.3. *Areas and Limits.* Virtual eAtoN may also be used to mark specific geographic areas such as the Bering Sea and Aleutian Islands groundfish fishery designated conservation areas and protection zones. The availability of such functionality

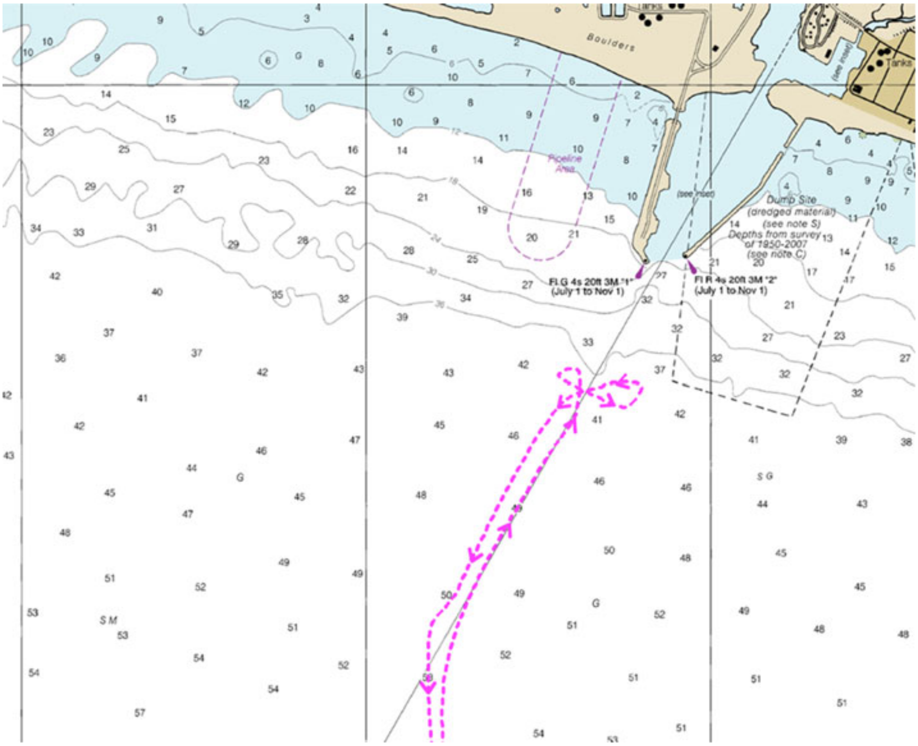

Figure 8. Portion of NOAA chart 16206 depicting virtual eAtoN icebreaker track on approaches to Nome, Alaska.

is valuable where conservation measures requires rapid action to temporarily and spatially limit fishing efforts, especially in relation to closures around areas involving marine mammals. One such implementation is shown in Figure 9(a), where transit of the area is normally allowed between 1 April and 15 August with a permit. During times when walrus activity is high it may be necessary to restrict entry with little advance notice during the normally open to transit period as shown in Figure 9(b) (FMP, 2015). This may be accomplished using virtual eAtoN depicting area and limit boundaries without having to emulate one or more buoys to achieve this same purpose. These boundaries may also rapidly expand and contract as local needs dictate. Such functions can be used to place no-entry zones and advisory areas near to coral reefs and other ecologically sensitive areas, disaster areas, race and other events that require time and spatial restrictions. This applies to other restrictions that pertain to offshore wind farms, fishing, anchoring and diving as well as marking bird and seal sanctuaries and marine parks.

Virtual eAtoN use in poorly surveyed regions where physical and AIS eAtoN are not practical can also enhance the safety of navigation where charting data is inadequate or does not exist at all resulting in blank white spaces on nautical charts. The use of aids to navigation in such areas is greatly restricted since the knowledge of where to place them is deficient due to lack of soundings. To help solve this

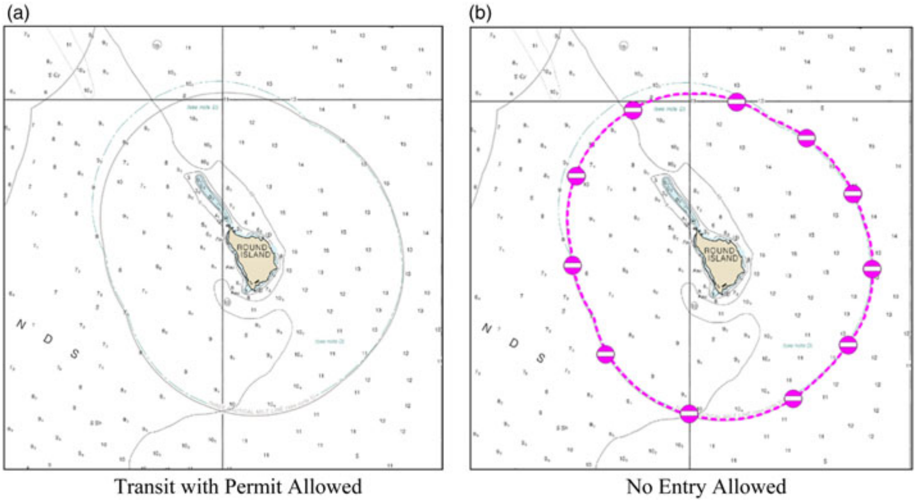

Figure 9. Portion of NOAA Chart 16315, Bristol Bay, Alaska depicting the Round Island virtual eAtoN walrus protection area: transit permit active and inactive.

problem research was performed using 3D-FLS for navigating poorly surveyed regions to avoid unintentional groundings (Wright and Baldauf, 2015a). Further research involved assessing the usefulness, resolution and accuracy of 3D-FLS to supplement hydrographic survey resources as externally sourced data (Wright and Zimmerman, 2015). The findings indicate that it is possible to perform examination with full bottom coverage using 3D-FLS to obtain an accurate characterisation of the sea floor, useful for nautical chart development and virtual eAtoN placement. Figure 10 provides an example of how multiple special purpose virtual eAtoN beacons may be placed along a track with a swath of sonar data where neither soundings nor AtoN previously existed, itself a virtual eAtoN representing an area. This data can be obtained from a vessel of opportunity equipped with 3D-FLS and used to define a route in an uncharted area.

4.2.2. *Capabilities.* Beyond the functions virtual eAtoN are able to provide in terms of use are the capabilities through which these functions may be delivered and observed on the bridge of the vessel while underway. This can also extend to shore-based vessel traffic service operators (including fleet operation centre operators), vessel owners and others involved in supervising vessel activity. Many of these capabilities are new, having become possible due to detailed hydrography data integrated within the International Hydrographic Organization (IHO) S-100 framework standard Universal Hydrographic Data Model and specifically the draft S-102 High Definition Gridded Bathymetry standard that supports development of new navigation products not possible under the S-57 and previous standards (S-102, 2012).

4.2.2.1. *Dynamic Virtual eAtoN Positioning for Marking Coaxial Waterways.* One example of new capability is dynamically repositioning virtual eAtoN considering vessel physical and performance characteristics rather than to maintain fixed geographic positions regardless of vessel size and draft requirements. This can be used to mark a deep draft channel within a wider waterway, a portion of which is illustrated

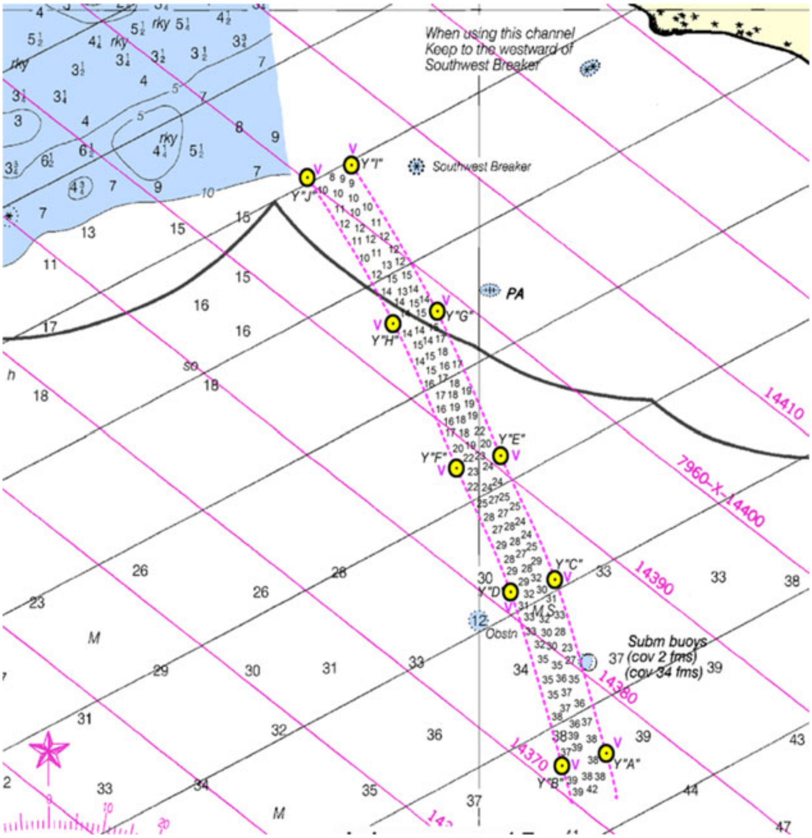

Figure 10. Portion of NOAA chart 16723, Controller Bay, Alaska, US depicting virtual eAtoN special purpose buoys and soundings swath from 3D forward-looking sonar equipped vessel.

in Figures 11(a) and 11(b), and is different from related ECDIS capabilities as the physical bottom configuration characteristics of the virtual eAtoN existing within ENC are used together with vessel draft parameters and live single-beam echo sounder measurements to determine lateral spacing requirements for channel width. This is based upon detailed hydrographic surface topography model data and is accomplished in real time considering bottom depths and the forward motion of the vessel. Here it is shown that the bottom configuration offers a much broader geographic area for the safe navigation of a vessel with a two metre draft compared to a vessel with a four metre draft where the vessels travel at the same speed.

4.2.2.2. *Single and Group Virtual eAtoN.* An additional layer of abstraction in the overall AtoN scheme has been added with AIS virtual eAtoN that may be placed on physical AtoN to supplement their characteristics, and at locations other than AtoN to project AtoN characteristics to locations where no AtoN exist at all. The introduction of completely virtual eAtoN provides an opportunity to further extend AtoN capabilities to create a "group" virtual eAtoN representing a "system of systems" that together provides capabilities beyond the sum of the individual virtual eAtoN components is comprised. For example, the Kotzebue channel shown

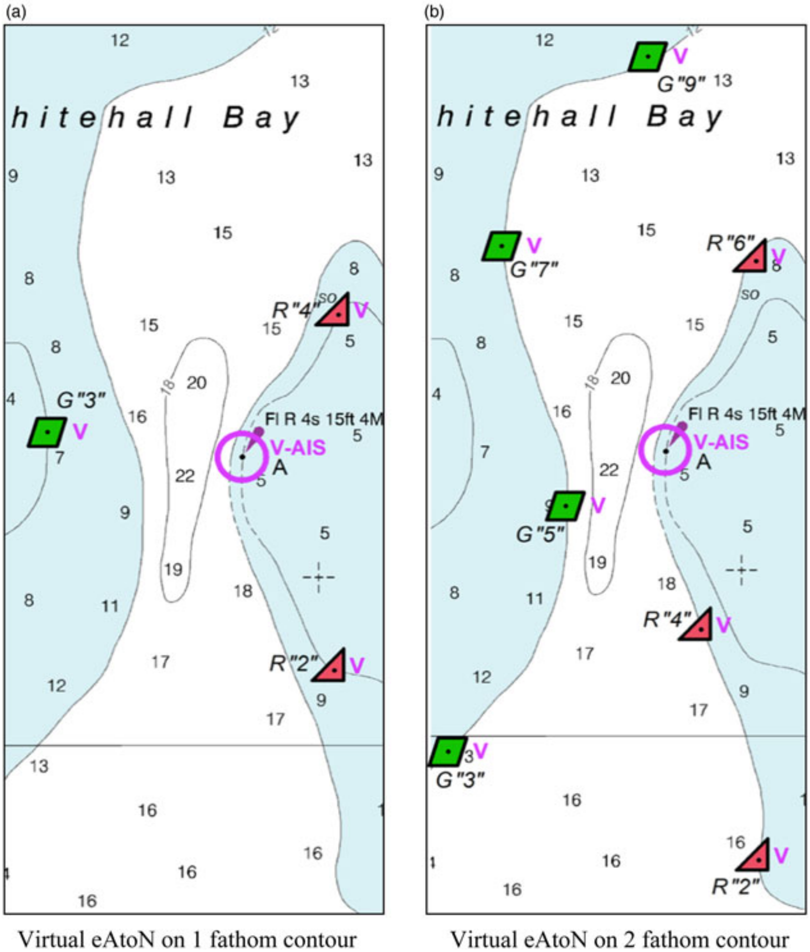

Figure 11. Portion of NOAA chart 12283, Annapolis, Maryland, US depicting mix of fixed position AIS eAtoN and dynamic positioning of virtual eAtoN to mark coaxial waterways.

in Figure 6 and the possible configuration of a Bering Strait TSS shown in Figure 7 can support new capabilities by linking individual virtual eAtoN characteristics when accompanied by detailed hydrographic surface model data in an ENC. This can include automatic determination of changes and shifting of bottom contours resulting from storm action and other causes by comparing the ENC terrain model data with live echo sounder measurements while underway. This same process could be used to detect whether AtoN (physical, AIS or virtual) are on station and watching properly in good water. Furthermore, this technique would rapidly detect poor GNSS availability due to atmospheric interference, spoofing or a denial of service attack taking place that results in the apparent vessel position being different from the actual vessel position based upon differences in bottom topography.

4.2.2.3. *Real-time Hazard to Navigation Detection.* Virtual eAtoN can be used to contribute new alarms and methods to notify in real time watchstanders on the bridge

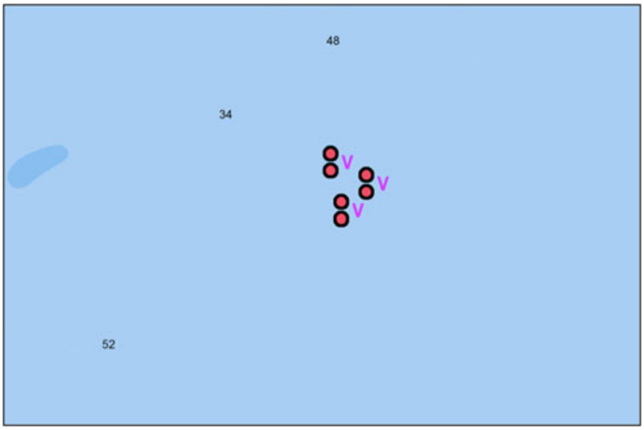

Figure 12. Live display of real time virtual eAtoN isolated danger mark using 3D-FLS integrated with ECDIS.

of the detection of uncharted hazards to navigation when integrated with 3D-FLS adequate to support this capability. This includes shoals, ledges and rocks, as well as floating hazards and those suspended in the water column in the path of transit based upon research performed by Wright and Baldauf (2015b). Notable case studies were presented illustrating how *MVs Clipper Adventurer, Exxon Valdez, Rena* and *Costa Concordia* could have been provided 1·7 to 2 minutes advance warning of grounding had 3D-FLS been installed and operational. This would have also been useful for a situation such as was encountered by Carnival's *Ecstasy* in April 2010 which responded in very short time to miss a large, partially submerged data buoy adrift in the Gulf of Mexico (Yanchudas, 2010).

The detection of such hazards to navigation can be accomplished using algorithms already available within 3D-FLS. However, their display to watchstanders must conform to existing human-machine interface conventions and standards. Hazards to navigation may be displayed on ECDIS by placing an isolated danger mark shown in Figure 3 directly at one or more positions where contact was made using 3D-FLS as illustrated in Figure 12. The background shown within this figure corresponds to many poorly charted and uncharted locations in the Arctic where ECDIS is essentially blank since the underlying ENC contains no or sparse sounding information. The isolated danger marks shown in this figure represent a hazard to navigation detected in real time while making way and within the range of the 3D-FLS providing a significant acoustic target when compared to surrounding waters. These targets can represent a shipping container, growler, whale or other target. A transient virtual eAtoN is something that is neither permanent nor temporary in nature, and is likely to exist only momentarily until the hazard passes. Such an approach is wholly unorthodox in terms of the present AtoN development lifecycle as the mark has not been promulgated by a competent authority. However, consideration by a competent national authority of the processes that make such capabilities possible through the integration of new technologies must be considered, especially when risk is heightened while transiting unknown waters.

4.2.3. *Virtual eAtoN Adoption.* Examples of virtual eAtoN realised as beacons, areas and limits, and tracks and zones are provided to illustrate functions that are possible. The capabilities described to employ these functions are also illustrative, as are the specific characteristics that have been described for implementation. Determination of virtual eAtoN adoption for future test, evaluation and/or operational use must be made by the competent national authority after the development and validation of the processes required to assure their performance and technical viability have themselves been validated.

4.2.4. *IHO S-100 Framework Standard.* A key component of virtual eAtoN implementation includes high resolution three-dimensional digital terrain model data of the sea bottom incorporated into ENC represented as IHO S-102 High-Definition Gridded Bathymetry featuring level 1 (harbour) 0·02° x 0·02° grid sizes and a final surface grid resolution of 0·0001° or approximately 8 metres (Journault et al., 2012). Sufficient resolution exists within these data to perform the verification of virtual eAtoN physical characteristics using the metrics described and illustrated by Wright and Baldauf (2015c). Similar resolution available from 3D-FLS data as a source for hydrographic survey data from vessels of opportunity in inadequately surveyed areas can accelerate the deployment of virtual eAtoN (Wright and Zimmerman, 2015). Issues yet to be resolved include the transport architecture that will be used to convey ENC from shore to on board vessels, cyber security enhancements needed to ensure trust in data sources, training in the use of this infrastructure and the range of new products to be delivered. One issue still to be addressed is the orientation of gridded data with the meridians and parallels at the higher latitudes of the Arctic.

5. CONCLUSIONS.

The ability of virtual eAtoN to emulate beacons and buoys, tracks and routes, areas and limits and other functions with minimal investment and recurring cost for physical assets and support infrastructure is very appealing to supplement physical AtoN and AIS eAtoN in the many inaccessible, remote and ecologically sensitive regions of the world. The trend of increasing budget constraints for AtoN research, development, deployment and maintenance is contrasted with the rise in vessel traffic in regions that are the least amenable to support such traffic. These regions are the least surveyed, most remote, devoid of AtoN infrastructure, lacking safe harbours and adequate search and rescue capabilities, and among the most ecologically fragile on the planet.

Results of this research reported to date indicate a realistic potential for the use of virtual eAtoN, especially in locations and regions where traditional AtoN are not practical or feasible. Evidence has been presented to indicate the proposed approach provides advantages over physical AtoN and AIS eAtoN in overcoming the vulnerabilities and limitations of GNSS and AIS technology. New functions and capabilities available using virtual eAtoN integrated with 3D-FLS can provide significant enhancements to safety of navigation especially in regions that are not surveyed and remain uncharted such as the Arctic. An initial starting point may include the adaptation of existing 3D-FLS in-water hazard and obstruction detection algorithms to produce standard ECDIS symbology. Also, the Polar Code should be amended to mandate 3D-FLS as an echo-sounding device having forward-looking capabilities as a vessel carriage requirement in the Arctic (MSC.385(94), 2014). Alternatively, 3D-FLS should qualify as one of the two already required independent echo-sounding devices.

The concepts involved have already been proven in the aviation industry, where aircraft plying the airways at speeds orders of magnitude faster than vessels at sea routinely navigate in safety. All airborne AtoN are virtual. There is not one physical AtoN suspended in the air to help guide aircraft to their destinations. The described implementation of maritime virtual eAtoN is firmly grounded in high-resolution geodetic data traceable directly to the local environment in which they are deployed. Such characteristics provide the means by which assurance of their correct implementation and watching properly can be established and continuously monitored. These concepts can be extended to existing physical AtoN and AIS eAtoN, enhancing overall confidence in short-range AtoN performance throughout the maritime industry.

6. NOTE. The symbols shown in Figures 3 through 12 are used for illustration purposes only and do not correspond with the current IMO Guidance (IMO Circ. 243).

DISCLAIMER

The opinions expressed are solely those of the authors and do not represent the U.S Coast Guard, U.S. National Oceanic and Atmospheric Administration, International Maritime Organization, International Hydrographic Organization or any other organisation.

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Correlation of Virtual Aids to Navigation to the Physical Environment

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ABSTRACT: Virtual electronic aids to navigation are being introduced into the present short range aids to navigation system in the form of Automated Information System radio-based aids. Research is also underway into the development of their equivalents for use in regions that feature hostile environments, are poorly charted and lack any infrastructure whatsoever to support traditional or radio navigation aids. Such aids are entirely virtual in nature and exist only as a digital data object that resides within an electronic navigation chart for display to mariners through an Electronic Chart Display and Information System. They are at present experimental in nature, and are not intended to replace existing physical or radio-based aids to navigation. Results of research are described in terms of fulfilling traditional navigation aid functions and the development of new functions that are only possible using virtual aids. Their advantages in design and implementation are highlighted, as are their limitations and shortcomings as compared to present methodologies. Notable, however, is the approach used to overcome limitations and shortcomings by considering attributes of the physical environment to ensure their proper location and display of correct characteristics. Such an approach is unique in the modern world, yet it emulates ancient methods of navigation using known landmarks and terrain features.

1 INTRODUCTION

Virtual aids to navigation (AtoN) are defined by the International Association of Lighthouse Authorities (IALA) as something that "does not physically exist but is a digital information object promulgated by an authorized service provider that can be presented on navigational systems" (IALA O143). Truly virtual aids that do not require physical infrastructure of any kind are still relegated to the future. However, similar capabilities are presently being implemented through the use of Automated Identification System (AIS) radio-based devices that can project their presence directly from a buoy or other physical location such as a bridge abutment. AIS radio AtoN are electronic in nature and distinguished from physical AtoN with the addition of an "e" to the AtoN designation (eAtoN). They can project their presence to remote locations where, for example, a buoy should exist but placement and/or maintenance of a physical AtoN is too difficult. The intended location must be in the line of sight of the very high frequency (VHF) radio required to originate AIS transmissions. One such example is an Isolated Danger mark located on Tarapunga Rock in Doubtful Sound near the South Island of New Zealand (Marinetraffic VIRT).

This concept is revolutionary to vessel navigation in much the same manner as was the introduction of radar – with many of the same problems likely to be encountered in terms of training and operation. Real potential exists to instill new vessel navigational capabilities that cannot be achieved using traditional, physical AtoN. However, the probability of encountering many limitations and fragilities unique to virtual eAtoN is high, and it is necessary to anticipate and adequately prepare for such eventualities to ensure safety of navigation is maintained.

This paper describes research into the development of truly virtual eAtoN that do not require radio transmitters or other physical presence at the eAtoN location. Significant portions of this research addresses eAtoN needs critical to their proper installation and verification of performance by authorized service providers and safe and reliable use by mariners. An expanded range of eAtoN physical, performance, environmental and computational factors are considered in this analysis. Strategies are also provided to overcome some of the potential vulnerabilities of such devices at various points in the eAtoN lifecycle to avert threats by opportunists to render such devices themselves useless or even hazardous to navigation.

2 PHYSICAL ATON VS. VIRTUAL EATON

Physical AtoN have been used for thousands of years to guide vessels along their routes and provide assurance of safe passage using known landmarks and structures to indicate safe waters. In the modern era technology has provided us with buoys, lighthouses, light ranges, day marks and other devices to accomplish this capability. AtoN complemented with radar, depth sounders, precision positioning and timing devices broadens situational awareness by helping identify environmental features and tracking vessel progress while underway.

Virtual eAtoN are intended to supplement and not replace existing AtoN in areas where the timely marking of hazards to navigation can be performed faster and more effectively than placing physical AtoN. This may be on a temporary basis until physical AtoN can be installed such as in marking new wrecks or where previously uncharted hazards to navigation are detected. They can also be installed on a permanent basis where the use of physical AtoN is problematic or not possible. This includes coral reefs where sinkers cannot be placed due to their adverse environmental effects, in the Arctic where ice movement can carry away physical AtoN, and along rivers and tributaries where water levels and channel locations are subject to frequent change. Another possibility is that eAtoN functionality can provide flexibility in terms of purpose and positioning that may be tailored to the unique requirements of individual vessels for determining adequate widths of channels, placement locations and other capabilities such as aid to vessels having lost their way and in need of position assistance.

3 EATON IMPLEMENTATION TECHNOLOGIES

The IALA definition of a virtual aid to navigation cited earlier provides no direction as to the implementation technologies through which such a capability may be achieved. However, earlier guidance recognized that AIS can be applied to AtoN to further improve and enhance services to mariners and assist AtoN authorities to ensure the safe provisioning of such aids to navigation as the volume of traffic justifies and by the degree of risk (IALA G1081).

The use of AIS to effect eAtoN implementations must rely on physical infrastructure to accomplish their objectives. This in itself is not problematic in areas where ready access is available and adequate financial resources exist to install and maintain such physical infrastructure. However, this is not the case over vast portions of the planet where eAtoN capabilities are needed most – the Arctic and in sensitive tropical regions. Indeed, regions that are without adequate financial resources and those affected by war can benefit from the ability to rapidly install eAtoN without physical infrastructure that fulfill the IALA definition, "does not physically exist but is a digital information object". Such an approach requiring no physical infrastructure has recently been presented that can overcome other limitations such as the lack of hydrographic survey, sporadic and low-bandwidth communications, and an absence of government support (Wright and Baldauf 2014). Both such implementations require eAtoN presentation on navigational systems, with the primary system for navigation being the Electronic Chart Display and Information System (ECDIS) (MSC 82). AIS signals are also presented on radar and other appropriate displays.

AIS eAtoN have been deployed along both coasts of the United States, in the Great Lakes and in the interior along portions of the western rivers. (Lewald 2015). Deployment of these eAtoN is being accomplished in an effort to best determine their use and application for future waterway guideline development. Descriptions may be found in Local Notice to Mariners chart corrections and illustrated eAtoN portrayals on paper charts, electronic nautical charts (ENCs) and radar for:

- Physical AIS eAtoN: AIS signal broadcasts originate from a physical AtoN,
- Synthetic AIS eAtoN: AIS signals originate from a remote AIS base station and are broadcast to a location where a physical AtoN exists,
- Virtual AIS AtoN: AIS signals originate from a remote AIS base station and are broadcast to a location where no physical AtoN exists but are displayed on ENCs and ECDIS.
  (USCG 2014; see also IALA G1062).

The US National Oceanographic and Atmospheric Administration (NOAA) announced an expanded set of symbols used to portray AIS eAtoN on ECDIS and that NOAA charts would be updated to add AIS eAtoN locations (OCS 2014). These symbols include a magenta radio ring surrounding the AIS eAtoN reflecting the radio transmission of the signal, which does not apply to non-AIS virtual eAtoN.

4 CHARACTERISTICS

The term "characteristics" when used in relation to AtoN have generally referred to their physical and performance aspects as can be readily seen and measured to determine whether they are "watching properly" which is defined by the U.S. Coast Guard as, "an aid to navigation on its assigned position exhibiting the advertised characteristics in all respects" (USCG 2005). However, with the introduction of eAtoN that exist solely as digital information objects this concept has become somewhat muddled. Even virtual eAtoN have a physical presence on navigation display devices such as ECDIS and radar.

The following paragraphs attempt to clarify these issues by introducing their digital representations within the context of characteristics by which an assessment of watching properly may be determined. A discrepancy is defined as any failure of an AtoN to display its characteristics as described in the Light List or to be on its assigned position. When a discrepancy is reported, a response level for its correction is determined based upon severity and availability of assets (USCG 2005a).

The lines of demarcation as to whom discrepancies are to be reported must also be redrawn. The US Coast Guard is the cognizant organization for reporting AtoN discrepancies, while NOAA is cognizant for charting discrepancies that include ENCs and ECDIS. However, if AIS or virtual (non-AIS) eAtoN are portrayed incorrectly on a chart this occurrence should also be reported to the US Coast Guard.

4.1 *AtoN Characteristics*

For traditional AtoN, two main aspects of their design encompass various characteristics that must be verified to determine they are watching properly. These include:
– Physical, and
– Performance.

Physical AtoN characteristics consist of nominal operating and discrepant conditions and include type (buoy, daymark, range, lighthouse, racon) color, shape, numbering, light features (red/green/yellow, flashing/ steady/occulting), sound features (bell/gong/horn/ whistle), position (lat/long, on station, off station, adrift, missing, not marking best water) as well as condition (sinking, stranded, capsized, excessive rust). Performance aspects include light and sound intensity, racon (operational, not operational, operating improperly), rhythms and rates of installed devices, and visibility (day boards faded, lights/numbers obscured), etc. (USCG 2010).

AtoN are documented and described in databases (ATONIS/USAIMS, ENC) and data products (e.g., Light List, Notice to Mariners, Coast Pilot). However, these data objects and representations are secondary to their physical manifestation in terms of performance. Indeed, physical AtoN have existed and stood watch properly for centuries with little more representation as "data objects" than a written note on a hand-made chart.

4.2 *eAtoN Characteristics*

Both physical and synthetic AIS eAtoN share the characteristics cited in the previous paragraph with their associated physical AtoN that must be considered during verification and when reporting discrepancies. However, this does not necessarily apply to AIS or non-AIS virtual eAtoN since neither are associated with a physical AtoN. Although the IALA definition of virtual AtoN describes them as data objects, they actually do exist in the physical sense when they are depicted on a navigational display to be observed and acted upon by a watchstander. The physical characteristics of AIS eAtoN include the symbols for physical, synthetic and virtual; and non-AIS virtual (USCG 2014). ENC depiction of physical characteristics for virtual eAtoN (AIS and non-AIS) on ECDIS includes symbols for cardinal marks (N/E/S/W), lateral marks (IALA A/B port and starboard), isolated danger, safe water, special purpose and emergency wreck marking (OCS 2014). The bulk of eAtoN characteristics exist in the form of data object representations in the domain of the authorized service provider. In the United States this is the Coast Guard and NOAA. These characteristics include the Light List number, type of aid, name, position, class, inspection dates and other information.

eAtoN performance characteristics are determined in part by the specifications for each specific device. From a practical perspective for operational verification they either work as specified (operational) or don't work (not operational) in much the same fashion as a racon installed on AtoN.

4.3 *Data Object Characteristics*

Recently efforts have been undertaken by IALA to define a common structure resulting in the creation of a Product Specification for AtoN Information (IALA PS1). This specification is intended to include information about lights, buoys, beacons, racons, AIS and sound signals and can also form the basis for the exchange of virtual AtoN information. Figure 1a summarizes the key elements of the AtoN application schema in its current form while figure 1b integrates the essential elements of virtual eAtoN.

Critical to this schema is the establishment of single and group virtual eAtoN that can share geospatial model point, curve and surface data to provide new capabilities for virtual eAtoN operation. This is accomplished through inheritance of attributes between group virtual eAtoN and the individual constituent virtual eAtoN elements. Included is a capability for live comparison between known hydrographic data used for chart production and single-beam echosounder data obtained from own vessel sensors to help determine the validity of GNSS positioning information. Additional capabilities can include automated verification of virtual eAtoN watching properly, which may also be extended to physical and AIS eAtoN.

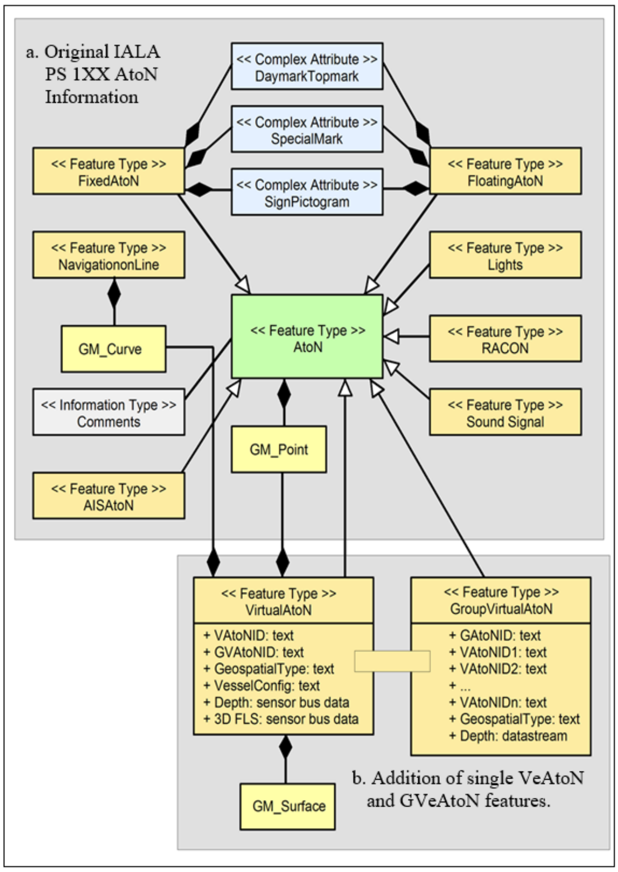

Figure 1. Virtual eAtoN application schema embedded within the IALA AtoN Information Product Specification 1XX, draft 0.0.5 – June 2013.

4.4 *Virtual eAtoN Adoption*

Examples of virtual eAtoN realized as beacons, areas and limits, and tracks and zones in the text that follows are provided to illustrate functions that are possible. The capabilities described to employ these functions are also illustrative, as are the specific characteristics that have been described for implementation. Determination of virtual eAtoN adoption for future test, evaluation and/or operational use must be made by competent national authority after the development and validation of the processes required to assure their performance and technical viability have themselves have been validated. A discussion of these concepts follows.

5 VIRTUAL EATON LIFE CYCLE CONSIDERATIONS

There is a dual responsibility for the ultimate safety and efficiency of vessel traffic and protection of the environment by competent national authority. A simplified flow of tasks performed by each authority is illustrated in figure 2. The first responsibility involves performing hydrographic surveys to determine the configuration of waterways and the development of nautical charts that accurately portray survey results. The second responsibility has to do with the design, provisioning and maintenance of AtoN systems based upon these surveys. Historically under normal circumstances these authorities perform their tasks accurately and efficiently.

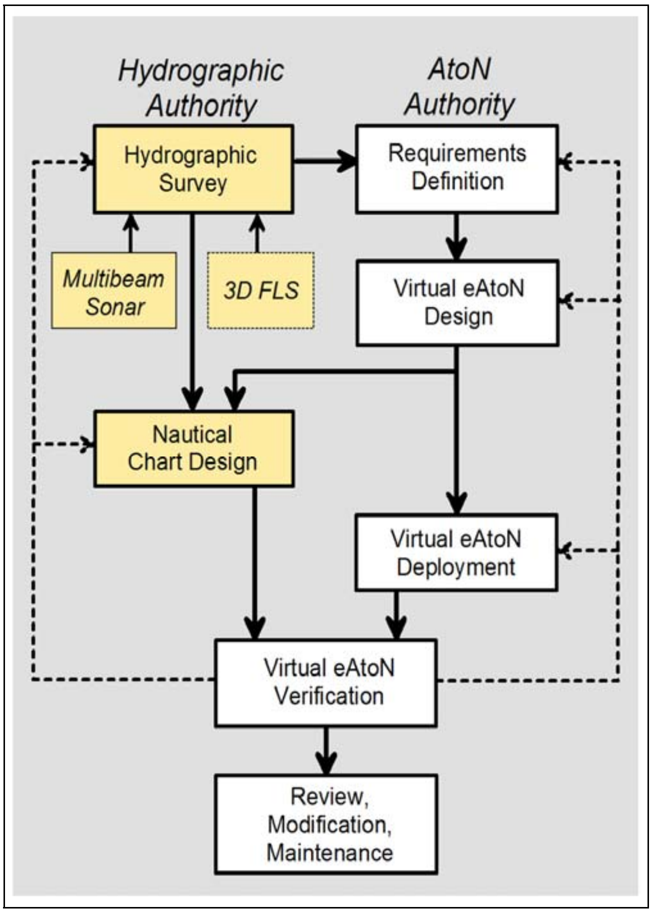

Figure 2. Virtual eAtoN life cycle representing roles of national hydrographic and AtoN authorities.

However, the rapid expansion of vessel navigation in the Arctic has exposed deficiencies of existing capabilities to perform hydrographic surveys, produce updated nautical charts and design AtoN systems to keep pace with this expansion. For example the original NOAA Arctic Nautical Charting Plan published in 2011 proposed the creation of 14 new charts. As of the 2015 update to this plan three of these charts have been produced and released for use by the public with no definite schedule to produce the remaining 11 charts identified in the Plan (NOAA 2015).

There are many ways that new technology and virtual eAtoN can contribute towards enhancing the safety of navigation. This includes the gathering of high resolution, full bottom hydrographic data from 3-dimentional forward looking sonar (3D-FLS) equipped vessels of opportunity to supplement scarce national hydrographic resources to help in eAtoN positioning. The expansion of capabilities provided by physical AtoN through the use of AIS eAtoN technology can also be further accelerated through the deployment of virtual eAtoN in areas not suitable for physical AtoN or AIS eAtoN. This would also embrace new eAtoN concepts such as the display of recent transits by icebreakers within a set time frame as well as the real time detection of hazards to navigation for display on ECDIS on a momentary or transient basis while the hazard exists. Discussion of these concepts in terms of the AtoN development lifecycle is provided in the paragraphs that follow.

5.1 *Establishment of Requirements*

Determination of requirements for traditional AtoN, AIS eAtoN and virtual eAtoN is based jointly upon the results of hydrographic surveys and the needs associated with vessel navigation. The factors comprising each of these needs are assessed by different independent organizations according to different regulations. Coordination and cooperation between national authorities for hydrography and buoyage is essential to effect comprehensive national systems. Adequate representation and participation by national representatives in activities and committees of the International Hydrographic Organization (IHO) and International Maritime Organization (IMO) can help ensure effective implementation and compliance with international standards.

5.1.1 *5.1.1 Hydrographic Survey*

Decisions regarding the performance of hydrographic surveys are made by competent national authority based upon guidance provided through the IHO concerning how hydrographic surveys are performed, the products of these surveys and the methods by which survey and AtoN information is depicted in nautical charts. For the purposes of this discussion reference is made to shallow water surveys in areas of less than 100 meters in depth in accordance with IHO Standards for Hydrographic Surveys (IHO SP44). Specifically, this refers to Order 1a surveys intended for harbors, harbor approach channels, recommended tracks, inland navigation channels and coastal areas with high commercial traffic density. Many hydrographic survey projects require the use of multibeam echosounders capable of obtaining hundreds more soundings per unit time than single-beam systems and cover a wide swath of the sea floor. Other methods include the use of side scan sonar systems to assist in detecting objects that project from the sea floor. Both of these systems provide nearly 100 percent bottom coverage of the sea floor, greatly enhancing the ability to detect hazards undiscovered by less modern surveys.

An alternative form of multibeam sonar that appears suitable for hydrographic survey is 3D-FLS. Some systems are capable of scanning wide swaths of the sea floor with up to 100 percent coverage. Rather than being aimed athwartships at right angles to the path of transit, 3D-FLS is aimed directly ahead of the vessel and is used as a navigation sonar to avoid vessel grounding on uncharted shoals and to detect hazards to navigation that reside below the waterline both attached to the bottom and floating within the water column. With a range of up to 1,000 meters, a 60 degree conic projection and vertical range to depths of up to 50 meters, widespread use of such equipment by vessels in uncharted regions such as the Arctic and sharing of this data through independent sourcing could well supplement national hydrographic survey resources in these areas. Although research into the use of this technology to supplement surveys is in the earlier stages and generally related to autonomous underwater vehicles (see i.a. Zhang et al, 2008 and Suman et. al, 2015); Wright and Zimmerman (2015) determined that full sea floor swath data obtained using 3D-FLS is useful for nautical chart development and virtual eAtoN placement. The availability of detailed hydrographic sensor data through any or all of these resources is a first step towards determining locations suitable for establishing waterways regardless of whether traditional AtoN or eAtoN are intended for use.

5.1.2 *AtoN Requirements*

The identification of AtoN requirements is based upon the combination of hydrographic survey results and the needs of vessel navigation. The main objectives to be achieved in defining requirements include assisting navigators in identifying their position, determining a safe route of transit, warning of dangers and obstructions, promoting the safe and economic movement of commercial vessel traffic and the safe and efficient movement of military vessel traffic and cargo of strategic military importance. This includes reasons for rejecting other obvious or more economical solutions to the problem that might be indicated from an examination of the relevant nautical chart such as, for example, physical AtoN and AIS eAtoN. As much as practical, AtoN are established within the confines of the lateral system to mark channels and other areas of safe water as well as hazards to navigation and wrecks (USCG 2005b, 2005c).

The process used to define requirements in terms of initial justification based upon user needs, benefits accrued and the cost to achieve these benefits remains unchanged. Justification is accomplished on a site by site basis, and general guidance for accomplishing this for virtual eAtoN is provided later in the text in the discussion on design. However, the availability to use virtual eAtoN as an option to fulfill AtoN requirements becomes apparent as new capabilities are created in previously inaccessible locations. Characteristics associated with the implementation of virtual eAtoN are defined based upon the same criteria as for traditional AtoN, but may be moderated in terms of guidance and advisories rather than regulatory requirements. This may be especially warranted, for example, to reduce or eliminate warnings from ECDIS due to close proximity to buoys rather than reporting points.

5.2 *Design*

The design of virtual eAtoN systems and the selection of individual elements thereof is performed to define the data constructs and types that comprise the characteristics of the digital data object illustrated in figure 1. The original IALA AtoN application schema is modified to incorporate abstraction, encapsulation and inheritance properties required to implement geospatial characteristics that comprise essential elements of the concept. However, there is nothing in this modified schema that is necessarily unique to virtual eAtoN. Both physical AtoN and AIS eAtoN can also take advantage of these characteristics to bolster the automated verification of their watching properly and to obtain the same benefits of immunity to disruption of GNSS and AIS services. The concepts of individual and group virtual eAtoN are also introduced that enable the inheritance of characteristics of individual virtual eAtoN amongst the group virtual eAtoN in this system of systems implementation. The products of design should be tested using simulations and through emulation of the processes used in the creation of the design to determine compliance with and traceability to requirements and to detect potential deficiencies in implementation and use.

An example of a permanent implementation of virtual eAtoN is where the individual system elements (VirtualAtoN) consisting of green and red lateral marks correctly depict the conventional direction of buoyage along a channel. The IALA AtoN Information Product Specification convention is followed with the addition of two new characteristics one of which points to a geospatial surface (GM_Surface), curve (GM_Curve) or point (GM_Point) of the area in the vicinity of the virtual eAtoN within the ENC. A second characteristic identifies a live single-beam echosounder digital data stream obtained via a vessel's sensor bus (e.g., NMEA 2000 or equivalent) that is compared to the ENC to provide automatic, real-time checking of GNSS and AIS functionality along with verification that the virtual eAtoN are watching properly. The system comprising a channel (GroupVirtualAtoN) includes each individual (VirtualAtoN) element and points to a geospatial surface model (GM_Surface) that corresponds to the overall group. This group model exceeds the sum of individual virtual eAtoN elements as it also includes areas of transition, allowing for seamless verification of each element of the system and the entire system itself.

An example of a permanent and complex hybrid system is a traffic separation scheme (TSS) that contains AIS eAtoN and virtual eAtoN combined with communication reporting points along two distinct transit corridors separated by a boundary between them. Rather than using green and red lateral marks, special purpose TSS buoys can be used to represent the port and starboard sides of the traffic lanes. However, the same process in accordance with the modified IALA AtoN application schema is used in defining each individual element of the system and the entire system of systems.

Another example of a permanent virtual eAtoN is where soundings data along with the boundaries of the useful data are delineated using multiple special purpose marks in an area that contains sparse or no soundings data at all. A likely origin for such data is envisioned to be the result of independently sourced inputs promulgated via cognizant national authority from a vessel of convenience equipped with 3D-FLS capable of providing a swath of full bottom coverage. Such data would undergo several stages of quality checking based upon compliance with product and process verification standards prior to issuance.

The permanent dynamic marking of coaxial channels using virtual eAtoN is accomplished through the introduction of additional characteristics that describe vessel draft and speed in combination with the geospatial surface model (GM_Surface). One of two or more distinct group virtual eAtoN (GroupVirtualAtoN) models are selected in real time based upon assurance of adequate bottom clearance considering vessel draft, turning requirements based upon vessel speed and momentum, and other relevant criteria.

A much simpler design of a temporary individual virtual eAtoN is comprised of a set of curves (GM_Curve) that correspond to the boundaries of the no-transit zone. The symbols for no-entry can be dynamically placed on ECDIS and dependent on the scale to which the system is set, affecting both the number of symbols and the density in which they are displayed. The actual effective times for the area can be encoded within the ENC and updated periodically as revisions become available.

The AIS track that comprises a portion of a virtual eAtoN depicting the recent path of an icebreaker is another example of a temporary mark. AIS data is correlated with the ENC geospatial curve model to create a soundings representation for the track used with live single-beam echo sounder data to verify virtual eAtoN are watching properly and not being spoofed or interfered with through the interruption of AIS and/or GNSS services. The useful duration of the track can be determined by cognizant national authority based upon contemporary observations of environmental and other conditions and encoded within the AIS data and/or the (VirtualAtoN) feature itself.

A new virtual eAtoN capability is also introduced for marking transient or momentary potential hazards to navigation. Available only as a result of enhanced situational awareness of the underwater environment made possible using 3D-FLS, these represent hazards affixed to the bottom that include reefs and ledges, and hazards present within the water column such as growlers, shipping containers and whales. An example is where one or more Isolated Danger marks are displayed on ECDIS at positions that correspond to the hazard locations. A similar capability using 3D-FLS is already integrated into many existing ECDIS installations via a vessel's sensor bus network, but this must be further refined in terms of display features, symbols and operator training to become an effective means of alerting watchstanders to real time hazards to navigation.

5.3 *Implementation*

Once the AtoN requirements and design tasks have been completed, the products of these tasks must be forwarded to cognizant authority for inclusion into nautical charts. This is accomplished in parallel with preparing to deploy virtual eAtoN through the performance of local surveys to confirm positioning and other tasks as may be deemed necessary prior to their introduction. In all implementation tasks it is vital ensure that the processes used during requirements definition and design ensure the correct virtual eAtoN aid is created and translates into a proper implementation of the aid.

Feasibility of the approach is enhanced through the identification of challenges encountered during development and testing, the implementation of contingency plans in recognition of these potential challenges, and maximizing possible opportunities that result throughout the development life cycle. An example of such a challenge includes the identification of differences between the conditions represented by the most recent survey, which may be years out of date, and present-day conditions that reflect a different bottom configuration as a result of storm activity and bottom shifting due to currents.

Achievability is heightened through the identification and management of significant risk elements throughout the development process. Metrics are needed to determine development progress and overall system effectiveness. This is accomplished by continually reassessing the virtual eAtoN implementation plan and deviation from plan for resource use (human, facilities, etc.) and risk assessment in terms of task achievement, effort indicators and milestone fulfillment. Requirement and design modification processes need to be established along with tracking of changes needed throughout development to facilitate metric reporting of requirement, design and implementation of both ENC and virtual eAtoN. Metrics focusing on risk assessment of the quality and structure of the schedule, work breakdown structure consistency, critical path analysis and the identification of high risk activities and events, and risk mitigation scenarios should also be identified.

The system is complete when all steps necessary to implement the virtual eAtoN system have been identified and metrics established to ensure measurable progress indicates completion. This approach will ensure virtual eAtoN feature and capability traceability to product specification and design, system configuration stability, adequacy of testing, and overall system maturity.

5.4 *Verification*

The same processes and procedures used to verify physical AtoN and AIS eAtoN characteristics in determining they are watching properly can be applied to virtual eAtoN. However, additional procedures are required in verifying virtual eAtoN across three levels that include:

– Data object,
– Technical performance, and
– Physical characteristics

Data object verification involves a continuous process used by cognizant authorities and service providers to examine AtoN-related data across multiple databases to detect errors and inconsistencies inherent to database operations as well as hacking and infiltration. Verification of virtual eAtoN technical performance focuses on determining that the system is operational and performs the required functions. Verification of physical characteristics for establishing and verifying virtual eAtoN is based upon references to features that exist within the local environment.

Further insight into verifying physical characteristics of virtual eAtoN was demonstrated by the authors in experiments under nominal conditions as well as when precise positioning information that should normally be available using GNSS, AIS and other sources was unavailable due to a variety of manmade and natural events (Wright and Baldauf 2015). Under nominal conditions experimental results indicated that live sensor measurements coincided with expectations in terms of local physical environmental features represented by a geospatial surface model of ENC soundings and echosounder depths indicating a high level of confidence of proper positioning. Under conditions simulating GNSS/AIS unavailability, denial of service and spoofing, discrepancies were found between vessel position sensor measurements and local physical environmental features that provided a high level of confidence that virtual eAtoN could not be verified as watching properly. Environmental feature discrepancies were also identified as well as differences between depths represented by ENC soundings and depths reported by the echosounder after compensating for tide levels, hull depth and transducer offset. Differences were also detected between the bottom slope derived from ENC soundings and bottom slope derived from echosounder readings. An additional measure was examined where significant differences were detected between the rates of change of the bottom slope derived from the echosounder readings as compared to the ENC. An example of this process is provided in paragraph 7 of the text.

5.5 *Maintenance*

The use of independently sourced 3D-FLS data obtained from vessels of opportunity can provide significant advantages to the update and maintenance of all AtoN (physical, AIS and virtual) as well as nautical charts on a continual basis, and can supplement existing hydrographic survey resources. No significant differences are anticipated in the maintenance of databases and the installation and operation of virtual eAtoN beyond the normal evolution and enhancement of the methods, processes and procedures already established by cognizant national authority for physical AtoN and AIS eAtoN.

6 LIMITATIONS AND VULERABILITIES

Potential limitations and vulnerabilities associated with the implementation of eAtoN technology exist, some of which are described below. With careful planning and diligent design and implementation practices these limitations may be managed and overcome to ensure their reliable and verifiable operation is achieved.

6.1 *AIS Broadcast Range*

The range of AIS broadcasts in the VHF Frequency spectrum is limited to line of sight based primarily upon the height of the base station transmitting and vessel receiving antennae. The range of VHF signals is estimated at nominally 20 miles at sea (USCG 2015). This limits the placement of AIS eAtoN to achieve reliable performance at other than remote locations to a distance of less than 20 miles, especially inland where terrain and ground-based structures can interfere with signal propagation (Baldauf 2008).

AIS is also subject to the effects of Tropospheric ducting that can propagate VHF signals hundreds of miles from their origin (Biancomano 1998). Such effects can introduce interference sources to signals from AIS stations within the nominal AIS reception range and can result in performance reduction of AIS both ashore and on vessels (ITU 2007).

6.2 *AIS Spoofing and Jamming*

The ability to spoof and jam AIS broadcasts has particular significance where AIS eAtoN signals are used for vessel navigation. A lack of security controls can facilitate a ship being diverted off course by placing eAtoN in undesirable or even dangerous locations inadvertently, for hijacking or for other nefarious purposes (Simonite 2013).

The vulnerabilities of AIS have also resulted in its use by criminals to an attempt to evade law enforcement (Middleton 2014). Another report found that AIS data is being increasingly manipulated by ships that seek to conceal their identity, location or destination for economic gain or to sail under the security radar, and concludes that this is a fast growing, global trend undermining decision makers who rely, unknowingly and unwittingly, on inaccurate and increasingly manipulated data (Windward 2014).

6.3 *GNSS Spoofing and Jamming*

Similar to AIS, Global Navigation Satellite System (GNSS) signals can also be spoofed and jammed causing unreliable and even deceptive navigation signals to be received by vessels (Forssell B. 2009). A recent example is an experiment by a group of University of Texas at Austin researchers where a yacht was driven well off course and essentially hijacked using spoofing techniques (Zaragoza 2013). This phenomena was also the subject of a recent article in the US Coast Guard Proceedings acknowledging this as being of concern beyond the maritime industry to include the transportation sector as a whole (Thompson 2014). Jamming can have the same effects as an outage, as was demonstrated in 2010 when numerous, low power personal privacy jammers were detected as interfering with GPS involving airport operations at Newark, NJ (Grabowski 2012).

6.4 *GNSS Outages*

The worldwide GNSS is comprised of the United States GPS, Russian GLONASS, European Galileo and Chinese BeiDou systems which are at various stages of completion. These multiple systems imply that backup capabilities exist if one or more of these systems were to go out of service, either temporarily or on a permanent basis. This was demonstrated during the ten-hour GLONASS outage that occurred on 1 April 2014 where a Broadcom 47531 receiver performing the simultaneous tracking of GPS, GLONASS, QZSS and BeiDou signals was able to successfully identify and remove the bad GLONASS satellite positions (Gibbons 2014). Multiple GNSS receivers are only beginning to come into the commercial marketplace. Under normal conditions the performance of these systems is likely to equal or exceed existing, single technology systems.

All GNSS regardless of technology used are subject to the same atmospheric and signal propagation limitations, multipath interference, orbit errors, satellite geometry and orbital debris. One or a combination of such factors may degrade GNSS signals to reduce their accuracy or make their signals unreliable or unusable. With the discontinuance of Loran and no commitment to establish any backup system to GNSS using a fundamentally different positioning technology such as that used by eLoran, there is presently no alternative available for navigation other than that provided by traditional aids to navigation. The georeferencing of eAtoN to bottom features may help to reduce the overall effect of GNSS outages.

6.5 *Database Hacking*

One of the greatest vulnerabilities of eAtoN is their primary existence as data objects in cyberspace, without having a traditional physical presence to provide backup in the event of their electronic corruption or disappearance. This property makes them susceptible to hacking and denial of service attacks that can render them useless or even detrimental and hazardous to navigation.

Widespread corruption can occur at the source databases within which eAtoN objects reside at the authorized service provider. In the United States this responsibility is shared between the Coast Guard for AtoN and the Light List, and NOAA for ENC that form the nation's navigation charts. Corruption can also occur at the local level, where individual or groups of eAtoN in the same geographical area may be corrupted.

Initiatives exist at both the Coast Guard and NOAA aimed at defending their computer networks from attacks (Radgowski 2014; NOAA 2014). Both initiatives acknowledge the threats involved and are steps in the correct direction to manage and even overcome the adverse effects on national security imposed by these threats. Issues that pertain to eAtoN design, development and implementation cross agency lines, barriers and firewalls; making the solution to these problems even more difficult.

7 METHODS FOR VERIFICATION

There are three levels at which verification of eAtoN must be considered. The first level focuses on where they are represented in electronic form as data objects. Numerous vulnerabilities can exist ranging from simple data entry errors to the intentional hacking, manipulation or destruction of the data content. Compounding the severity of the problem is that eAtoN data is represented in multiple data systems across Government agencies that may be altered or modified from their original content, making the ENC a product of collaborative datasets.

The second level of verification is the actual technical performance of the eAtoN device and mechanisms themselves. The third level involves verification of the physical eAtoN characteristics as manifest at the deployed location on ECDIS.

7.1 *Data Object*

A data object defined as an item or group of items, regardless of type or format that a computer can address or manipulate as a single object implies characteristics contained within the database are highly correlated with the unique eAtoN object it represents. The corruption of these data can fundamentally alter the behavior, functionality and/or performance of eAtoN. Such corruption can occur throughout the lifecycle of the object from the characterization of data as requirements, design of the structure in which these data reside, initial entry of the data into the data structure, process of extracting the data, its fusion with other data to effect a process or outcome using a navigational display, and the final representation of the data in its intended use for navigation.

The process flow depicted in figure 3 provides a simplified example of a generic verification process that could be used on a continuous basis by cognizant service provider(s) to examine the contents of multiple databases to detect errors and inconsistencies caused by database hacking as well as errors inherent to database operations. This approach is conceptually aligned with the United States Department of Homeland Security Continuous Diagnostics and Mitigation (CDM) Program designed to protect government networks and their data.

7.1.1 *Database Structures*

Multiple databases and data structures distributed geographically across different government agencies host the data required to create, implement and support eAtoN operations. These include legacy systems already supporting AtoN characteristics modified to support eAtoN and the equivalent data requirements within the ENC, with legacy processes used to integrate these data and create their final products. The implementation and hosting of eAtoN data representations exists on different data platforms and host software, with diverse formats and timing of system updating and maintenance. How these data and relevant metadata are shared, the flow of these data managed, and the processes and frequency through which this occurs is the focus of the Committee on the Marine Transportation System (CMTS), a Federal interagency coordinating committee in the United States. This should be accomplished in a manner that coincides with the update and revision cycles of the contents of the data structures independent of the development of products derived from the data contents. This also requires proper filtering and assurance that the destination system and associated processes be sufficiently robust so as not to be overwhelmed by the volume of data received.

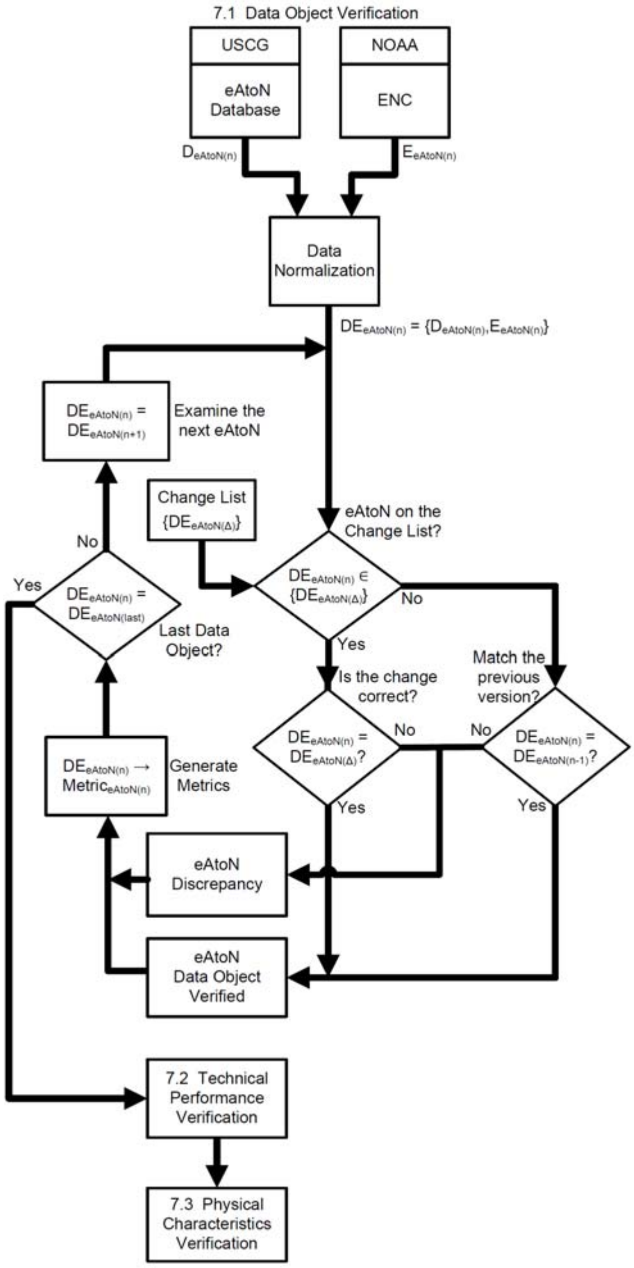

Figure 3. eAtoN Data Object Verification Process.

7.1.2 *Data Normalization*

Prior to initiating data object verification it is necessary that the contents of the data streams be processed and normalized from their native formats contained within the source databases to a common format ensuring proper comparisons of the data may be accomplished. This includes data for both AtoN and eAtoN since they are integrated together into the same legacy systems; ensuring data objects for both forms are verifiable and can be verified using the same process. This also requires that inputs of metadata, human interface and guidance, a priori data, and other machine data necessary to perform verification are prioritized and properly associated with the data for subsequent processing.

The product of the data normalization stage represents the totality of the data from all sources necessary to accomplish verification:

$$DE_{eAtoN(n)} = \{D_{eAtoN(n)}, E_{eAtoN(n)}\} \quad (1)$$

where D=AtoN/eAtoN; and E=ENC data objects. Note that the process flow of figure 3 has been simplified to show eAtoN data, however both AtoN and eAtoN data objects from the same data sources can be verified using this same technique. These data are provided at a rate sufficient to process changes in synchronization with the data at their source databases.

7.1.3 *Verification Process*

Verification of normalized data is accomplished with the knowledge of changes that are supposed to have occurred and the implication that any other changes that may be detected are therefore discrepancies. Each individual normalized AtoN/eAtoN data object is compared to the change list to determine whether it is contained within the set of changes expected for that specific individual process:

$$DE_{eAtoN(n)} \in \{DE_{eAtoN(\Delta)}\} \quad (2)$$

If the data object is part of the set of changes then the characteristics of the normalized data object are compared to those on the Change List to ensure their proper implementation:

$$DE_{eAtoN(n)} = DE_{eAtoN(n\Delta)} \quad (3)$$

where an affirmative result causes a determination of the AtoN/eAtoN as a verified data object and a negative result causes a determination of a data object discrepancy.

If the data object is not part of the set of changes then the characteristics of the normalized data object are compared to those of the previous revision (n′) of the data object:

$$DE_{eAtoN(n)} = DE_{eAtoN(n')} \quad (4)$$

where an affirmative result causes a determination of the AtoN/eAtoN as a verified data object and a negative result causes a determination of a data object discrepancy.

Completion of individual data object verification is achieved with a determination of verified or discrepancy, wherein metrics are generated followed by the examination of the next data object:

$$DE_{eAtoN(n)} \rightarrow Metric_{eAtoN(n)} \quad (5)$$

$$DE_{eAtoN(n)} = DE_{eAtoN(n+1)} \quad (6)$$

Upon detection of the last data object, data object verification for this process run is completed and initiation of Technical Performance is then followed by Physical Characteristics verification.

7.1.4 *Metrics*

Data object examination is complete when steps necessary to determine verification or discrepancy have been achieved. Metrics to measure verification progress and resultant products must be established to indicate process completion and performance scores are created to indicate product quality and deficiency levels. Such metrics must also ensure feature and capability traceability to product specification and design, stability of software configuration, adequacy of depth and breadth of testing, and overall product maturity. Configuration controls and trouble reporting procedures need to be established to track the rate, type and severity of discrepancies as well as required changes to software, processes, design, and requirements resulting from discrepancies found and corrected.

7.2 *Technical Performance*

Verification of the technical performance of AIS eAtoN lies primarily in determining that the system is operational and performs the required functions. General guidance on this subject may be found in the appropriate IALA guidelines (IALA G1028). Guidance on verification of AIS equipment should be found in the technical specifications, acceptance test procedures and maintenance test procedures appropriate for specific equipment configurations.

7.3 *Physical Characteristics*

The existence of eAtoN as data objects without having a traditional physical presence does not necessarily preclude their verification using many of the same physical parameters as AtoN. This may provide an ideal opportunity to demonstrate the use of technology to resolve doubts and concerns regarding navigation strictly by electronic means rather than traditional methods by using live environmental sensor data to obtain fixes to known landmarks, structures, bottom terrain features and buoys.

Many of the physical characteristics of physical and synthetic AIS eAtoN are shared with their associated AtoN. Characteristics unique to physical, synthetic and virtual eAtoN include type, position and operational status as well as the presentation of these characteristics on navigational displays, e.g., radar and ENC/ECDIS. The highest priority is depiction of position, which is closely followed by the other characteristics.

7.3.1 *Position*

The easiest and most risky means of verifying the eAtoN characteristic associated with position is though the use of GNSS to compare the measured position with the charted position. In the case of physical and synthetic eAtoN there is a physical AtoN present at the location as well as an AIS/ECDIS representation to corroborate the GNSS fix, assuming that verification of AtoN position has already been accomplished. Prudence would dictate that bearings to physical landmarks and features be also made to further confirm the reliability of the fix.

For AIS and non-AIS virtual eAtoN, the problem becomes more complicated since there is no physical AtoN presence at all. A fix developed based upon bearings taken to physical landmarks and features would be a suitable method for verifying location only in the case where such features were visible and not obscured or out of visual or radar range. However, there is another means to take such a fix through reference to ground. This may be accomplished, again using modern technology, through verification using known surface landmarks (radar bearings to known landmarks, etc.). This can include bottom features obtained through wireform and/or point cloud ENC models compared to live 3D-FLS and/or echosounder measurements made over time intervals using running averages and derivative trend information. ENC information is already on board vessels in the charting equipment (e.g., ECDIS) and requires the proper resolution and correlation to determine bearings, produce the necessary fixes and generate warnings. Such capabilities are possible through the use of the IHO S-100 Universal Hydrographic Data Model that supports a wider variety of hydrographic-related digital data sources and products than the IHO S-57 IHO Transfer Standard for Digital Hydrographic Data. Specifically, this includes new spatial models to support imagery and gridded data, 3-D and time-varying data, and new applications beyond those of traditional hydrography.

Fix and bearing information to known physical environmental features for each eAtoN can be taken during initial installation and encoded as part of its characteristics. These characteristics can then be used anytime thereafter to verify position accuracy during normal use and subsequent verification. Data encryption of position characteristics can also be used to ensure their security and validity.

Such methods can also be used to detect the effects of AIS and GNSS jamming and spoofing since the presumed location based upon GNSS is likely to not coincide with environmental features. Used with inertial backup, it would also be possible to verify position in the event of GNSS outage. Data obtained from echo sounder measurements using this technique on ground tracks 1, 2 and 3 shown in figure 4 may appear similar to that shown in table 1.

Transit of the intended track (Track 2) is dependent upon accurate GNSS position correlation with chart location data. Should either AIS or GNSS spoofing or jamming occur resulting in inaccurate positioning, differences in both the depth and/or the rate of change of depth profiles between the intended and actual transited courses would be detectable. For example, should spoofing occur where the vessel believes itself to be on the intended Track 2 based upon AIS/GNSS sensor readings yet follows either of error Tracks 1 or 3, deviation from the proper course will be detected through comparison of derived bottom feature and contour data illustrated in table 1 with independently obtained echo sounder readings even though AIS and/or ECDIS is falsely displaying the intended course. Should GNSS jamming or outage be encountered, these same bottom reference data can be used with inertial system backup to continue navigation and accurately update the vessels position.

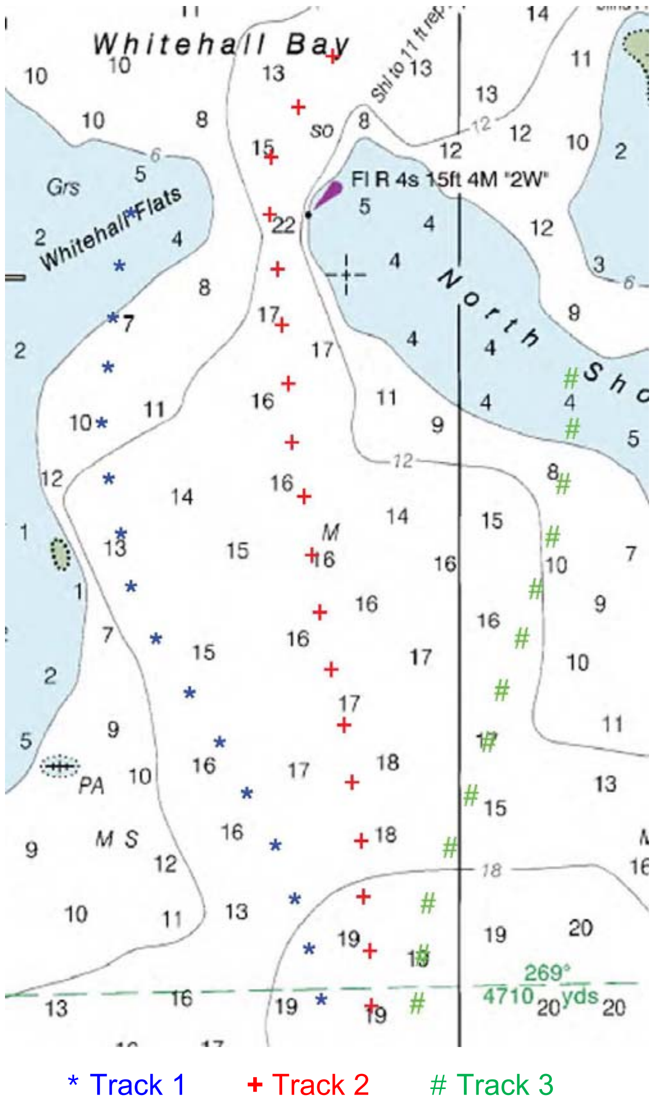

Figure 4. Divergent Ground Tracks 1 and 3 Compared to the intended Ground Track 2.

Table 1. Difference and Rates of Change of Error Track 1 and Error Track 3 from Intended Track 2 shown in Figure 2.

	t=	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
* Track 1	Depth	19	17	15	16	16	16	15	15	14	13	13	10	8	7	3
	dD/t	0	2	4	2	2	1	2	1	2	3	4	9	14	8	11
	dD/dt		2	2	-2	0	1	1	-1	1	1	1	5	5	-6	5
+ Track 2	**Depth**	**19**	**19**	**19**	**18**	**18**	**17**	**17**	**16**	**16**	**16**	**17**	**19**	**22**	**15**	**14**
	dD/dt		**0**	**0**	**1**	**0**	**1**	**0**	**1**	**0**	**0**	**-1**	**-2**	**-3**	**7**	**1**
# Track 3	Depth	19	19	19	18	15	17	17	16	12	10	8	4	4		
	dD/t	0	0	0	0	3	0	0	0	4	6	9	15	18		
	dD/dt		0	0	0	3	-3	0	0	4	2	3	6	3		

time (t) track from bottom to top of chart.

7.3.2 *Other Characteristics*

Once verification of accurate eAtoN positioning has been accomplished, verification of additional characteristics that include eAtoN type, name, etc., would be performed by examining the contents of the AIS/ECDIS information on the navigation display. For example, the type indication should correlate with the proper valid symbol for cardinal marks (N/E/S/W), lateral marks (IALA A/B port and starboard), isolated danger, safe water, special purpose or emergency wreck marking as published for that location. eAtoN name and other characteristic verification would be accomplished using the same method.

7.3.3 *Metrics*

Physical characteristic examination is complete when all steps necessary to determine verification or discrepancy have been accomplished. Metric results provide traceability of verification and identify areas where further product and process maturation is needed. Data collection for many metrics can also be automated, ensuring measurable progress in completing verification and generating performance scores to aid in their understanding.

8 PRESENT STAGE OF MATURITY

eAtoN technology is very much in an early stage of development with only a handful of AIS virtual eAtoN deployed in experimental evaluation program locations worldwide. Non-AIS virtual eAtoN configurations are even less mature as theoretical concepts and implementations have yet to materialize outside the laboratory. Participation of the maritime community is being actively solicited by cognizant authorities and authorized service providers to ensure progress is constructive and meeting user needs. This is evidenced by U.S. Army Corps of Engineers (USACE), NOAA, and Coast Guard invitations to maritime stakeholders to participate in Future of Navigation Public Listening Sessions and Navigation Information Days throughout the country to collect comments and feedback regarding requirements for navigational information and service delivery system needs (Smith 2014; NOAA 2014a). Additional AIS eAtoN installations are being deployed throughout the United States in an attempt to fulfill a wider set of maritime needs.

9 CONCLUSIONS

Installation of AIS-based eAtoN system facilities are continuing as operational experience and results showing their utility are documented. A critical need exists for non-AIS eAtoN technology for use in remote and sensitive environments as described. Further research and development should be encouraged in this area.

Significant limitations and vulnerabilities exist in the AIS and GNSS technologies that support eAtoN operations. Spoofing and denial of service attacks will accelerate due to the lack of security in both of these areas as states and criminal organizations gain experience in using and misusing these technologies. Opportunities exist using currently available data fusion and sensor technology to mitigate these problems and reduce the severity of and even eliminate their effects, increasing marine safety in general and specifically the safety of navigation. The techniques proposed for verification of eAtoN can also be applied to improve and automate portions of existing verification practices for all AtoN: physical, AIS and virtual.

Potential also exists for expanding IMO e-Navigation capabilities through integration of 3D-FLS technology as a means for enhancing the safety of navigation. One aspect of this is that the Polar Code should be amended to mandate 3D-FLS as an echo-sounding device having forward-looking capabilities as a vessel carriage requirement in the Arctic. Alternatively, 3D-FLS should qualify as one of the two already required independent echo-sounding devices.

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Hydrographic Survey in Remote Regions: Using Vessels of Opportunity Equipped with 3-Dimensional Forward-Looking Sonar

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ABSTRACT
Areas of the world where the physical environment is relatively unknown in terms of hydrographic surveys and nautical chart content are under pressure from increasing vessel transits as well as tourism and exploration for natural resources. These areas include the Arctic, Antarctic, and even remote tropical regions. Research efforts are described that are intended to exploit the capabilities of commercial off-the-shelf 3-dimensional forward-looking sonar installed on expeditionary and other vessels of opportunity that operate in these regions. This approach can provide high-resolution full-bottom survey data to supplement the assets of national hydrographic survey authorities in exploring and charting these regions.

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Introduction

The world's frontier is represented by the Arctic, Antarctic, and some tropical regions, where comparatively few have ventured and many dangers lurk in the paths of those who are ill-equipped and unprepared to deal with the risks and consequences inherent to operating there. This includes mariners engaged in such operations as well as those whose mission is to rescue them. In these regions hydrographic surveys to modern standards are rare and charts are unreliable. It is advantageous for a vessel to be equipped with sensors to detect bottom terrain ahead of the vessel rather than to transit an area blind as to the perils that lie ahead. This topic has taken on greater significance as Arctic waters open up to increased vessel traffic between ports that exist within the region, as well as transits between Asia and Europe to reduce route distances and shipping times. This is demonstrated as Arctic Sea ice coverage reached the lowest recorded minimum in 2012, averaging a rate of decline of 13.3% per year between 1981 and 2010 (NASA 2015). The minimum sea ice coverage for 2015 was the fourth lowest of all previous satellite observations (Viñas 2015). In 2015, maximum sea ice coverage was the lowest on record (NOAA 2015a).

The present state of Arctic hydrography

According to the U.S. National Oceanographic and Atmospheric Administration (NOAA), the Arctic is severely deficient in many of the capabilities extended to the rest of the Nation

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as there is virtually no geospatial infrastructure for accurate positioning and elevations; sparse tide, current, and water-level prediction coverage; obsolete hydrographic data; and poor nautical charts (NOAA 2011). Large gaps are acknowledged in the information that NOAA does have, illustrated by empty white space on nautical charts of the region. Most Arctic waters off of Alaska that are charted were surveyed with obsolete technology dating back to the 1800s.

The Northwest Passage (NWP) and the Northern Sea Route (NSR) are the two primary transit routes through the Arctic as shown in Figure 1. The portion of the NWP that crosses the top of the United States includes the Beaufort and Chukchi Seas and the Bering Strait. Figure 2 illustrates one of many areas in the Arctic, where soundings effectively do not exist across a large portion of an official NOAA chart. Similar conditions exist on the Canadian portion of the NWP where it was reported in 2009 that less than 10% of the Arctic in Canada was surveyed to modern standards (Arctic Council 2009). Arctic survey coverage along the NSR in Russia appears more comprehensive than the NWP, where recent efforts focused on survey of the route's least-studied areas encompassing over a 31,000 square km area of the

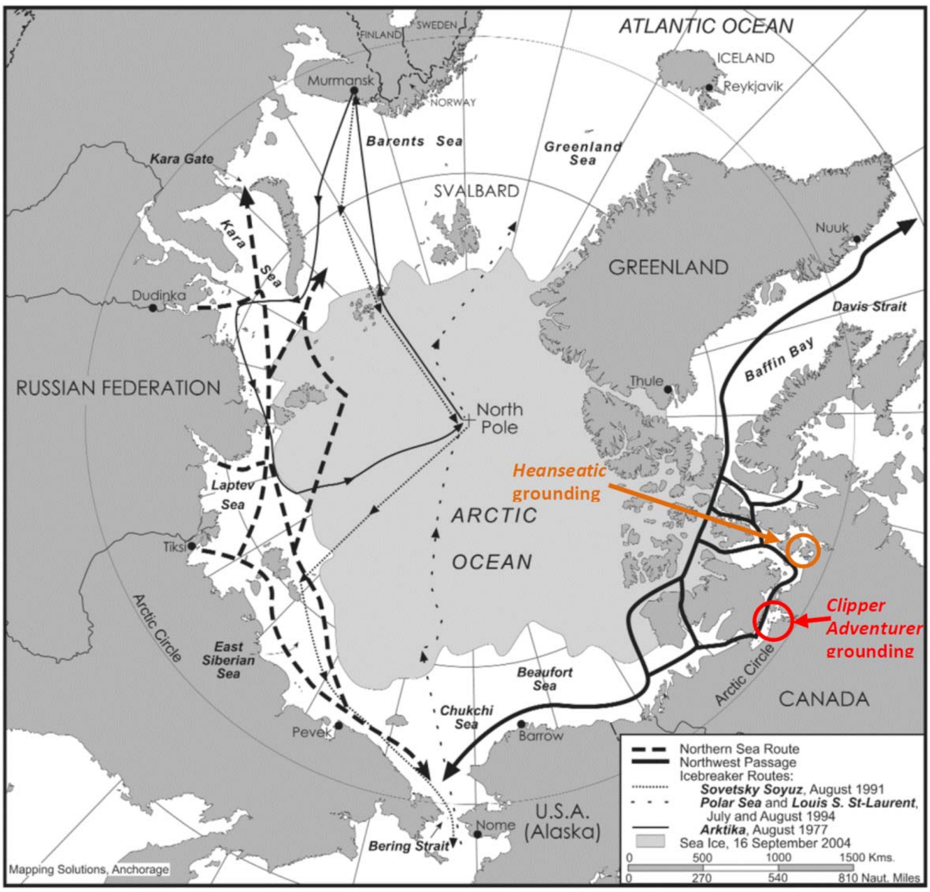

Figure 1. Arctic routes: Northern Sea Route (NSR) and Northwest Passage (NWP). Source: Arctic Marine Transport Workshop, 28-30SEP2004, U.S. Arctic Research Commission. Annotations for *Clipper Adventurer* and *Hanseatic* by Authors.

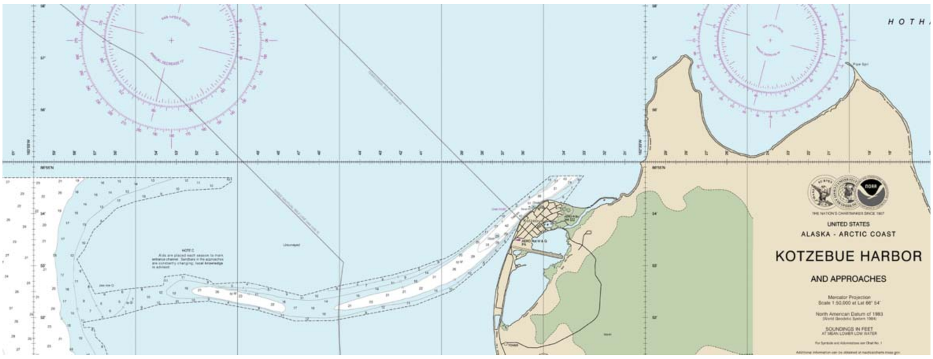

Figure 2. Portion of NOAA chart 16161 for Kotzebue Harbor, Alaska with large areas of unsurveyed waters shown in solid blue and without soundings.

sea floor (AMSA 2013). In addition to its use in the development of nautical charts, proper hydrographic survey at high resolution with full-bottom coverage is essential to the placement of physical aids to navigation (AtoN) such as buoys that are used visually or by radar to assist vessel navigation. However, AtoN are difficult to place and maintain in the Arctic due to the large distances involved and the movement of ice.

Increased traffic in the Arctic

Despite these difficulties, vessel traffic is increasing with the transit of 30 vessels through the NWP in 2012 as compared to 2–7 vessels completing this transit each year from 1990 to 2006 (Macfarlane 2012; NTDENR 2015). NSR traffic saw 46 vessels transiting in 2012 increasing to 53 in 2014 (NSRIO 2012, 2014). The potential exists between 2040 and 2059 for non-ice-classed vessels to navigate previously inaccessible areas of the Arctic without icebreakers (Sullivan 2013). Challenges posed by the environment, the lack of hydrographic information, and AtoN by which vessels navigate increase the risk to vessels operating in the Arctic. Shipping casualties in the region have risen from approximately one per year, with a total of seven occurring during the period between 2002 and 2007, to an average of 45 per year between 2009 and 2013 (Allianz 2014). Total losses experienced in the Arctic regions of Russia, Canada, and Alaska were 46 (3.1%) of the 1,462 total losses worldwide between the years 2002 and 2011. This increased to 6 (5.1%) of 117 total losses in 2012 and 4 (4.3%) of 94 total losses in 2013 (Allianz 2014, p. 12).

Greater consequences of Arctic groundings

Unintentional groundings can occur with greater frequency in areas such as the Arctic where water depths are unknown, and represented the leading worldwide cause of oil spills of greater than 700 tons between the years 1970 and 2009 (Butt et al. 2012; Nicolas-Kopec 2012; NMD 2011; TSB Canada 2013; Zhu et al. 2002). Even when not sustaining a total loss, groundings have serious implications in terms of casualties to life, property, and the environment due to physical impact and chemical spills. Increasing vessel traffic engenders more severe consequences of grounding in remote regions, where harsh weather and a lack of resources exists for search and rescue, salvage, pollution remediation, and support infrastructure. One example is M/V *Clipper Adventurer* that grounded in 2010 with 128 passengers on an uncharted shoal in Coronation Gulf, Nunavut in Canada along the Northwest Passage, also illustrated in Figure 1. The Transportation Safety Board of Canada concluded the route followed was inadequately surveyed, consisting of a single line of soundings in an area where the depths were virtually unknown (TSB Canada 2012). Another example is the grounding of *Hanseatic* in the Simpson Strait, Canada, in August 1996. The accident investigation report states that the ship ran aground when the Master was relying on a critical navigational buoy that had previously been moved by ice from its original position (TSB Canada 1996). Despite the eventual safe outcomes of both accidents there was significant risk and potential for adverse consequences.

Dramatic and highly publicized groundings continue to occur throughout the world resulting in many lives lost, pollution of the seas and shorelines, salvage costs that have been enormous, and incalculable damage to ecosystems and wildlife. The names of the vessels involved have become infamous and include *Exxon Valdez, Petrozavodsk, Rena*, USS *Guardian*, and *Costa Concordia*. Although accidents of such magnitude in the Arctic have yet to occur in the modern era, the combination of increased vessel traffic in the region, poor charts, harsh environment, and lack of infrastructure only increases the potential that such a catastrophe will eventually take place in the region at an unprecedented and calamitous cost.

Three-dimensional forward-looking sonar solution

The approach presented describes an opportunity to expand the scope and coverage of environmental data captured from vessels of opportunity plying these waters to help reduce the many limitations of products available to mariners in the region. This is accomplished from the perspective of using 3-dimensional forward-looking sonar (3D-FLS) as a means to navigate poorly-charted and unknown waters.

Previous research has investigated the use of relatively short-range FLS systems for use in underwater obstacle detection and avoidance for use by autonomous underwater vehicles (AUV) and remotely operated vehicles (Fallon et al. 2013; Ferreira et al. 2014; Koh et al. 2009; Martin et al. 2000). Others have considered the techniques of implementation and image analysis using 2-dimensional FLS (Berdnikova et al. 2010; Hurtos et al. 2012). Recent research in the area of 3D-FLS addresses both the technical aspects of such systems as well as their use in obstacle avoidance by AUVs and ships (Assalih 2013, Yakubovski et al. 2014). However, the use of 3D-FLS for hydrographic survey has received little attention by industry or in academic research.

3D-FLS technology is relatively new to commercial shipping with range capabilities now suitable for use by larger vessels. It is not designated as a requirement for carriage by vessels of any sort by the International Maritime Organization (IMO) or national authorities. 3D-FLS capabilities are currently judged based upon manufacturers' performance specifications, and their limitations are relatively unknown except for rules of thumb based upon range in terms of depth. Yet the benefits that result from its use may be enormous. Experiments are described where results help to determine the accuracy of 3D-FLS with respect to the Electronic Navigation Charts (ENC) required for vessel navigation. Additional experiments are described using 3D-FLS to identify bottom topography characteristics useful in verifying position. The successful accomplishment of these experiments can form a basis to consider the data acquired from 3D-FLS as an independent means to supplement existing hydrographic resources worldwide for chart making and other maritime uses.

Objectives

Two different sets of experiments have recently been accomplished to explore the usefulness and versatility of 3D-FLS to carry out different tasks. The first focused on determining its accuracy in representing the physical environment in which it operates, and the second involved its capability to provide data of sufficient resolution to assist in verifying position using geographical features of the bottom. Based upon the results obtained in completing these two objectives, an initial assessment was attempted to determine whether the quality of such data may be useful to expand the corporate body of hydrographic knowledge for poorly surveyed regions. Although embodying different requirements, our expectations are that high-quality 3D-FLS with suitable range, regardless of manufacturer, should be capable of providing data necessary to accomplish these objectives as follows:

(1) Comparing 3D-FLS full-bottom coverage measurements with an ENC derived from hydrographic survey data. The expected result is a number representing a sounding derived from 3D-FLS that can be compared with a sounding for the same location as indicated on an ENC.

(2) Establishing geographical references to assess the feasibility of verifying positions of virtual AtoN as being correct as part of a determination of their watching properly. The expected result involves the calculation of several measures used to determine whether or not a vessel's apparent position is different from the expected position.

Modern 3D-FLS technology is designed to aid vessel navigation by creating a representation of the underwater environment enabling detection of bottom features forward of the bow out to a distance of up to 1,000 m. This is contrasted with multi-beam sonar which is used primarily for hydrographic survey by specialized vessels and not for navigation. With both systems using similar technologies, the 3D-FLS transmitter is aimed forward instead of downward. Bottom features, objects, and soundings are detected by determining range, azimuth, and elevation information using a sonar signal steered across and ahead along the path of the vessel, or by creating a single ping from which snapshots of the environment are obtained. It is presently available as a commercial off the shelf product and can directly and significantly reduce the risks of passage by those operating in Arctic waters.

Integral to these experiments are factors associated with bottom conditions and sea water salinity. Bottom conditions can greatly influence sonar horizontal range, which can extend from eight to twenty times the depth ahead. Sea bed topographies that slope upwards with targets that are large and consist of hard rock and/or coral provide much better acoustic signatures than sandy bottoms covered by grass or vegetation or bottoms that slope downward. Salinity can be highly variable, especially in the Arctic (Serreze et al. 2006). These experiments represent initial attempts to explore the effect of such factors on accomplishing the objectives.

Two different locations, illustrated in Figure 3, were chosen to conduct these experiments based in part on the availability of each system for use, sea bottom characteristics and the properties of the water column. Narragansett Bay near Newport, Rhode Island, US was the location of experiments conducted during 2014 and 2015 and is included in NOAA ENC US5RI22M using a scale of 1:20,000. This area is open to the Atlantic Ocean with salt water,

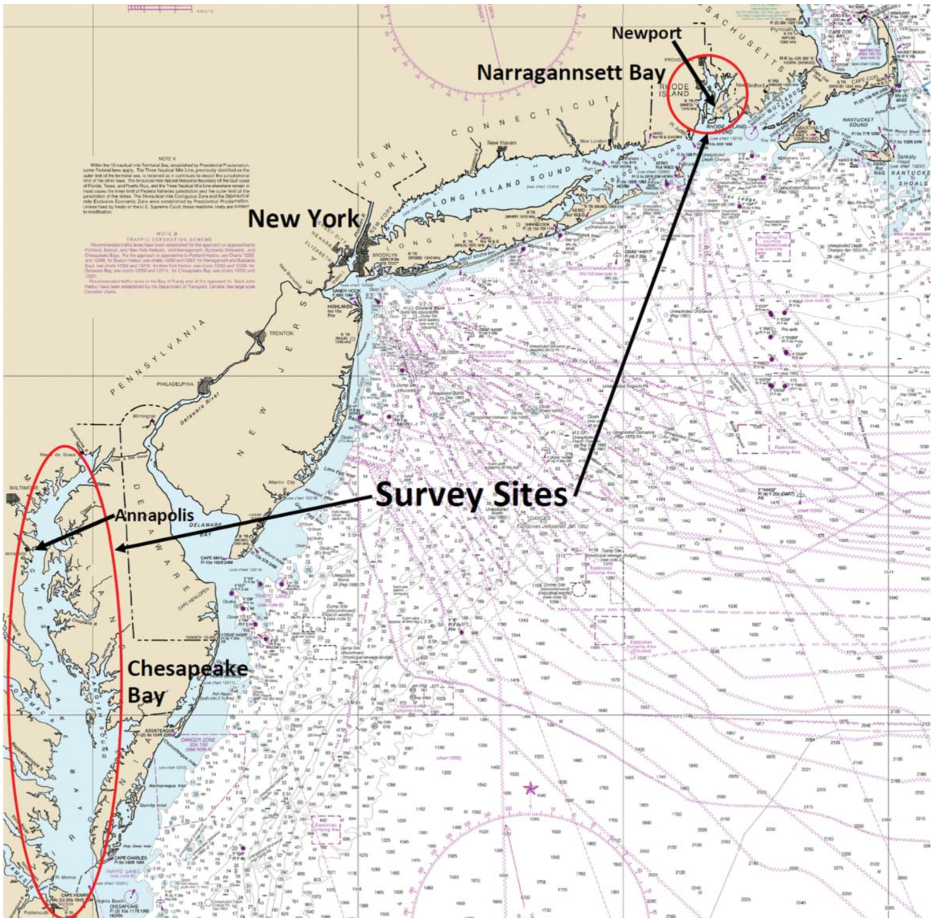

Figure 3. Survey sites near Newport, Rhode Island (shown in Figure 4) and Annapolis, Maryland (shown in Figure 5). Source: NOAA chart 13003.

and the bottom consists primarily of mud and rock. It was surveyed by the National Ocean Service between the years 1990 and 2011 with full bottom coverage. The Chesapeake Bay in the vicinity of Annapolis, Maryland, US included in NOAA ENC US5MD22M was the location of experiments that were conducted in 2015. The scale of this chart is 1:25,000. This area contains brackish water and was surveyed by the National Ocean Service between the years 1940 and 1969 with partial bottom coverage. The bottom generally consists of mud and sand with large areas of grass.

The first objective was accomplished in the Narragansett Bay using System "A," 500-m-range 3D-FLS system. The investigation examined sonar data accuracy, refresh rate, and span of geographic coverage to help assess the potential to supplement hydrographic survey efforts (Wright and Zimmerman 2015). This system represents the latest technological state-of-the-art capable of installation on vessels from approximately 10 m to the largest of vessels using one transducer mounted at the bow, and is very similar to their other product having range capability to 1000 m. These 3D-FLS systems are priced relatively near the top of the range for such equipment. This system was installed on the research vessel *Cap'n Bert*, owned and operated by the University of Rhode Island Department of Fisheries, Animal and Veterinary Sciences.

Table 1. Comparison between forward-looking sonar system specifications.

Specifications	System "A"	System "B"
Maximum detection depth (m)	50	100
Operating frequency (kHz)	61	200
Maximum detection range (m)	500/1,000	200
Vertical coverage (°)	60	90
Horizontal field of view (°)	60 or 90	60
Maximum transmit power (W_{rms})	$<$1,500	Not specified
Angular accuracy (°)	1.6	Not specified
Roll/pitch compensation (°)	$\pm$20	Not specified
Roll/pitch accuracy (°)	0.5	Not specified
Maximum vessel speed (kts.)	25	Not specified
Screen refresh rate (seconds)	~1.6	1–2
Equipment price ($US)	~ 140,000	~ 11,000

The second objective was accomplished in the Chesapeake Bay using System "B" 200 m range 3D-FLS. This investigation focused on detecting bottom topography and features to facilitate georeferencing as a means to determine position under compromised GNSS and AIS conditions (Wright and Baldauf 2015). This system is suitable for installation on smaller vessels of approximately 7–30 m in size, uses two transducers mounted at the stern of the vessel and is priced an order of magnitude less than System "A." System "B" system was installed on a research vessel and test bed leased to GMATEK, Inc.

Specifications for both 3D-FLS systems are summarized in Table 1. Each transmits single pings to create a mosaic representing a swath of the bottom topography and specific targets ahead as the vessel progresses along its course. The systems chosen are representative of 3D-FLS technology that is commercially available, albeit with different capabilities at widely divergent prices. A significant difference between these two systems is their data recording capabilities. System "A" records high-resolution data from an array of hydrophones approximately every 1.6 seconds corresponding to each sonar ping. Bottom topography may be reproduced both numerically and graphically in imagery using these data. System "B" does not record depth measurement data in electronic format that is available for later analysis, with the only available information provided live through the user interface.

Methodology

When evaluating the capability of 3D-FLS as a means to navigate by providing visibility into the undersea environment, it is necessary to have a practical, reliable, and traceable baseline for data against which comparisons may be made. For the purposes of this study there are two possible criteria: The ENC that mariners are required to use for navigation, and multibeam sonar data obtained during hydrographic surveys from which ENC are created.

The legal requirement for all ship navigation irrespective of size is stipulated in IMO and national regulations that nautical charts and nautical publications are required to plan and display the ship's route for the intended voyage and to plot and monitor positions through the voyage (SOLAS 2011). Authorization for all the U.S. vessels to use ENC in fulfillment of chart carriage requirements was issued by the U.S. Coast Guard in February 2016 (NVIC 01–16). According to NOAA specifications, the highest resolution that hydrographic data can support is rarely needed, resulting in the use of a compromise grid resolution between the highest resolution possible and a resolution required for navigation products (NOAA

2015b). Grid resolution generally increases from the open ocean to coasts and embayments to better represent sea floor complexity and shallow water features. The nautical chart is then produced from scale-appropriate generalizations of the navigation surface elevation model created from the survey data. For example, where multiple soundings of the same value exist across a portion of the sea floor, one or more of the soundings may not be shown on the chart. These generalizations are needed to create a visual chart representation of soundings and other information that is suitable for viewing by mariners. Otherwise, nautical charts and the ENC that provide information for display on vessel Electronic Chart Display and Information Systems (ECDIS) used would be densely crowded with overlapping numbers and symbols that would render the display unintelligible.

The legal standard by which ships are required to navigate are the ENC derived from hydrographic surveys and not the hydrographic data itself. Comparisons in our experiments were made between 3D-FLS data representing the undersea environment and the ENC corresponding to the areas of transit where the experiments were conducted. This is consistent with the customary use of a single-beam echo sounder to determine water depths corresponding to an ENC while a vessel is underway as a means to ensure safe passage. Neither the 3D-FLS nor the single-beam echo sounder perform speed of sound or salinity measurements to calibrate their performance to International Hydrographic Organization (IHO) hydrographic survey standards. However, crowd sourcing of single-beam echo sounder data is currently being considered to address a significant lack of bathymetric data by IHO (NGDC 2016). The results achieved in pursuing the objectives of these experiments will help determine the viability of independently sourced 3D-FLS data for this same purpose.

Experimental procedures

Objective 1

The vessel on which System "A" was installed transited a course of 180° (±2°) at a speed of 5 kts. along a bottom that slopes downward from depths ranging from approximately 60 ft (18.3 m) to 80 ft (24.4 m). This track is shown in Figure 4 spanning a distance of 0.41 nautical miles (0.76 km) with four prominent soundings laying along and abeam the track within a range of 5–45 m from the track centerline. The charted locations α, β, γ, and δ were then correlated with the closest position from which sonar ping data were available and where sonar data provide coverage of the depth soundings locations (Positions A, B, C, and D). Full-bottom coverage measurements were made at Positions α, β, γ, and δ along the transit path. Positions 1–4 were identified on the NOAA chart as being the closest pings at right angles to the depth soundings (Positions A through D) marked by "X" representing points ahead of the vessel on the same distance arc abeam to where the ENC soundings lie that are circled.

Data acquisition was performed at a rate of 1.6 seconds per ping resulting in full-bottom image sampling every 13 ft (4 m) and accumulating 190 samples along the centerline of the 90° arc of sonar coverage along the entire transit route. Bearings were taken at four locations along the transit route from the transducer location at the bow to the locations of four soundings that appear on the ENC. Depth measurements made at each of the four sounding locations were noted, adjustments were made based upon transducer offset and tides, and subsequently compared with the soundings shown on the ENC.

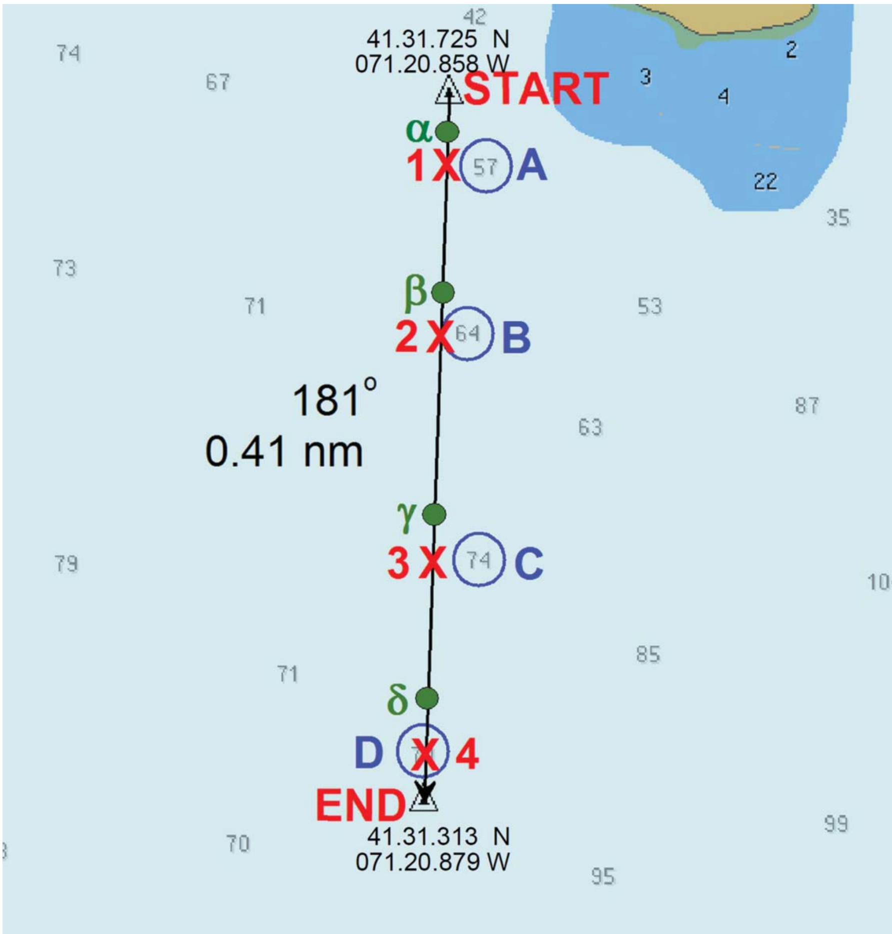

Figure 4. Portion of research vessel transit near Newport, Rhode Island along a track to assess 3D-FLS accuracy, with soundings in feet (Wright and Zimmerman 2015).

Objective 2

The vessel on which System "B" was installed transited four different tracks from south to north at a speed of 10 kts. along a bottom whose depth ranged from approximately 9 to 20 ft (3–6 m). Data acquisition was accomplished by capturing raster screen images at a rate of approximately once every 5 seconds resulting in sampling every 90 ft (27.4 m) and accumulating 14 samples along the centerline of the 60° arc of sonar coverage along each of the transit routes. Bottom topography data were acquired and compared with ENC soundings data, with similarities noted between the sonar imagery and the ENC using the visual display. The four tracks depicted in Figure 5, one of which (Baseline) passed directly over a wreck depicted on an ENC and the other three tracks (Error West, Error Middle, and Error East) transited along parallel courses that did not pass over the wreck. A simulated AIS virtual AtoN was also placed over the wreck location in the ENC. Each track covers a distance of approximately 0.2 nautical miles (370 m). The Baseline Track establishes a reference where navigation was accomplished using valid Global Navigation Satellite System (GNSS) data, while Error Tracks West, Middle, and East simulate navigation using erroneous GNSS data

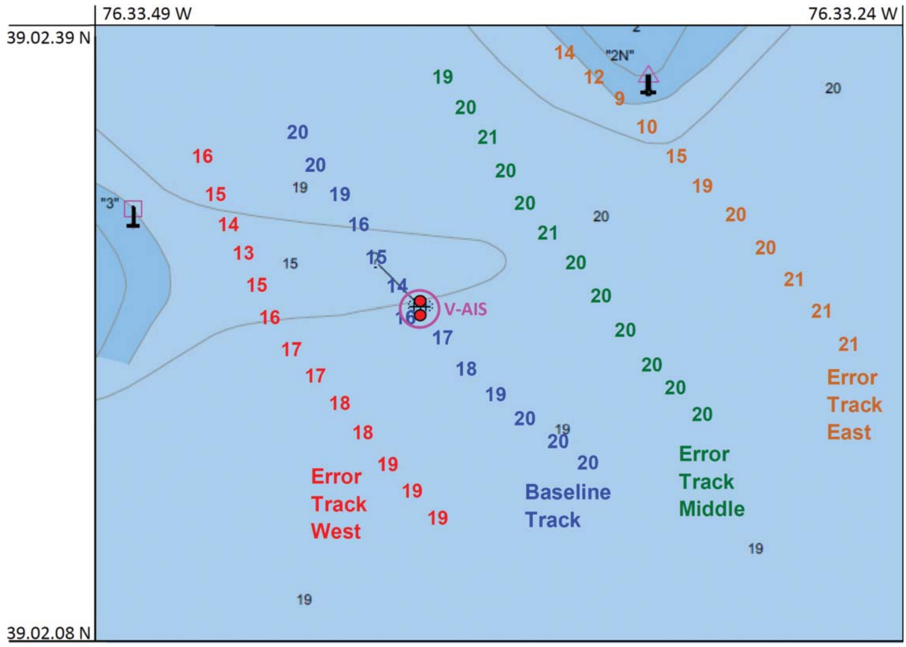

Figure 5. Wreck mark for simulated AIS virtual AtoN verification by georeferencing near Annapolis, Maryland showing correct track (Baseline Track) and error tracks (Error Tracks West, Middle, and East) transited as a result of GNSS spoofing. Depths are in feet (Wright and Baldauf 2015).

as may result from spoofing and denial of service attacks caused by jamming or other nefarious deed.

The process shown in Figure 6 was followed to create a soundings model near a wreck appearing on the ENC and in the Light List that contains a list of lights, sound signals, buoys, daybeacons, and other aids to navigation (Light List V2). This was accomplished by producing a surface elevation model of System “B” soundings data through conversion of raster image attributes to vector values in a machine-readable layer supplementing the original ENC soundings (Pendleton and Wright 2002). The technical approach integrated feature extraction using edge detection algorithms and optical character recognition. In addition to soundings, depth information is represented in part by lines and edges that interrupt relatively large uniform regions of the raster image. Methods used exploit a multiresolution analysis scheme with the underlying principle being that the edges and lines of the sonar display features (e.g., soundings, contours, etc.) within the raster image contribute most of the information, while numeric characters provide context. Data were also acquired from a single-beam echo sounder installed on the research vessel during transit of the Baseline Track and traced over the corresponding path in an ENC using GNSS. Data gathered were tested using the measure:

1. Depth soundings contained in an enhanced ENC comparison to single-beam echo sounder depth measurements (D) adjusted for tide, transducer offset, and other relevant factors.

The research vessel transited the Baseline Track using correct GNSS data, and then Error Tracks West, Middle, and East as a result of GNSS signals simulating spoofing that indicated the vessel appeared to be transiting the Baseline Track. These paths were traced over the bottom terrain using a single-beam echo sounder and compared to values expected for the

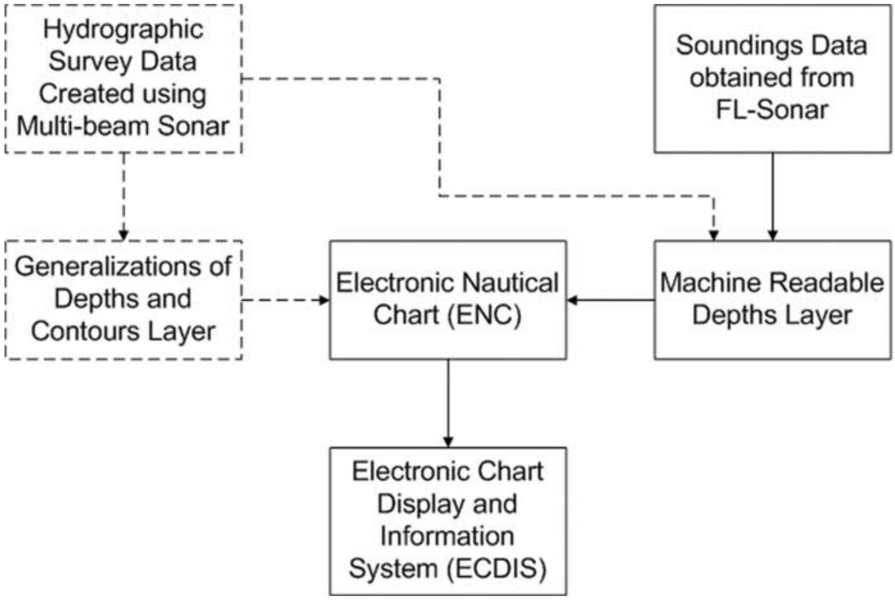

Figure 6. Process for virtual AtoN wreck mark verification by georeference, using a machine-readable soundings (depths) layer in the ENC.

Baseline Track in the full-bottom coverage ENC machine-readable soundings layer using two additional measures that include:

2. Change of bottom slope represented in an enhanced ENC comparison to single-beam echo sounder depth measurements (Dm).
3. Rate of change of bottom slope represented in an enhanced ENC comparison to single-beam echo sounder depth measurements (Dm_a).

Results

Objective 1: Compare 3D-FLS full-bottom coverage measurements with an ENC

The measurement results accomplished during transit along the track shown in Figure 4 are illustrated in Table 2. Vertical uncertainty averaged just less than 1.4 ft (0.4 m) and horizontal uncertainty approached 5 m using Wide Area Augmentation System (WAAS) Global Positioning System (GPS) sensors. The elapsed time to transit the route was just under 5 minutes during which information from 190 sonar pings were obtained resulting in 2.1 gigabytes of data collected. Additional experiments were conducted at two other nearby locations in the survey area using the same methods, with similar results.

This scenario compares depth soundings obtained from the System "A" 3D-FLS with soundings present on ENC of the same area. After compensating for vessel offsets and environmental factors, the differences in soundings measured by System "A" 3D-FLS and the ENC ranged from 3 to 4.4 ft (0.9–1.3 m) at measurement depths ranging from 57 to 74 ft (17.4–22.5 m), or 3–7% of the ENC soundings value. The measurements obtained are generally in line with expectations. Under ideal conditions, the differences in these measures would be zero. In practice, anomalies due to bottom irregularities, offset tolerances, equipment

Table 2. Comparisons between charted depths and 3D-FLS depths.

	Charted depth		FL-sonar depth		Vertical uncertainty		Difference		
Location	(ft)	(m)	(ft)	(m)	(±ft)	(±m)	(ft)	(m)	(%)
Position A	57	17.4	59	18.0	1.0	0.3	3.0	0.9	105
Position B	64	19.5	67	20.4	1.2	0.4	4.2	1.3	107
Position C	74	22.5	75	22.9	1.3	0.4	2.3	0.7	103
Position D	74	22.5	77	23.5	1.4	0.4	4.4	1.3	106

accuracies, and changes to the environment that may have occurred since the survey was performed on which the ENC was based. These measurements indicate that soundings measured using System “A” 3D-FLS generally correspond to ENC in an area where recent survey has been performed. One assertion that may be made given these results is that, in the absence of soundings on an ENC that is blank, the soundings shown on System “A” are likely to be similar to that of an ENC had hydrographic survey been performed. Further study in this area is needed to establish a sufficiently large sampling to definitively substantiate this assertion.

Objective 2: Establishment of navigational references based upon bottom features and characteristics

Measurement results for transit along the Baseline Track shown in Figure 5 reflects accurate GNSS positioning and transit on three Error Tracks, where GNSS positioning is compromised based upon simulated spoofing or denial of service conditions. The elapsed time to transit the routes was approximately 5 minutes during which information from 49 sonar

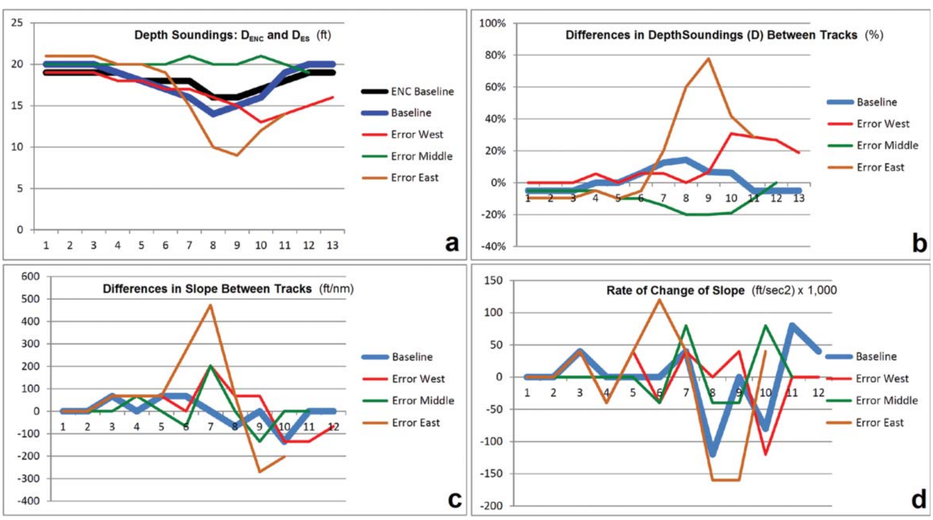

Figure 7. Measures of depth and slope of research vessel transit along a track, with soundings in feet (Wright and Baldauf 2015). The horizontal axis corresponds to consecutive soundings measurement locations from south to north for each track shown in Figure 5. (a) ENC soundings and echosounder depths comparisons (ft); (b) ENC soundings and echosounder depths comparisons (%); (c) bottom slope comparisons between reference and alternative tracks; and (d) bottom slope rates of change between reference and alternative tracks.

pings were obtained resulting in 100 megabytes of data collected. Comparisons between measured values for these tracks are illustrated in Figure 7.

Baseline track

Depth soundings (D) and the differences in depth soundings were calculated between the Baseline Track echo sounder measurements and the ENC machine-readable soundings layer obtained using the System "B" 3D-FLS. For the Baseline Track in Figure 7a the extremes of the measurements obtained ranged from a low value of −1 ft to a high value of 2 ft (−0.3 to 0.6 m).

Change of bottom slope (D*m*) between the Baseline Track echo sounder measurements and the ENC machine-readable soundings layer obtained using System "B" for the Baseline Track ranged from −135 ft/nautical mile (nm) to 68 ft/nm (−22.2 to 11.2 m/km). Rate of change of bottom slope (Dm_a) between the Baseline Track echo sounder measurements and the ENC machine-readable soundings layer obtained using System "B" for the Baseline Track ranged from a value of −0.120 to 0.080 ft/sec^2 (−0.019 to 0.013 m/sec^2). These values in themselves are not particularly significant except when compared to the Error Tracks, as discussed below.

This scenario represents the case where GNSS measurements correspond to the actual desired ground track being followed. The measurements obtained for the three measured parameters: D, D*m* and Dm_a, are generally in line with expectations. Under ideal conditions the differences in these measures would be zero. In practice, anomalies due to bottom irregularities, offset tolerances, equipment accuracies, differences in the methods by which single-beam and multi-beam echo sounder measurements are performed and inaccuracy attributed to the raster to vector process that was used can contribute towards these results.

The values obtained are slightly better than expected but still in line with other measurements taken at different survey locations in the same area when repeating this experiment. These results indicate an apparent correlation exists between ENC soundings and sonar measurements along a known track, a critical finding that indicates proceeding with the computation of additional measures for verifying positioning is warranted.

Error tracks

Depth soundings and the differences in depth soundings (D) between Error Tracks West, Middle, and East echo sounder measurements and the ENC machine-readable soundings layer for the Baseline Track are shown in Figures 7a and 7b. These values ranged from −4 to 7 ft (−1.2 to 2.1 m) between the single-beam echo sounder readings and the bottom topography. This represents 5–78% of the depths of between 9 and 21 ft (3–6 m) as a result of following terrain that was different from the ENC soundings model.

Differences in the change of bottom slope (D*m*) are shown in Figure 7c between Error Tracks West, Middle, and East echo sounder measurements and the ENC machine-readable soundings layer for the Baseline Track. These values ranged from −270 to 473 ft/nm (−44.4 to 77.8 m/km) as a result of following terrain that was different from the ENC soundings model. Differences in the rate of change of bottom slope (Dm_a) shown in Figure 7d between Error Tracks West, Middle, and East echo sounder measurements and the ENC machine-readable soundings layer for the Baseline Track. These values ranged from −0.160 to 0.120 ft/sec^2 (−0.022 to 0.019 m/sec^2) as a result of following terrain that was different from the

ENC soundings model. Additional experiments were conducted at two other nearby locations using non-AIS virtual AtoN lateral marks and the same methods, with similar results.

This scenario represents the case where a lack of correspondence exists between GNSS and the actual ground track being followed since GNSS measurements are purposely being spoofed and altered to show a false course. The measurements obtained for the three measured parameters: D, Dm, and Dm_a, are again generally in line with expectations. Specifically, significant differences in bottom contours are being detected at the actual route of transit as compared to the desired route. Under ideal conditions, the differences in these measures would be anything but zero, with the actual difference dependent upon the bottom characteristics. However the effect of bottom characteristics resulting from transiting an incorrect route would be cumulative to these anomalies as shown in Figure 7.

Differences between the Baseline Track and Error Track data sets positively indicate the detection of GNSS and/or bottom topography anomalies suggesting the location of the vessel and/or the environmental conditions deviate from the expected. In terms of the positioning of virtual electronic AtoN and determining whether it is watching properly, the implications of these findings may include that the AtoN is in the wrong position, or the geographic location where the AtoN is located may no longer be suitable due to changes in bottom configuration due to storms, currents, or other natural phenomena since AtoN deployment.

Discussion

Inputs and results

Data from System "A" system originated directly from the transducer hydrophones and was obtained through the system computer independent of the user interface. These results appear to be repeatable based upon the measurements performed at two different locations as well as at the same locations on different days. They also appear to be accurate for navigation purposes based upon comparison to the baseline ENC used in fulfilling objective (1).

Data obtained in pursuing objective (2) was acquired from System "B" system indirectly from the transducer hydrophones as interpreted and represented to the user through the raster interface since direct access to these data was not possible. The results obtained were repeatable and also appear to be accurate within the specified range when compared to the ENC and the measurements obtained using single-beam echo sounder in this experiment. Clearly indicated in this outcome is that a vessel following Error Tracks West, Middle, or East rather than the intended Baseline Track would be able to identify a position error without the use of GNSS or AIS, or with the use of GNSS/AIS that was not indicating the proper position. This is significant in that such capabilities could have detected poorly surveyed bottom and possibly help to prevent incidents such as the 1992 grounding of *Queen Elizabeth 2* off Martha's Vineyard, Rhode Island and the incorrect positioning that led to the 1995 grounding of *Royal Majesty* near Nantucket Island, Massachusetts in the United States (MAIB 92, NTSB MAR97/01). The bottom configurations for both areas are similar to those featured in these experiments in that bottom terrain depth and slope varied along the routes of transit. Evaluation of this approach in areas with steady bottom depths across the entire experiment setting has not yet been accomplished.

In both of these experiments, comparisons were made between the 3D-FLS and the ENC with which mariners are legally obligated to use for vessel navigation. The next test of the precision of these measurements should be accomplished through comprehensive experiments designed to compare 3D-FLS data against hydrographic survey data obtained using multibeam sonar, the baseline from which ENC themselves are created, corrected for speed of sound and salinity. These experiments should be performed simultaneously with 3D-FLS data acquisition under controlled conditions and to the same requirements as for hydrographic surveys in general. Plans are currently being prepared to accomplish this at several locations along the Arctic coast of Alaska. However, the results obtained thus far provide a basis to demonstrate the feasibility of such experiments.

Field of view and area measurement

System "A" has a maximum range of 500 m given ideal depths and bottom configurations. However, assuming nominal sound propagation conditions and a distance to depth ratio of 8:1 for estimating sonar range, a depth of 50 m can serve as a safety margin for which grounding may become a concern in costal navigation. At this depth an effective range can be estimated at 400 m along the centerline of the sonar. Given a 60° arc of coverage ahead of the bow, a swath of approximately 430-m width is possible. With a 90° arc of coverage a swath of 800-m width is possible. However, with the most frequently sampled areas within these arcs being toward the centerline, a conservative estimate of effective swath coverage may be achieved by halving these values to 215 and 400 m, respectively. These values are within the same range of values (195–390 m) for maximum swath width typically available for multibeam sonars from various manufacturers. The primary difference is that 3D-FLS may enhance safety of navigation by providing watchstanders with visibility ahead of the bow by which hazards to navigation may be avoided, while traditional multibeam sonar is directed downward toward the bottom and provides no indication as to what lies ahead.

Sound speed measurements

The measurement of sound speed propagation through the water is a routine and necessary practice in the performance of modern hydrographic surveys. Such measurements were not performed during the experiments described as this is not practiced while using forward-looking navigation sonar, which is intended for grounding and allision avoidance. Nor is this practiced while using single-beam echo sounders to measure water depth. IMO mandates an echo sounder as a carriage requirement on vessels conforming to the Safety of Life at Sea (SOLAS) convention as a means to verify water depths below the keel. It is used in conjunction with nautical charts and ENC in planning and executing voyages. The post processing of data obtained from independently sourced single-beam echo sounder and 3D-FLS to improve accuracy through consideration of speed of sound factors should be further investigated. However, this limitation should not preclude the use of the high-resolution data products obtained from 3D-FLS to independently supplement existing multibeam sonar sources of hydrographic data. Further, the coverage and consistency of 3D-FLS data are more precise with orders of magnitude greater geographical coverage than single-beam echo sounder data that are currently becoming widely available in the public domain through crowd sourcing initiatives.

Process for verification by georeference

The process illustrated in Figure 6 was used to acquire 3D-FLS data, normalize the data into a common format, and insert these data into a machine-readable ENC layer. This same process can be used with traditional multibeam sonar data to achieve the same result. Additionally, this verification process using georeferencing could also be used to verify whether physical, AIS radio-based, and virtual AtoN are watching properly.

International hydrographic organization S-100 universal hydrographic data model

Reference has been made repeatedly in the text regarding "full bottom coverage ENC machine-readable soundings layer." This experiment was envisioned with the S-100 Universal Hydrographic Data Model in mind that supports a wider variety of hydrographic-related digital data sources and products than the IHO S-57 IHO Transfer Standard for Digital Hydrographic Data. Specific reference is made to new spatial models to support imagery and gridded data, 3D and time-varying data, and new applications beyond those of traditional hydrography. Further potential also exists for expanding IMO e-Navigation capabilities through the integration of 3D-FLS technology.

Additional study limitations

Additional uncertainty exists within the experimental results as statistical processing of the raw data correlated to a gridded depth product was not accomplished and a validated uncertainty model does not presently exist in relation to ENC. The next logical step in this research is following an approach considering these criteria as may be achieved with the additional use of multibeam sonar with measurement of sound speed, salinity, and other environmental factors in conjunction with 3D-FLS. Further research in these areas is planned.

Conclusions

The results obtained in the performance of experiments to accomplish the two objectives of this research appear to support the following conclusions:

1. Apparent correlation was found to exist between the data acquired from 3D-FLS and the ENC mandated for use in vessel navigation at the two separate geographical locations described, as well as at other locations examined during these experiments. It is notable that these results were obtained from two systems with different capabilities and characteristics produced by different manufacturers. Results were found to be repeatable and consistent at different times and locations using the described methodology.
2. Salinity and bottom slope and consistency in terms of rocky bottom versus sandy and grassy bottom does not seem to have been a significant factor in these experiments as strong sonar returns were evident and consistent at the survey sites using both 3D-FLS systems. This may be attributed to the relatively shallow depths surveyed at both locations. However, shallow areas are those of most interest to this study. Further exploration of these factors will take place in future experiments.
3. The data obtained from 3D-FLS appear sufficiently comprehensive to support the objectives of national hydrographic authorities in surveying unknown waters such as found in

the Arctic and contributing to nautical chart development as independently sourced data under present standards as well as under the IHO S-100 Universal Hydrographic Data Model. Further study of post-processing methods to enhance 3D-FLS measurement values to integrate speed of sound and other factors should be performed. Innovation is desirable in the design of sensors to measure sound of speed that may be integrated with 3D-FLS and echo sounder equipment to further enhance the accuracy of these systems.

4. Based upon the results of these two sets of experiments an assertion can be made that the use of 3D-FLS in areas such as the Arctic can provide watchstanders with a useful and accurate tool to determine the depths of water ahead of the bow to fulfill IMO requirements to maintain an effective watch. Further, it can be an invaluable resource to detect uncharted and unmarked shoals, reefs, shelves, rocks, and other underwater hazards to navigation that may jeopardize safe vessel navigation.
5. Future research should only consider 3D-FLS systems that provide direct access to hydrophone data through a suitable electronic interface. The raster-to-vector conversion process that was used with System "B" system provides an unnecessary layer of overhead that can introduce error and inaccuracies in the data. This lack of data interface stymies data collection for subsequent hydrographic use.
6. In addition to the positive outcome achieved for hydrographic survey, the authors see potential for the use of FL-sonar onboard vessels as part of an integrated bridge environment. Although integration of 3D-FLS into ECDIS has occurred in several instances, further research into standard symbology and user interface issues, operator training and vessel outfitting requirements is warranted. Contributions to improvement of navigator situational awareness may be investigated and established by further experimental studies using bridge simulators and analyzing the behavior of navigators. A useful side benefit may be the collection of useful hydrographic data.

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Arctic Environment Preservation through Grounding Avoidance

R. Glenn Wright and Michael Baldauf

Abstract Research results are described that explore technological innovation to reduce ship groundings and collisions by significantly increasing watchstander situational awareness to environmental conditions below the waterline. This is especially relevant to ship navigation in the Arctic requiring transit through shallow, draft-constrained coastal and archipelago waters that are relatively uncharted, lack aids to navigation, without adequate search and rescue facilities, and teaming with surface and underwater hazards to navigation. Add to these risks the potential for satellite service outages, denial of service and spoofing along with hacking and possible terrorism in various forms. Such conditions and events create excessive risk to life and property through grounding and greatly expose the environment and wildlife to pollution damage through oil and chemical spills. Results of research accomplished to date are provided and strategies developed to enhance ship owner and operator diligence in better preparing for Arctic transits. Recommendations for future work in related capacities are also provided for enhancing the Polar Code, International Maritime Organization (IMO) carriage requirements and the Convention on Standards of Training, Certification, and Watchkeeping (STCW).

Keywords grounding, Arctic navigation, underwater sensing, geo-referencing, GNSS, spoofing, forward-looking sonar

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1 Introduction

According to statistics of accident investigation reviews issued from various sources ship groundings are the leading cause of large oil spills, yet human error remains one of the main reasons for their occurrence. The underpinnings of groundings contributed to or even caused by direct human error can in many cases be traced to the watchstander simply being unaware that grounding was about to occur. This illustrates an extraordinary lack of situational awareness regarding the specific underwater terrain in which the vessel was operating and a loss of orientation toward ongoing events [1,2]. Such occurrences may be due to the fact that the only direct knowledge available to the watchstander regarding the physical environment below the waterline being a two or three-digit number provided by an echo sounder that represents depth immediately beneath the keel – and nowhere else. Deduction of grounding implications based upon such scanty sensory inputs is problematic at best, and is easily overlooked if the watchstander is distracted by another task. Modern Integrated Navigation Systems according to IMO Performance Standards [3] provide alarm facilities that can be configured to warn of crossing a safety depth contour that may assist in avoiding groundings. However, these alarms do not work properly where few if any soundings exist within the electronic navigation chart (ENC) data, and in areas exhibiting rapid changes in depths as warning is likely to come far too late to avoid rising bottom terrain.

Research is presently underway leading to the invention and application of new technology that can aid in reducing vessel groundings. One focus specifically chosen for this research is the Arctic, where new inroads are being made to explore this pristine frontier and make it accessible to pioneers ready to exploit claims to natural resources and to open new trade routes. The geological and ecological aspects of the Arctic as represented by the Northern Sea Route (NSR) and the Northwest Passage (NWP) are described to illustrate the unique characteristics of these routes that make them particularly vulnerable to grounding events, and why the consequences of groundings in these areas are intensified. Also discussed are the vulnerabilities of technology used routinely in worldwide ship navigation that are accentuated in the Arctic environment, considering both the limitations of equipment as well as susceptibilities to human factor deficiencies and man-made interference and disruption. The potential for this research to contribute towards building new infrastructure in areas where the establishment of traditional infrastructure is difficult or impossible is identified. Accomplishments achieved to date are also cited that illustrate the potential to approach the goal of increasing watchstander situational awareness of the underwater environment along the route of transit, along with problems encountered and limitations identified in this work.

2 New Technology to Navigate a New World

The navigation capabilities of modern vessels plying the world's oceans include ENC representing the latest in multibeam full coverage hydrographic surveys contained within and displayed to watchstanders using Electronic Chart Display Information Systems (ECDIS). Vessel positioning is accomplished to accuracies of a few meters using Global Navigation Satellite Systems (GNSS) integrated with a growing number of sophisticated sensors and tracked by other vessels and land-based operators, service and support organizations using terrestrial and space-based Automatic Identification System (AIS) receivers. Physical aids to navigation (AtoN) are supplemented with AIS-based AtoN capable of being placed where physical aids cannot.

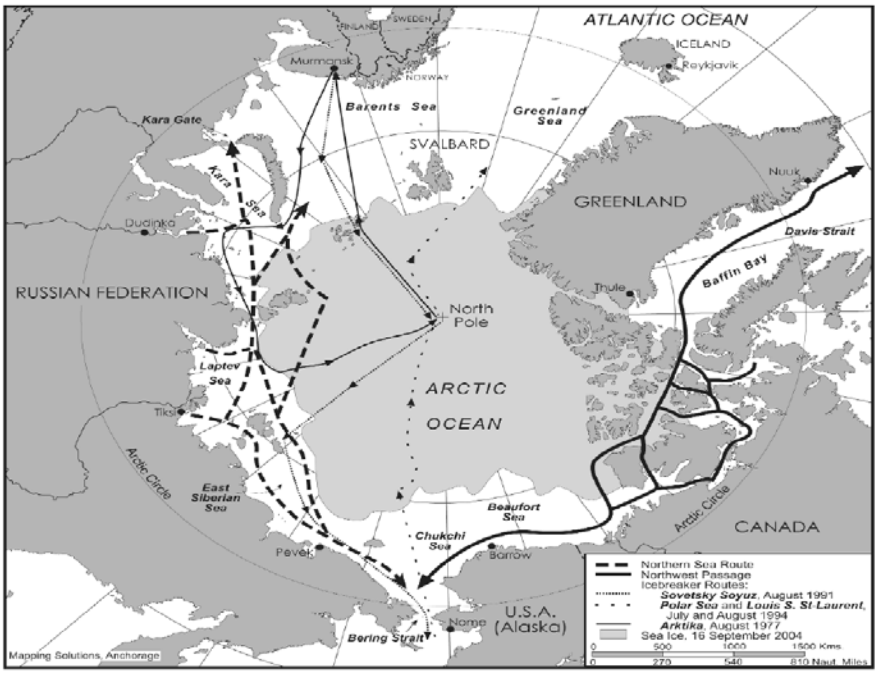
Unfortunately, little of this is true in the Arctic. Navigation charts are in many cases blank or are inaccurate. Hydrographic surveys rarely exist and, if they do, are likely to be decade's old and performed using obsolete technology. Satellite positioning systems and communications can be unreliable. Physical AtoN cannot be placed throughout much of the Arctic due to ice movement and AIS-based AtoN lack infrastructure required for their use.

It is quite possible for mariners today to be in much the same situation as the explorers of the 15th and 16th centuries when aiming their bows towards the unknown. However, research is currently underway to help reduce this problem, the timing of which is especially significant in that the Arctic is experiencing increasing vessel activity resulting from the development of natural resources as evidenced by the 22 July 2015 granting by the U.S. Bureau of Safety and

Environmental Enforcement of final approval for drilling by Shell Oil at the Burger Prospect in the Chukchi Sea off Alaska [4]. Transit shipping across the Arctic is also dramatically increasing to take advantage of shorter routes between Europe and Asia. This is made possible in part due to diminishing sea ice coverage opening shipping routes that have previously been impassible. These routes include the NSR across the top of Russia and Norway, and the NWP along Denmark (via Greenland) and through Canada and along the United States that span thousands of nautical miles across shallow coastal seas and archipelagos where the potential risk for grounding is high. Accentuating these risks is the harsh climate that can cause the breakdown of machinery vital to safe vessel operation. The lack of adequate hydrographic survey and accurate nautical charts providing sparse depth information along much of this route can also render modern ECDIS equipment ineffective and unreliable.

3. The Arctic Routes

A series of different sailing lanes, the NSR covers some 2,200 to 2,900 nautical miles depending upon ice conditions. Likewise, the NWP covers a distance of about 1,300 nautical miles from Baffin Island to Banks Island plus another 1,000 nautical miles from Banks Island to the Bering Strait. These routes are illustrated in Figure 1.



Source: Arctic Marine Transport Workshop, 28-30SEP2004, U.S. Arctic Research Commission.

Fig 1. Arctic Routes: Northern Sea Route (NSR) and Northwest Passage (NWP)

A great variety of wildlife can be found in the Arctic including over 35 species of mammals such as whales, seals and walrus, and other carnivores that include polar bears [5]; over 200 different species of birds that occur in marine and coastal areas [6]; over 65 species of fish that include salmon, cod, herring, flatfishes, halibut, whitefish, pollock and sharks [7]; and many species of invertebrates that include sea urchins, anemones, jellyfish, crabs and worms [8].

3.1 Northern Sea Route

The NSR encompasses all routes across the Russian Arctic coastal seas from Kara Gate (at the southern tip of Novaya Zemlya) to the Bering Strait [9]. Shallow waters generally characterize the length of the coastline from the Norwegian-Russian border in the west (in the Barents Sea) to the Bering Strait where average depths of the East Siberian and Chukchi seas are 58 meters and 88 meters respectively, the Laptev Sea where 66 percent of its area along the coast is in depths of 100 meters or less, the Kara Sea with an average depth of 90 meters and the Barents Sea with 10-100 meter depths along the coast in the southeastern region sloping to depths of 200-300 meters to the northwest [10]. Depth limitations at various straits along the route result in an overall controlling depth of 12.5 meters [11]. Approximately thirteen million seabirds nest along Russia’s Arctic coastline [12]. Wrangel Island is home to the most important onshore denning habitat for polar bears in the Arctic and the largest site for a Pacific subspecies of walrus. Laptev walrus is a subspecies endemic to Russian waters while the Barents and the Kara Seas play a pivotal role in maintaining populations of the endangered Atlantic walrus. The White Sea is the breeding area for the entire Northeast Atlantic population of the harp seal, the keystone species in the pelagic ecosystem now affected by the climate change. Six of the sixteen Large Marine Ecosystems (LMEs) defined as areas of heightened ecological significance in the Arctic exist along the NSR [13].

3.2 Northwest Passage

The NWP is comprised of the marine routes between the Atlantic and Pacific oceans along the top of North America that span the straits and sounds of the Canadian Arctic archipelago and along the northern slope of Alaska in the United States [9]. This archipelago is comprised of approximately 36,000 islands with variable depths, especially as the continental landmasses and islands are approached, providing a highly complex geography for vessel navigation [14]. The overall controlling depth is 10 meters [11]. The Alaska portion of the NWP north of the Bering Strait is bordered by sea ice in the winters of all years and pack ice may be just offshore all summer. Most of the coastline is sedimentary and portions have extensive barrier islands and lagoon-forming spits. Beach ridges surrounding aquatic habitats, serpentine barrens, limestone outcrops, marshes, sloughs and other ecologically important and fragile regions in the arctic and western coasts provide habitat for many unique species of plants and animals [15]. Four of the sixteen LMEs defined as areas of heightened ecological significance in the Arctic exist along the NWP [13].

4. Increasing Arctic Groundings

The increase in shipping activity in the Arctic engenders corresponding increases in groundings that comprise a significant percentage of shipping casualties. Data depicting such a trend indicates shipping casualties in Arctic waters increased to 45 per year between 2009 and 2013 from only 7 during 2002-2007. Damage to machinery caused a third of these incidents, higher than the average elsewhere, reflecting the harsher operating environment [16]. When viewed in terms of total losses, the Russian Arctic/Bering Sea and the Canadian Arctic/Alaska experienced 46 (3.1%) of the 1,462 total losses worldwide in the ten year period between 2002-2011; increasing to 6 (5.1%) of 117 total losses worldwide in 2012 and 4 (4.3%) of 94 total losses worldwide in 2013 [17]. The potential environmental impact of groundings may include containers lost overboard from vessels aground but otherwise intact that wash up in the Arctic. An incident occurred in 2004 when a container tank filled with plastic polymers was lost from a vessel enroute to Korea from South Africa four months earlier that washed up close to a remote Russian community in the Commander Islands in the Bering Sea [18]. Attempts to move the container led to spilling about 15 tons of the chemical. Local residents were poisoned and the community did not understand how to handle such an emergency [19]. Ståle Hansen, President and CEO of the Skuld Property and Indemnity (P&I) Club, recently cited cost estimates of $500 million to remove the wreck of the container ship M/V *Rena* that grounded in New Zealand and stated that the potential cost of such incidents in the Arctic would almost certainly be significantly higher [20].

Groundings involve a moving navigating ship either under command, under power, or not under command that are drifting, striking the sea bottom, shore or underwater wrecks [21]. Casualty data shows groundings are consistently at or near the top of the most frequent types of shipping accidents [22-25]. Where accidents resulted in oil spills over 700 tons in the years 1970 to 2009, grounding was the leading cause at 36%, followed by collisions at 29% [26]. Although not all groundings result in a total loss, the consequences of groundings can result in a serious accident in terms of cost to the safety of crew, vessel and cargo and damage to the environment due to physical impact and chemical spills.

The causes of groundings are many and include loss of machinery (e.g., engine, rudder, propeller and/or anchor); poor hydrographic surveys and nautical charts that fail to accurately depict bottom contours and identify hazards to navigation; human factors such as fatigue, errors in properly operating and interpreting ship sensors, indicators and alarms, and poor voyage planning. A recent report assessing probabilities for groundings based on accident reports indicates inadequate communication and cooperation on the bridge is the most significant contributing factor in a grounding accident [27]. In 2008 poor hydrographic surveys were cited by the Helsinki Commission as a contributing factor to an increase in groundings in the Baltic, particularly in the shallow waters around Denmark [28]. These are just two of several factors that are of greater significance in the Arctic environment for ships that are poorly prepared and ill-equipped in terms of physical machinery, navigation equipment as well as crew training and experience that contribute towards the increase in accidents.

5. Challenges of Arctic Navigation

There are many operational, logistical and technical challenges to ship navigation in the Arctic. Those challenges having to do with expanding watchstander environmental situational awareness center on navigation charts, aids to navigation and sensors that provide direct insight into the environmental factors relevant to transit. Another factor is the potential for terrorism, an occurrence from which the Arctic is not immune. In the Arctic, infrastructure is minimal and knowledge of the underwater environment is imprecise at best and wholly without survey in many areas. The risks and consequences of grounding dramatically increase due to potentially long rescue times and a lack of assets for salvage and environmental remediation in the event of casualty. This risk extends to both civilian and Government operations. Adm. Paul Zukunft, Commandant of the U.S. Coast Guard, when speaking about icebreaker capacity recently stated that the United States currently has no self-rescue capability in the higher latitudes [29].

5.1 Navigation Charts

According to the U.S. National Oceanographic and Atmospheric Administration (NOAA) charting data in much of the Arctic is inadequate or nonexistent [30]. The *U.S. Coast Pilot* states that much of the Bering Sea area is “only partially surveyed, and the charts must not be relied upon too closely, especially near shore. The currents are much influenced by the winds and are difficult to predict; dead reckoning is uncertain, and safety depends upon constant vigilance” [31]. The overall status of charts and hydrographic survey for United States Arctic waters may be described as:

> “The Arctic is severely deficient in many of the capabilities that NOAA extends to the rest of the Nation. The region currently has virtually no geospatial infrastructure for accurate positioning and elevations; sparse tide, current, and water-level prediction coverage; obsolete shoreline and hydrographic data; poor nautical charts; insufficient weather and ice forecast coverage; inadequate oil spill response capacity; and poor understanding of baseline conditions for existing ecosystems. There are large gaps in the information that NOAA does have, illustrated by empty white space on

> nautical charts of the region and limited capabilities for modeling spills in ice conditions. Most Arctic waters that are charted were surveyed with obsolete technology, some dating back to the 1800s, before the region was part of the United States. Most of the shoreline along Alaska's northern and western coasts has not been mapped since 1960, if ever, and confidence in the nautical charts of the region is extremely low" [32].

NOAA has expanded the deployment of survey ships to improve navigational safety in the Arctic, conducting surveys of the ocean floor to measure water depths and search for navigational dangers and increasing Arctic charting activities in anticipation of growing vessel traffic in the region. Hydrographic projects for Alaska in 2015 cover an area of 2,800 square nautical miles, plus the 12,000 linear nautical miles for a potential Arctic shipping route from Unimak Island to the Chukchi Sea [33]. The NOAA Arctic Charting Plan providing information about existing, recently added, and proposed new ENC coverage in U.S. Arctic waters was recently released for public comment [34].

Most of Canada's Arctic waters have not been surveyed to modern standards except for Lancaster Sound, Barrow Strait, the Beaufort Sea, Amundsen Gulf, and the approaches to settlements and some mining sites. Spot soundings through the ice or reconnaissance track soundings are the only survey data available in much of the Arctic. In the Beaufort Sea, a route through the area with a large number of pingos has been surveyed in greater detail [35]. It was reported the Canadian Hydrographic Service says that 10% of the Canadian Arctic has been surveyed to modern standards [36].

Russian Arctic survey coverage along the NSR, illustrated in Figure 2, appears more comprehensive than the NWP. The Russian Federation's Hydrographic Service reported to the Arctic Council since 2011 the Northern Sea Route's least-studied areas are being surveyed over a 31,000 square km area of the sea floor. Survey results have been digitized and developed into electronic navigation charts. Sixty-eight marine electronic navigation charts were issued based on the survey results. In 2012 two hundred charts were developed [37].

Overall, of a total of 7,018,392 linear nautical miles (LNM) in the Arctic across the waters of Canada, Denmark (Greenland), Norway and the United States; 4,989,368 LNM (71.1%) of the depths remain unassessed by hydrographic survey [38]. Navigation charts depicting these areas are often blank and/or contain soundings that should not be relied upon. Of further concern are navigation charts for the Arctic that have been created according to different datums used to define the heights, depths and locations of hydrographic features. This requires extreme diligence to ensure accurate positioning when transiting areas using a chart with a datum different from that of the Global Navigation Satellite System (GNSS) in use, and when transiting areas from one chart to another where the charts were compiled using different datums.

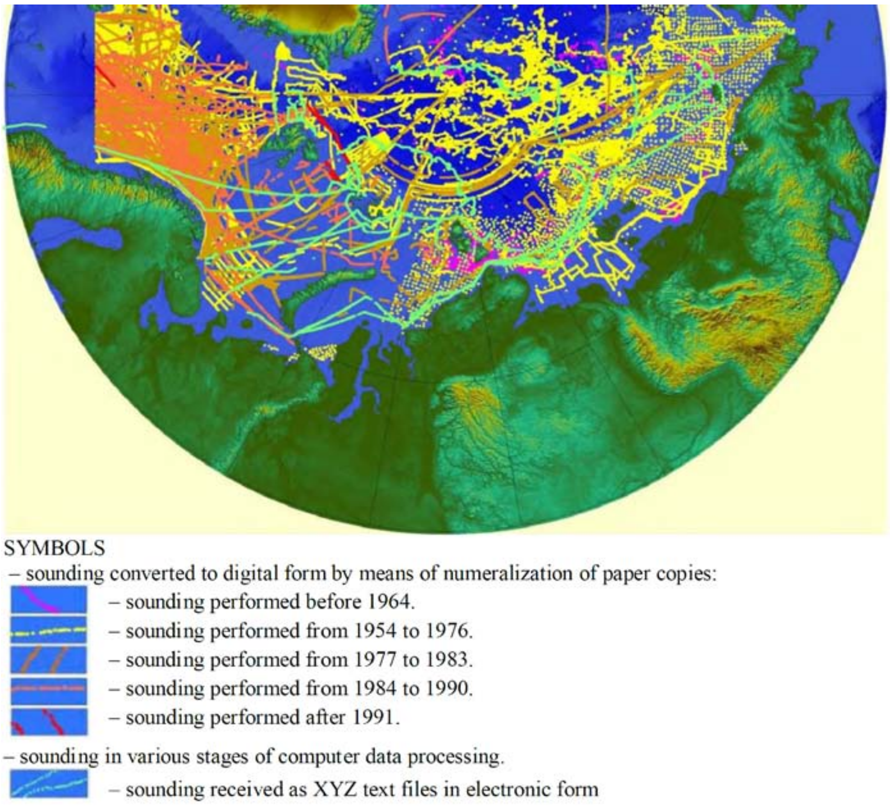


Fig 2. Survey Coverage of the Arctic Based on the Systematic Sounding Data [39]

5.2 Electronic Chart Display and Information System (ECDIS)

ENC include a Category of Zone of Confidence (CATZOC) rating that indicates the level to which the data meets minimum criteria in terms of position and depth accuracy [40]. Except for ENC that contain the most recent modern surveys most Arctic charts do not have an assigned CATZOC value. This condition has direct implications on voyage planning and monitoring activities in terms of deriving keel depth and beam clearance safety margins when planning route(s) of passage. Safety contour and depth alarms required to be triggered by ECDIS would not be available in areas exhibiting a lack of soundings. Where soundings do exist on charts without an appropriate CATZOC rating, reliance upon them to set alarms would be foolhardy as the soundings should be assumed to be unreliable. In addition, incorrect setting of own-ship safety depth to a value greater than the current setting may provide an ECDIS display that omits any obstructions and shallows that may be present in the ENC.

5.3 Aids to Navigation (AtoN)

The inability to place navigational aids and buoys in constantly changing ice conditions produces increased risk in vessel navigation activity in the Arctic and sub-Arctic regions. This has resulted in there being few, if any physical aids to navigation existing along the coast and outside of heavily trafficked areas nearby and within ports. Buoy placement and maintenance activity in sensitive ecological areas is also problematic, and underdeveloped regions lack assets and infrastructure needed to provide navigation services. The absence of physical aids to navigation also eliminates the potential to use radar navigation to identify physical aids during times of poor visibility.

This shortcoming may be alleviated somewhat in the near term through the use of AIS-based AtoN at some locations in the Arctic. Deployment of this technology is currently being accomplished across the rest of the United States to supplement physical AtoN in areas where additional aids are beneficial to navigation. Their use in the Arctic is limited to areas where infrastructure exists to install and maintain these aids, and by the line of sight to their deployment locations due to very-high frequency (VHF) radio transmission characteristics.

5.4 Communications

The ability to reliably communicate in the Arctic region will become much more important over time as vessel activity increases. One factor that affects reliable communications is the large distances involved that favor the use of satellite and high frequency (HF) communications over shorter range VHF and ultra-high frequency (UHF) communications that is generally limited to the line of site. The negative influence of atmospheric effects on HF and satellite communications can make these methods unreliable during magnetic storms initiated by solar flare events. Heavy precipitation and antenna icing can also interfere with satellite communications. VHF and UHF communications is useful for communications between vessels, for tactical control and for emergency communications with mariners operating in the local area. Further research in the Arctic is needed to evaluate system coverage limitations and create improved signal modeling techniques.

There is also a lack of reliable navigation safety information to help mariners identify, assess, and mitigate risks the in Arctic region due to minimal Maritime Safety Information infrastructure in the region. The U.S. Coast Guard currently does not own any of its own electronic Maritime Safety Information (eMSI) infrastructure in Alaska, and is examining the use of existing AIS infrastructure to demonstrate the delivery of critical eMSI information to local mariners and ultimately improve navigational safety [41]. Similar efforts are also underway elsewhere including the European MonaLisa project that aims to integrate environmental sensitivity data and dynamic route planning within Maritime Spatial Plans, and the Accessibility for Shipping, Efficiency Advantages and Sustainability (ACCSEAS) project for improving maritime access to the NSR by developing and implementing eNavigation regional services and to prototype novel marine navigation and communication concepts.

5.5 Environmental Sensing

Several technologies such as GNSS, radar and sonar fulfill mandatory carriage requirements on-board modern vessels worldwide, provide vessel positioning information and offer navigation assistance by directly sensing the immediate physical environment. However, each of these technologies exhibit specific limitations as a result of their use in the Arctic. For example, special challenges to GNSS exist at high latitudes due to low elevation with satellite inclination (55° for GPS). Limited services like Wide Area Augmentation System (WAAS) and dynamics associated with the auroral region and polar cap also make it difficult to predict ionospheric corrections and integrity [42].

The use of radar as a means to fix vessel position is also limited in the Arctic. Absent the presence of short range AtoN, radar piloting that relies on these aids while in inland, harbor and approach, and coastal navigation is not possible. Using radar to determine bearing and distance to known objects and land features is possible where islands are present at sea and mountains extend along the shoreline. However, much of the Arctic landscape is regular and featureless, sloping gradually from the shoreline with low and grassy inland terrain making the detection of natural features difficult at best. Since much of the area is uninhabited, there is also a lack of manmade objects from which bearings may be taken.

Sonar technology may be used to identify bottom features, gradients and depth contours useful to navigation. The echo sounder provides instantaneous depth information directly below the keel that can reassure the mariner there is sufficient water at the present time to avoid grounding. However, there is no assurance that the depth immediately forward of the bow is sufficient for continued navigation. Little navigational assistance is provided through the comparison of live echo sounder readings against navigation charts containing no or few soundings.

5.6 Terrorism

The potential exists in the Arctic for deliberate vessel grounding as an act of terrorism, with much greater effectiveness in terms of negative economic and ecological impact than would be the case in most other parts of the world. This can be caused by launching service denial and spoofing attacks on both GNSS as well as AIS that are relied upon for vessel navigation. The ability to spoof these services is well documented, taking advantage of inadequate security inherent in their system architectures. In 2013 scientists from the University of Texas successfully spoofed the GPS on a yacht, directing it on a parallel path hundreds of meters off course while the chart display showed only a straight line [43]. Such attacks could easily be accomplished to target vessels, mobile offshore drilling units and other maritime assets using small boats as well as highly mobile unmanned undersea vehicles (UUVs). Small platforms such as these that are capable of supporting sensors and required technology can easily achieve such attacks designed to mislead and misdirect vessels into believing their position is other than their actual position.

At present there is little capability to reduce these threats in terms of detection and establishing countermeasures against such operations. Much of today's focus targets terrorism using the Arctic as a means to traffic in arms, weapons of mass destruction as well as for the transportation of terrorists [44]. In 2009 the United States identified fundamental homeland security interests in preventing terrorist attacks and mitigating those criminal or hostile acts that could increase the United States vulnerability to terrorism in the Arctic region [45]. Although denial of service and spoofing attacks have not yet been documented in the Arctic, acts of eco-terrorism are on the increase. An incident occurred in April 2015 when Greenpeace activists from their ship *Esperanza* boarded the Royal Dutch Shell oil drilling ship *Blue Marlin* bound for Alaska, and previously in 2013 when the group occupied a Russian oil rig resulting in the arrest and imprisonment of over 30 activists [46]. Subsequently Russia passed amendments in a federal law on the protection of oil and gas objects and infrastructure that allow Russian oil companies to establish their own protection units against hostile action and terrorism [47]. The Canadian military has also routinely deployed a counter-intelligence team in the Arctic to guard against possible spying, terrorism and sabotage [48].

6. Enhanced Environmental Situational Awareness

The basis for an innovative means of vessel navigation in the world's uncharted frontier involves original research in the progression and integration of three seemingly unrelated technologies: forward looking sonar, Virtual (non-AIS) AtoN, and georeferencing. The approach described is eminently suitable for Arctic service in terms of usefulness, ease of deployment and low cost for installation and maintenance.

6.1 3-dimensional Forward Looking Sonar

This research is based upon the assertion that own ship sensors should be adequate to detect soundings and bottom configuration both at its current position as well as forward of the vessel in the path of transit sufficient to ensure safe navigation. Such capability is especially appropriate where soundings and bottom configuration are inaccurate or not available due to poor or lack of accurate hydrographic survey. This is possible through the use of 3-dimensional Forward Looking Sonar (3D-FLS), which is a variation of the multibeam echo sounder that detects bottom features and objects within the water column forward of the bow. Despite its usefulness and the availability of this technology in the commercial marketplace for over two decades, it is rarely included within the ships' complement of navigation sensors. Historically, this is likely due to a lack of suitable range, low vessel speed of use requirements and confusing 2-dimensional displays. There is also no IMO carriage requirement for 3D-FLS at present.

The detection of bottom features, objects and soundings by determining range, azimuth and elevation information uses methods that can generally be described as variations on transmitting a steerable sonar signal ahead along the path of the vessel or by transmitting a single ping from which snapshots of the environment are obtained. Through this process a mosaic of the bottom topography and specific targets is created as the vessel proceeds on its course. 3D-FLS systems have been developed with different capabilities supporting both unmanned undersea vehicle and vessel applications. Of those designed for use on vessels, most are intended for pleasure and small fishing boats. There are systems with range and resolution that make them suitable for use on larger vessels such as workboats, offshore service vessels, merchant and passenger vessels. However, operational constraints may create limitations on their usefulness. For example, effective range may be limited by tradeoffs in transducer design to minimize water resistance and drag.

At present, 3D-FLS is capable of detecting and displaying the underwater environment looking ahead as much as 1,000 meters forward of the bow at speeds up to 25 knots. In shallower waters the range of 3D-FLS can extend from eight to twenty times the depth ahead, depending on bottom and target conditions [49,50]. It is most effective when the bottom topography slopes upwards, and when targets are large and consist of hard rock and/or coral that provide good acoustic signatures.

The research focuses on the enhancement of 3D-FLS capability to survey the sea bottom as well as to detect hazards attached to the bottom and floating in the water column to aid in Arctic navigation, where soundings on charts rarely exist and the vast majority of hazards to navigation have yet to be discovered. The utility of this technology as a means to avoid such hazards has been explored in a simulation of the M/V Costa Concordia disaster [51]. Its use as a means to perform hydrographic survey has also been discussed in terms of International Hydrographic Office (IHO) standards [52,53]. The potential exists to accomplish complete survey coverage with 3D-FLS for the transit route with horizontal and vertical accuracies within IHO standards using this approach. Such data can supplement national hydrographic organizations' efforts in the collection of survey data in remote parts of the world and in areas lacking recent survey.

6.2 Virtual Aids to Navigation

Virtual AtoN based upon AIS technology are rapidly being deployed on a worldwide basis as a supplement to physical AtoN. While this is a valuable technology, the use of AIS-based AtoN is severely restricted in the Arctic due to lack of existing infrastructure to provide power and communications for health monitoring, access for maintenance and VHF radio range limitations. The research focuses in the creation of (non-AIS) Virtual AtoN, defined by the International Association of Lighthouse Authorities (IALA) as something that "does not physically exist but is a digital information object promulgated by an authorized service provider that can be presented on navigational systems” [54]. Methods used for the creation of Virtual AtoN have been described in a real-time, shipboard implementation of this technology [55,56].

Virtual AtoN technology represents a major step beyond the capabilities of existing AtoN, although critical limitations exist that are inherent in their design and implementation. Qualifying as short range AtoN, Virtual AtoN appear neither visually nor directly on radar. AIS-based virtual AtoN appear on an AIS radar overlay and also on ENC/ECDIS displays. However, verification techniques to ensure AIS and ENC/ECDIS positions coincide have yet to be developed. Virtual AtoN may appear only on ENC/ECDIS displays. Such implementations can result in a potential “single point of failure” scenario that may cause false conclusions and possible system failures that may go undetected. A comprehensive Virtual AtoN verification approach to help overcome this deficiency and ensure virtual AtoN (AIS and non-AIS) are watching properly after deployment is possible using georeferencing techniques.

6.3 Georeferencing

Georeferenced navigation using terrain features and manmade object recognition has been in use for many years as a means of cruise missile and other unmanned aerial vehicle (UAV) navigation across the landscape. This has been made possible through highly detailed millimeter-resolution radar and laser-surveys of the land areas from aircraft and satellites, whereas the ocean depths are presently surveyed to a maximum resolution of about 5 kilometers [57].

This research utilizes a novel implementation of georeferencing based upon the extraction of features from both multibeam sonar and 3D-FLS data represented in the ENC, and correlation between vessel position indications and physical environmental features to verify that Virtual (and physical and AIS) AtoN are watching properly. Comparison between ENC soundings and echo sounder depths along the path of transit can be performed even if precise positioning information normally acquired using GNSS, AIS and other sources are unavailable due to a variety of manmade and natural events. The techniques used to accomplish this have been discussed based upon the results of a series of experiments conducted at sea [53,58]. Environmental features are identified in terms of bottom depth soundings for the ENC and echo sounder as well as the difference between these two sources, differences in bottom slope and differences in the rate of change of bottom slope resulting in new capabilities to automatically detect discrepancies in either bottom conditions or GNSS positioning that may require additional caution.

7. Grounding Avoidance Strategies

An overall strategy to reduce the potential for grounding in the Arctic must originate during vessel preparation and outfitting for Arctic operations, continue through voyage planning, be implemented throughout the entire voyage to monitor its progress, and result in products that preserve the information and knowledge acquired during transit useful for crew debriefing. Such products should also support the subsequent application of the information and knowledge gained to benefit future mariners who transit the same areas. Strategies must be developed in accordance with a Safety Management System that acknowledges the special circumstances of Arctic navigation and includes provisioning appropriate for correct vessel outfitting and crew training. Specific concepts that may be useful in developing strategies to avoid groundings are illustrated using the incidents cited. Applications and advantages that 3D-FLS and Virtual AtoN may provide in such circumstances are also discussed.

Official reports commonly include accounts of groundings that have occurred due to a seeming lack of environmental situational awareness regarding the proximity of the keel of a vessel with the sea bottom. In several cases the watchstander was not even aware that grounding had occurred even several minutes after it happened. Descriptions of incidents extracted from the Nautical Institute's Mariners' Alerting and Reporting Scheme (MARS) include:

- Chart corrections while navigating contribute to grounding (Report 201528)
- ECDIS unassisted grounding (201505)
- Self-induced fatigue contributes to grounding (201451)
- Fog bound grounding under pilotage (201420)
- Vessel strikes island (201356)
- Unpublished draft restrictions lead to grounding (201335)
- Improper bridge procedures and ECDIS use caused grounding (201257)
- Grounding in channel (200657)
- Cross checking positions lead to grounding (200524)
- Near grounding due to permanent highlighting of charts (200109)

These are a few of many examples of groundings in non-Arctic areas; many of which are highly travelled, well charted and represent the best of circumstances in terms of information and sensor availability. The Arctic is generally less than optimal in these terms. Groundings and their consequences can be considerably more serious in the Arctic where harbors of refuge are few, search and rescue facilities are scarce or non-existent, and salvage capabilities may take weeks or months to arrive on-scene due to weather and sea conditions. Several detailed accounts of groundings follow that will be used to illustrate grounding avoidance strategies based upon the results of research accomplished to date.

7.1 M/V *Clipper Adventurer*

On 27 August 2010 the cruise chip *Clipper Adventurer* ran aground in Coronation Gulf, Nunavut in the Northwest Passage on a shoal discovered in 2007, published in Canadian Notices to Shipping but not officially charted until June 2012. The Transportation Safety Board of Canada report concludes that the vessel ran aground after the bridge team chose to navigate a route on an inadequately surveyed single line of soundings, as shown in Figure 3 [59]. This occurred in an area where the depths of the waters were virtually unknown.

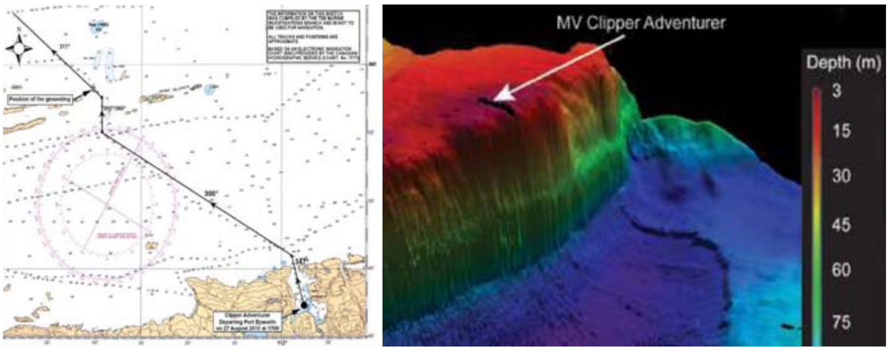


Fig 3. Navigation Chart and Bottom Topography: *Clipper Adventurer* Grounding [59]

Analysis**:** M/V *Clipper Adventurer* was proceeding on autopilot at a speed of 13.9 knots when the vessel ran aground on hard rock shelf [60]. Bottom depth directly before the shelf, illustrated in Figure 3, exceeded 100 meters. Using 3D-FLS with a 1,000 meter range, at a speed of 13.9 knots the vessel would have had approximately 128 seconds or 2.1 minutes advance warning before the grounding would have occurred based upon the following equation:

$$\textit{Advance Warning (sec)} = \frac{MDR\ (\mathrm{m}) - SRR\ (\mathrm{sec}) - APT\ (\mathrm{sec}) - WRT\ (\mathrm{sec})}{V\mathrm{s}\left(\frac{\mathrm{m}}{\mathrm{sec}}\right)} \quad (1)$$

where logical arguments may be made to establish values for each of these parameters:

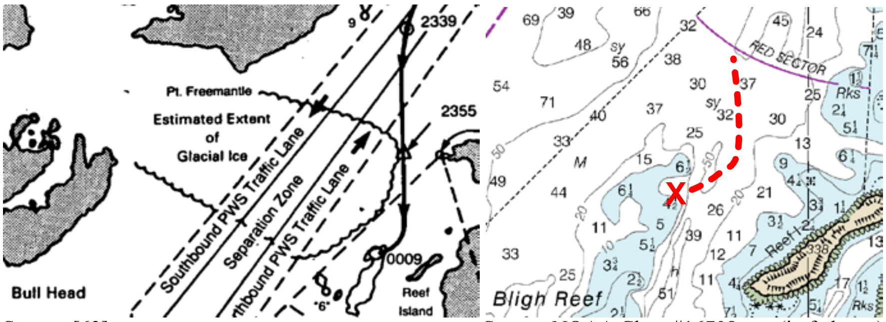
Speed of Vessel (*V*s) = 13.9 knots
Screen Refresh Rate (*SRR*) = 2 sec
Maximum Detection Range (*MDR*) = 1,000 meters
Alarm Processing Time (*APT*) = 4 sec
Watchstander Response Time (*WRT*) = 5 sec
1 m/s = 1.9438 knots

The Marine Investigation Report identifies that 3D-FLS was indeed installed on *Clipper Adventurer*, however it was not operational and in an unserviceable condition. This unit had a maximum detection range of 500 meters and, if operational and the vessel was operating at 6 knots, the report concluded the crew would have had approximately 2 minutes advance warning of the shelf [61]. In either case there may not have sufficient sea room to halt all forward motion of the vessel. However a reduction in speed and course change may have altered the final circumstances such that the grounding may have been avoided or the severity of the grounding may have been lessened.

Virtual AtoN placed to mark the perimeter of the shelf would have been visible on ECDIS, providing warning adequate for the crew to take action to alter course and speed to avert grounding.

7.2 M/V *Exxon Valdez*

On 24 March 1989 the U.S. Tankship *Exxon Valdez* loaded with 1,263,000 barrels of crude oil ran aground on Bligh Reef while departing the traffic separation scheme (TSS) to avoid ice. Approximately 258,000 barrels of oil spilled resulting in damage to the vessel and cargo estimated at $25 million and a cost for environmental cleanup in 1989 at $1.85 billion [62]. There was no indication in the report to contradict that the area was well surveyed and accurately depicted on nautical charts. The probable cause of the grounding was listed as failure to properly maneuver the vessel because of fatigue and workload along with several other factors.



Source: [63] Source: NOAA Chart #16708. (in fathoms)

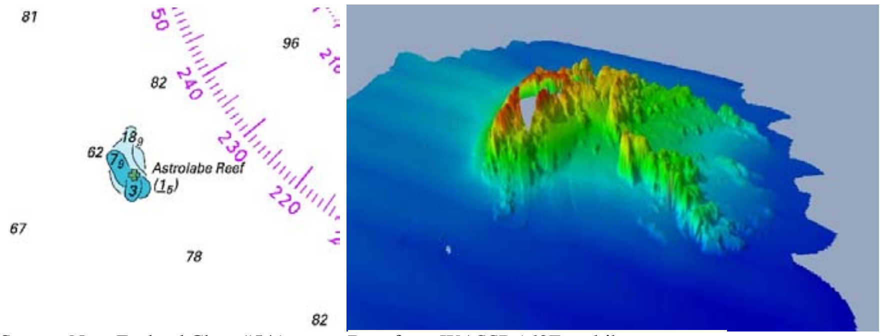
Fig 4. *Exxon Valdez* - Glacial Ice Intrusion into Traffic Lanes; Bligh Reef Navigation Chart

***Analysis*:** *Exxon Valdez* was proceeding at night on autopilot at a speed of 16 knots when the vessel ran onto Bligh Reef [63]. The depth of the hard bottom before the reef, illustrated in Figure 4, averaged 30 fathoms sloping to 50 fathoms before rising to 4 fathoms at the reef. Neither 3D-FLS nor ECDIS existed at the time of this grounding. A vessel transiting this same course today using 3D-FLS with a 1,000 meter range at a speed of 16 knots would have had several minutes advance warning that they were in trouble before the grounding. First significant indication (other than the depth was half what is should have been in the inbound lane of the TSS) would have occurred around 1,000 meters out as the bow was directed towards Reef Island, where a solid wall to the water's edge directly in the path of the vessel would have been displayed. The second and final indication would have occurred after the turn away from Reef Island towards Bligh Reef, where another solid wall to the water's edge directly in the path of the vessel would have been displayed. Conceivably, 3D-FLS might have been useful to navigate the channel between Reef Island and Bligh Reef once they found themselves in this situation.

Virtual AtoN placed to mark the perimeter of Bligh Reef, Reef Island and/or the channel between the two would have been visible on ECDIS, providing warning adequate for the crew to take action to alter course and speed to avert grounding.

7.3 M/V *Rena*

On 4 October 2011 the container ship *Rena* bound for the New Zealand port of Tauranga ran aground on Astrolabe Reef (illustrated in Figure 5) at a speed of 17 knots. The master authorized the watchkeepers to deviate from the planned course lines on the chart to shorten the distance and expedite their arrival. Instead of passing two nautical miles north of Astrolabe Reef the second mate reduced the distance to one nautical mile to save time. He then made a series of small course adjustments towards Astrolabe Reef to make the shortcut. As a consequence *Rena* made a ground track directly for Astrolabe Reef. About 200 tons of heavy fuel oil were spilled in the accident, and a substantial number of cargo containers were lost overboard [64].



Source: New Zealand Chart #541 Data from WASSP 160F multibeam system. www.oceanDTM.com (used by permission)

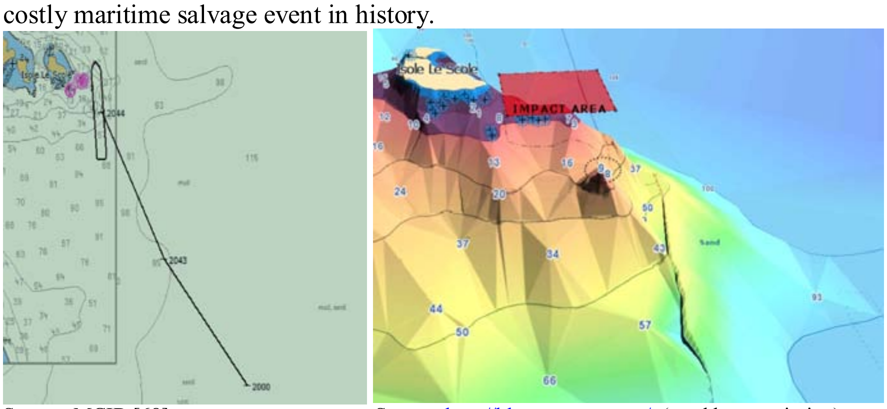
Fig 5. Navigation Chart and Bottom Topography: *Rena* Grounding

***Analysis*:** *Rena* was proceeding at night on autopilot at a speed of 17 knots when the vessel ran onto Astrolabe Reef [65]. The depth of the bottom before the reef, illustrated in Figure 5, averaged 80 fathoms rising to 4 fathoms at the reef. Were *Rena* equipped with 3D-FLS with a 1,000 meter range at a speed of 17 knots the vessel would have had approximately 1.7 minutes advance warning before the grounding. The approaches to the reef would have been evident before then.

Although paper charts were being used, Virtual AtoN placed to mark the perimeter of Astrolabe Reef would have been visible on ECDIS, providing warning adequate for the crew to take action to alter course and speed to avert grounding.

7.4 M/V *Costa Concordia*

On 13 January 2012 the passenger ship *Costa Concordia* with 4,229 persons on board while in navigation in the Tyrrhenian Sea off the coast of Italy collided with Scole Rocks adjacent to Isle de Giglio, as illustrated in Figure 6. The ship had recently departed the port of Civitavecchia and was enroute to Savona, Italy. The hull was breached, thirty-two souls are dead or missing and the vessel was lost [66]. Human error is cited as a primary cause for this accident [67]. Specifically, a chart of inadequate scale was used to superficially plan and execute a maneuver at night that was unsuitable in terms of distance from the coast and adjacent rocks and outcrops as well as depth below the keel. This grounding became the most costly maritime salvage event in history.



Source: MCIB [68] Source: http://blog.maxsea.com/ (used by permission)

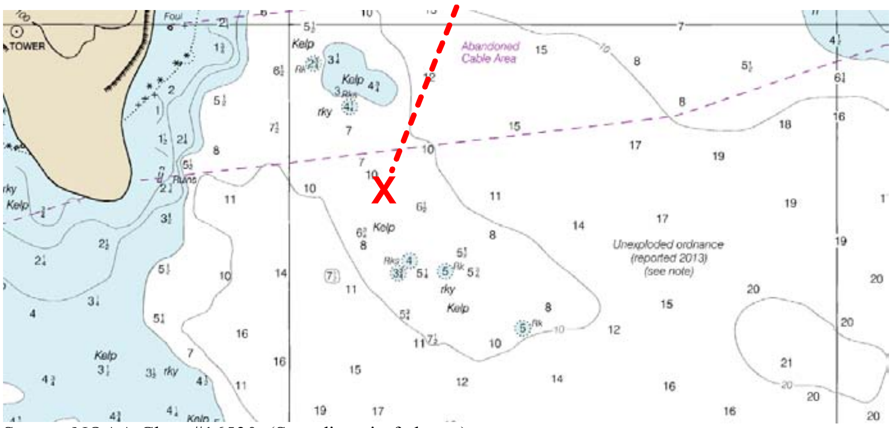
Fig 6. Navigation Chart and Bottom Topography: *Costa Concordia* Grounding

Analysis**:** *Costa Concordia* was proceeding at night at a speed of 16 knots when the vessel ran onto Scole Rocks. The position marked 2000 on the chart to the left lies approximately 1,100 meters from Scole Rocks with depth in excess of 100 meters with a mud bottom. The 100 meter bottom contour is approximately 500 meters further along the course, with upslope bottom rising to the 10 meter bottom contour at the maximum range of the 3D-FLS off the starboard bow. The bottom is also transitioning from mud to rock, with a resultant increase in acoustic reflectivity of the bottom material. Clear indications of the approaches to Scole Rocks would have appeared off the starboard bow on the 3D-FLS display. Even with the switched off ECDIS alarms, such an indication potentially should have initially alerted the Master to the existence of a problem since the appearance of Scole Rocks would have been expected off the port bow based upon the passage planning. Furthermore, the depth contour displayed on the 3D-FLS would clearly indicate insufficient depth in an unexpected location. Approximately 1.8 minutes advance warning could have provided of the pending grounding showing the approaches to Scole Rocks culminating with a wall extending up to the water's edge. Up until 150 meters prior to grounding, an escape path to clear water would have been evident off the starboard bow. Baldauf and Wright [69] provides a concept for triggering anti-grounding warnings taking into account simulation-based prediction of the ship's maneuvering behavior according to the prevailing circumstances of the concrete situation.

Virtual AtoN placed to mark the approaches to Scole Rocks would have been visible on ECDIS, providing warning adequate for the crew to take action to alter course and speed to avert grounding.

7.5 MSV Fennica

On 3 July 2015 the MSV *Fennica*, while enroute between Dutch Harbor Alaska and the Shell Oil drilling field in the Chukchi Sea, was holed when it traveled near a previously uncharted rocky shoal [70]. The nautical chart of the inadequately surveyed area indicated several meters clearance to the bottom existed along the route, and tides were favorable. However, a deeper route of transit was available nearby that could have easily been used as an alternative to the shallower route actually taken.



Source: NOAA Chart #16530 (Soundings in fathoms)

Fig 7. Navigation Chart: Location where MSV *Fennica* was Holed

***Analysis*:** At the time of this writing the official investigation into the grounding had just begun. The speed of the vessel at the time it was holed is unknown. The depth of the bottom, illustrated in Figure 7, averaged 7-10 fathoms then around 15 fathoms until rising to 4 fathoms at the previously undetected shoal. Were MSV *Fennica* equipped with 3D-FLS with a 1,000 meter range its useful range would have been restricted due to the shallow waters of the area to between 8 to 20 times the depth, or approximately 150 to 350 meters range. At a speed of 10 knots the vessel would have had approximately 20 to 60 seconds advance warning before the vessel was holed, possibly providing sufficient time to lessen the severity of the incident. The approaches to the shoal would have been evident before then.

Virtual AtoN placed to mark the perimeter of shoal would have been visible on ECDIS, providing warning adequate for the crew to take action to alter course and speed to avert the incident.

7.6 M/V *Petrozavodsk*

On 11 May 2009 the 1,250 gt. refrigerated cargo ship *Petrozavodsk* ran aground in heavy fog on the southern tip of Bjornoya (Bear Island) in the Arctic between Norway and Spitzbergen. Satellite tracking shows the ship held a steady course straight towards the shore and ran aground at a speed of 10 knots. The ship was declared a total loss. There were no injuries but up to 60 tons of fuel and other pollutants were spilled into the sea in an area with major sea bird populations. Many dead and injured seabirds were found along the coastline. The master and mate were reported to have high blood alcohol levels resulting in the vessel entering a protected area and running aground. Both were charged, convicted and sent to prison in Tromso, Norway [71].

***Analysis*:** This grounding is included to illustrate there is no fool-proof technological solution to prevent any situation where the master and mate are intent on criminally-negligent behavior that imperils the lives and safety of the crew and vessel.

8. Safety Management System

The unique risks and limitations associated with navigation in the Arctic necessitates a vessel safety management system that fulfills all appropriate company policies, port state regulations and IMO carriage requirements; as well as the COLREGS, the STCW convention, the Polar Code and other requirements that apply to the voyage. However, this is still not enough. The results of eNavigation, development of new carriage requirements and implementation of IMO initiatives take years to achieve fruition. A risk-adverse strategy must be followed towards equipping Arctic-bound vessels with 3D-FLS in a manner that will increase their potential to successfully complete their voyage in this risk-prone environment.

The Arctic is a frontier that requires initiative, innovation and forethought to anticipate circumstances and events that are not likely to occur at lower latitudes and in areas more frequently traveled. This concept applies specifically to technology that may assist mariners today in reducing risk to navigation, yet no carriage requirements exist for their installation or use on vessels. One such example of progress in this area is the use of an Inertial Navigation System (INS) as a means to supplement GNSS positioning where atmospheric and other phenomena may interfere with reception. Many vessels in the Arctic and elsewhere are presently equipped with INS as a result of prudence and proper planning despite the absence of any specific requirement to do so. In many parts of the world eLORAN capabilities also exist and vessels are equipped with receivers as a means to supplement GNSS positioning. 3D-FLS should be amongst this equipment on the bridge. The adoption of truly Virtual AtoN and their verification through the use of georeferencing techniques that would be immune to interference and spoofing attacks would also be a logical extension of this progress.

9. Conclusions

The technologies described provide new opportunities to increase maritime safety in the poorly-charted frontiers of the Arctic, the benefits of which would be applicable worldwide. 3D-FLS technology is not yet sufficiently tested or integrated on a widespread basis directly into existing navigation systems in its present form. Merely adding yet another sensor and display system to an already complex bridge environment without adequate engineering, planning and training is likely to make matters worse rather than improving them, and may result in increased risk to navigation similar to that which occurred upon the initial introduction of radar that lead to the collision between the M/Vs *Andrea Doria* and *Stockholm* [72]. Adequate training for watchstanders in the use of 3D-FLS by manufacturers should be mandated in anticipation of future enhancements to the STCW convention. Further, the Polar Code should be amended to stipulate the requirement for a second echo sounder is fulfilled using 3D-FLS.

However, it is also abundantly clear that payback in terms of cost avoidance of even one grounding requiring rescue or resulting in oil and/or chemical spillage in the Arctic would far outweigh any investment necessary to equip vessels with this equipment and technology. This will enable masters and crews alike to become familiar with operating and using the described technology as well as enjoy the benefits and enhanced safety provided by its capabilities.

Disclaimer

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

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ENHANCED SITUATIONAL AWARENESS THROUGH MULTI-SENSOR INTEGRATION

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ABSTRACT: Collisions and groundings are the two types of casualties in shipping that occur most often and cause serious damage. At all times Officers of the Watch (OOW) must be aware of the risks of collision and grounding and comply with rules and regulations as established, for example, in the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs), Guidelines for Voyage Planning (International Maritime Organization (IMO) resolution A.893(21)) and the Procedures Manual of a ship's Safety Management System (according to the International Safety Management (ISM) Code). Maritime education and training supports compliance with the legal framework by providing knowledge and skills and supporting application of best practice. This paper describes studies into the use of bridge alerts and an innovative approach to trigger alarms using forward-looking sonar. The development of the concept and basic functional and technological structure to support enhanced situational awareness will be explained and discussed from the perspective of the grounding of M/V Costa Concordia. Suggestions and recommendations for simulation-based test and training scenarios are also presented.

1.0 NOMENCLATURE

Symbols, abbreviations and acronyms used within this paper are identified as follows:

ATON	Aids to Navigation
COLREGS	International Regulations for Preventing Collisions at Sea, 1972
eATON	Electronic Aid to Navigation
ECDIS	Electronic Chart Display and Information System
ENC	Electronic Nautical Chart
FL-sonar	Forward-looking sonar
HMI	Human Machine Interface
HtoN	Hazard to Navigation
IMO	International Maritime Organization
INS	Integrated Navigation Systems
M/V	Motor Vessel
OOW	Officer of the Watch
STCW	Standards of Training, Certification and Watchkeeping

2.0 INTRODUCTION

An important aspect of basic and enhanced training in ship handling and navigation courses is the familiarization with and handling of equipment including transferring knowledge and experience on the capabilities, functionalities and constraints on their use. Bridge navigational equipment encompasses many and diverse systems to support safe and efficient navigation and protection of the marine environment. The present situation is characterized by an increasing level of integration of sensors, technical systems, displays and sophisticated decision support systems combined with complex alerts to ensure sufficient situational awareness of the bridge team. However, despite the presence of such sophisticated systems accidents in the form of groundings and collisions still happen. Regardless of the behaviour, the actions taken or not taken by the bridge team, the grounding of Costa Concordia equipped with very modern integrated bridge navigational systems can be seen as another prominent case where alerts implemented in most modern and highly sophisticated navigation systems failed to raise the attention to take action to avoid an accident.

The COLREGs and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) require an adequate watch be maintained.[1,2] However, there is presently no established means to maintain watch below the waterline to directly detect the presence of hazards to navigation. A key assertion of the research presented in this paper is that bridge watchstanders are generally provided only with indirect and/or secondary information from which safety-critical decisions are routinely formulated. Although the tragic grounding of Costa Concordia or more recently the grounding of M/V Marco Polo in Norwegian fjords provide convenient and fresh examples to illustrate this assertion, the problem has and continues to exist on a daily basis during virtually every vessel transit. For example, nautical charts and even most modern ECDIS provide navigation information as a secondary reference created by survey at some time in the past that was accurate at the time it was made but not necessarily reflecting actual conditions at the time of passage. Radar indicates only those nearby targets from which the proximity to underwater hazards to navigation should be deduced. A traditional echo sounder provides depth directly below the keel, but no indication of depth directly forward of the bow. These and other methods such as GNSS merely infer positional relationships to geographic locations of interest and concern, but none are capable of directly detecting the physical underwater hazard to navigation (HtoN) consisting of Scole Rocks off Isle del Giglio, or any other such hazard prior to grounding. Additional to this, there are floating hazards to navigation that cannot be charted such as drifting shipping containers, debris fields, whales, etc., having little or no presence on radar or other navigation sensors.

Another assertion is that the technology needed to detect hazards to navigation in real time at and below the waterline currently exists in the form of FL-sonar and is available as commercial off-the-shelf equipment ready to be installed on vessels at the next scheduled drydocking. This does not imply, however, that this technology is sufficiently tested, capable of being integrated directly into existing navigation systems in its present form, or adequate training exists for its use. Merely adding yet another sensor and display system to an already complex bridge environment without adequate engineering, planning and training is likely to make matters worse rather than improving them, resulting in increased risks to navigation. This is illustrated with the introduction of radar that lead to the radar-assisted collision between M/Vs Stockholm and Andrea Doria. Lack of proper training in the operation, use and interpretation of radar equipment combined with a lack of procedures for implementing corrective actions based upon radar indications created a scenario where established procedures for navigating in restricted visibility were not followed, resulting in the collision.[3]

The capabilities and limitations of forward-looking sonar technology are discussed in terms of their scope and capability to detect hazards to navigation, along with its suitability in terms of vessel type, speed and installation requirements. Also covered is the complexity of using FL-sonar for vessel navigation describing present capabilities as well as future requirements in terms of standards for integrated navigation systems (INS) and bridge alerts. This includes the introduction of electronic aids to navigation (eATONs) as a means to display hazards to navigation on electronic chart display and information systems (ECDIS). Integral to this process is the use of simulation technologies to test, verify and validate system processes, procedures and training requirements well in advance of the introduction of this technology to vessels by the introduction of carriage requirements through the IMO.

3.0 FORWARD-LOOKING SONAR TECHNOLOGY

Active sonar, commonly referred to as an echo sounder by the IMO, is used by vessels in determining the depth between the keel and the bottom.[4] A variation of the echo sounder is forward-looking sonar used to detect bottom features and objects within the water column forward of the bow. Despite its usefulness and the availability of this technology in the commercial marketplace it is rarely included within the ships' complement of navigation sensors.

1.1 SPECIFICATIONS AND CAPABILITIES

The methods used for detecting bottom features, objects and soundings by determining range, azimuth and elevation information can generally be described as variations on transmitting a steerable sonar signal ahead along the path of the vessel or transmitting a single ping from which snapshots of the environment are obtained.[5-8] A mosaic of the bottom topography and specific targets is then created as the vessel progresses on its course.

The range of FL-sonar can extend from eight to twenty times the depth ahead, depending on bottom and target conditions. It is most effective when the bottom topography slopes upwards and when targets are large and consist of hard rock and/or coral that provide good acoustic signatures. FL-sonar products are available that provide both 2-as well as 3-dimensional representations which provide a more realistic portrayal of the course ahead.

FL-sonar systems have been developed with different capabilities supporting both autonomous underwater vehicle and vessel applications. Of those designed for use on vessels, most are intended for pleasure and small fishing boats. There are systems with range and resolution that make them suitable for use on larger vessels such as workboats, offshore service vessels, merchant and passenger vessels. However, operational constraints may create limitations on their usefulness. For example, effective range may be limited by tradeoffs in transducer design to minimize water resistance and drag. A summary and examples of several FL-sonar systems, presently available on the market and each utilizing a different type of transducer, and their specifications are illustrated in **Table 1**.

Table 1 – Comparison between forward-looking sonar systems

Specifications	EchoPilot 3D FLS [9]	Furuno CH-270 [10]	FarSounder 1000 [11]
Maximum Detection Depth:	100 m (328 ft)	100 m (328 ft)	50 m (169 ft)
Operating Frequency:	200 kHz	180 kHz	61 kHz
Maximum Detection Range (MDR):	200 m (656 ft)	800 m (2,500 ft)	1,000 m (3,200 ft)
Vertical Coverage:	90°	180°	60°
Horzontal Field of View:	60°	360°	60°
Maximum Tramsnit Power:	not specified	800 W	<1500 W_{rms}
Angular Accuracy:	not specified	not specified	1.6°
Roll/Pitch Compensation:	not specified	not specified	±20°
Roll/Pitch Accuracy:	not specified	not specified	0.5°
Maximum Vessel Speed:	not specified	10 kts	25 kts
Screen Refresh Rate:	1-2 seconds	8 seconds	2 seconds
Advance Warning at MDR @ 10kts.:[A]	28 sec. (0.5 min.)	139 sec. (2.3 min.)	183 sec. (3.1 min.)

A. Calculation by author.

1.2 CONCEPTUAL APPROACH TO ESTIMATES OF ADVANCE WARNING AFFORDED BY FL-SONAR

As a very first basic step for establishing and further development of definitive parameters for the issuance of warnings to watchstanders using FL-sonar, certain guiding principles may be cited to achieve an estimate useful for broad guidance on the subject. For example, a calculation of the relative time afforded a vessel to begin corrective action such as altering course, reducing speed or otherwise reacting to an alarm generated by a FL-sonar would be based, at minimum, upon the following factors:

$$Advance\ Warning\ (sec) = \frac{MDR\ (\mathrm{m}) - SRR\ (\mathrm{sec}) - APT(\mathrm{sec}) - \mathrm{WRT(sec)}}{Vs\ (\frac{\mathrm{m}}{\mathrm{sec}})} \quad (1)$$

where logical arguments may be made to establish values for each of these parameters:

Speed of Vessel (*Vs*) = 10 knots
Screen Refresh Rate (*SRR*) = 2 sec, or as noted
Maximum Detection Range (*MDR*) = obtained from Table 1
Alarm Processing Time (*APT*) = 4 sec
Watchstander Response Time (*WRT*) = 5 sec
1 m/s = 1.9438 knots

Although some systems can perform at much higher speeds, a value of 10 knots was selected for the Speed of Vessel (*Vs*) to provide a common basis for evaluating the reaction time to FL-sonar system alarms. A value of two seconds for Screen Refresh Rate (*SRR*) on the display was assumed based upon system performance specifications. However, *SRR* for the Furuno CH-270 system may be as high as eight seconds or more as this system provides general coverage that extends beyond the area directly ahead of the bow. The value for Maximum Detection Range (*MDR*) is obtained from the performance specifications of the individual FL-sonar units.

Alarm Processing Time (*APT*) is the speed at which FL-sonar data can be evaluated by signal processing and alarm generation algorithms to determine whether a condition exists that breaches predetermined vessel-specific safety contours and depths. This includes draft, course, Maneuvering capabilities, lateral clearance margins and other factors pertinent to safety of navigation. As assumption is made that such criteria for FL-sonar are likely to be similar to those established by IMO for ECDIS.[12] Integral to this factor are time delays to prevent normal operating conditions from causing false alerts because of normal transients that may exist in the FL-sonar data.[13] This can add an additional one to several seconds to ensure target persistence, eliminating the generation of an alarm due to a single occurrence or short duration or transient target. A value of four seconds was selected based upon FL-sonar refresh rates as well as estimates of processing times for interface and communications systems handling software that may be required by INS.

Watchstander Response Time (*WRT*) is that needed for the OOW to acknowledge an alert and take appropriate corrective action based upon the nature of the alarm. This must take into account time lags necessary to assess rates of change in processes such as changing vessel course against targets' movements.[14] The time required for the OOW to confer with other bridge watchstanders and lookouts and to issue orders to the helmsman must also be factored into this calculation. Add to this the effects of fatigue and various other human factor elements, one can easily see that this factor is the most subjective and imprecise in the equation. A value of five seconds was chosen in part based upon the author's direct observations of bridge practices used on several vessels under similar conditions using ECDIS and radar indications.

Using these criteria the EchoPilot 3D FL-sonar provided approximately ½-minute warning, the Furuno CH-270 provided approximately 2¼-minute warning and the FarSounder 1000 provided approximately a 3-minute warning when considering their maximum detection range. The speed of 10 knots may appear somewhat slow for most vessels while underway. However, if a vessel is operating in unknown, poorly charted or known-hazardous waters it is prudent to increase safety margins by proceeding at a slower than normal pace.

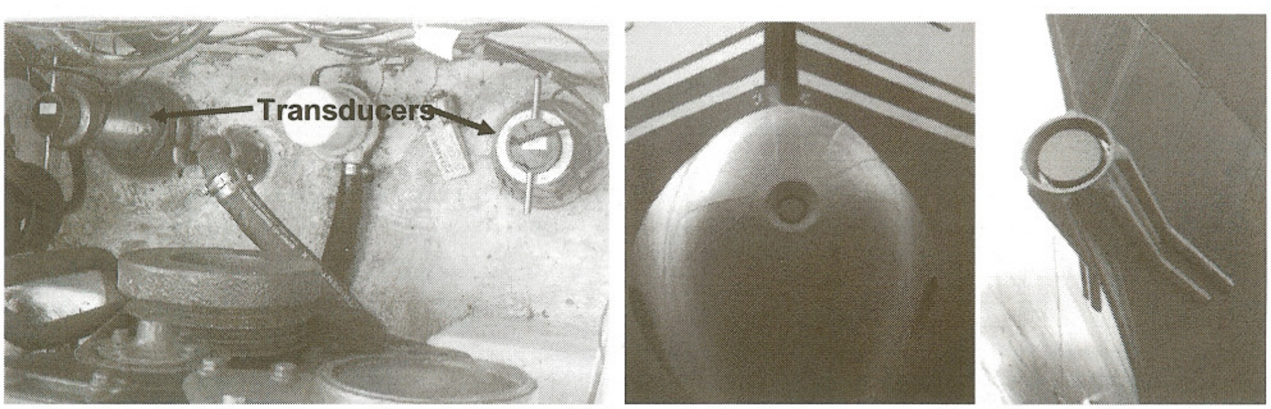
It should be noted that such advance warning calculations generally provide "best case" scenarios under ideal conditions, and that actual conditions and response times must be expected to reduce these margins – significantly in some cases. Actual conditions must also take into consideration both human and technological factors that can result in major deviations from these response times. Technological factors can include water turbidity, poor acoustic reflection qualities of potential HtoN and even growth on the hull that may reduce FL-sonar sensitivity. Human factors can range widely from distractions on the bridge, unfamiliarity with the equipment and general lack of training, proficiency or currency in watchkeeping procedures.

1.3 INSTALLATION

To achieve the most reliable and accurate performance FL-sonar transducer(s) must be located on an area of the hull that is free of turbulence from obstructions located forward of the mounting position. Each transducer must be provided an unobstructed view both horizontally towards the bow and vertically from the waterline to the bottom to achieve the best accuracy and effectiveness.

The EchoPilot 3D Forward Looking Sonar uses two transducers mounted athwartships, one either side equidistant to the keel - ideally on the rear third of the vessel. The interior installation of these transducers as visualized from within the hull is illustrated in **Figure 1a**.

The FarSounder 1000 Navigation Sonar uses one transducer mounted on the bow with a fairing tube inserted within an existing or standard bulb, or as a separate installation. The exterior installation of this transducer as seen from ahead of the bow is illustrated in **Figure 1b**.



a. Dual EchoPilot Transducers Mounted Athwartships **b. Single FarSounder Bow-Mounted Transducers**

Figure 1: FL-Sonar Transducer Installations

The Furuno Searchlight Sonar, Model CH-270 (not pictured) uses a single transducer that can be lowered from and retracted into the hull at speeds above 10 knots. This unit may be mounted anywhere on the vessel where an unobstructed view horizontally through 360° is available.

4.0 GROUNDING OF COSTA CONCORDIA

On 13 January 2012 Costa Concordia with 4,229 persons on board (3,206 passengers and 1,023 crewmembers) whilst in navigation in the Tyrrhenian Sea off the coast of Italy collided with Scole Rocks adjacent to Isle de Giglio. The ship had recently departed the port of Civitavecchia and was enroute to Savona, Italy. The hull was breached, thirty-two souls are dead or missing and the vessel was lost.[15]

Human error is cited as a primary cause for this accident. Specifically, a chart of inadequate scale was used to superficially plan and execute a manoeuvre at night that was unsuitable in terms of distance from the coast and adjacent rocks and outcrops as well as depth below the keel. Radar indications, had they been observed, would have clearly warned of the vessel's unacceptably close proximity to the coast as well as the outcropped rock showing above the waterline. These are just a few of the facts that came out of the official inquiry, and many mistakes in navigation were in evidence.

An attempt is made to depict information and alarms that would have been available to the bridge watch on Costa Concordia were FL-sonar installed, operational and integrated into the INS. Mistakes in navigation planning can be made, alarms deactivated, and watchstanders can be distracted and poorly communicate. However, perhaps the activation of an alarm based upon direct detection of the presence of an imminent HtoN would provide greater significance than an alarm requiring inference of HtoN based upon indirect methods and secondary data sources.

4.1 DETAILS OF NAVIGATION

A chronology of events leading to the grounding of Costa Concordia relevant to this discussion is as follows:

21:34:36	Master arrives on the bridge
21:39:30	Master orders helmsman to turn to 300°
21:40:00	... increase to 16 knots and turn to 310°
21:40:48	... turn to 325°
21:41:40	vessel is at position A in Figure 2
21:42:07	... turn to 330°
21:42:48	vessel is at position B in Figure 2
21:43:08	... turn to 335°
21:43:33	... turn to 340°
21:43:44	... turn to 350°
21:43:52	vessel is at position C in Figure 2
21:44:11	... starboard 10 (10 degrees to starboard)
21:44:15	... starboard 20
21:44:20	... hard to starboard
21:44:36	... mid ship (< 150 meters Scole Rock
21:44:43	... port 10
21:44:45	... port 20
21:45:55	vessel is at position D in Figure 2
21:45:05	... hard to port
21:45:07	CONTACT

From this chronology it appears that the Master, who had just come to the bridge minutes earlier at 21:34:36, exhibits some sense of situational awareness at 21:39:30 by his change of course to 300°. However, he seems to be completely unaware of the grave nature of the circumstances he has encountered at 21:40:00 (five minutes before the grounding) when he ordered an increase in speed to 16 knots. Beginning 48 seconds later at 21:40:48 the Master ordered the first of twelve course changes over the next four minutes. Clearly at some point he had to become conscious of the gravity of the situation, yet no attempt was ever made to stop the vessel, reduce speed or even execute a hard turn to starboard to achieve a small yaw radius earlier in the incident chronology. Indeed, ground track information indicates the vessel was accelerating in speed during these final segments of the voyage.

4.2 INSIGHT AVAILABLE FROM FL-SONAR

Simulation of the circumstances encountered by Costa Concordia is attempted through extraction of the ground track using the AIS data record, then overlaying FarSounder 1000 FL-sonar cone coverage onto the ground track to identify key events that may have provided opportunities to enhance situational awareness. Four noteworthy positions in the transit just prior to grounding identified as A, B, C and D are illustrated in **Figure 2** and recorded into the above chronology.

1.4.1 Ground Track Position A (10°56'32" E, 42°20'41" N; Speed: 15.3 knots; Course 325°, approx.)

This position lies approximately 1,600 meters from Scole Rocks with depth in excess of 100 meters with a mud bottom.[16] This location is outside the range of FL-sonar to detect bottom information and is not likely to have provided any information of significance to navigation.

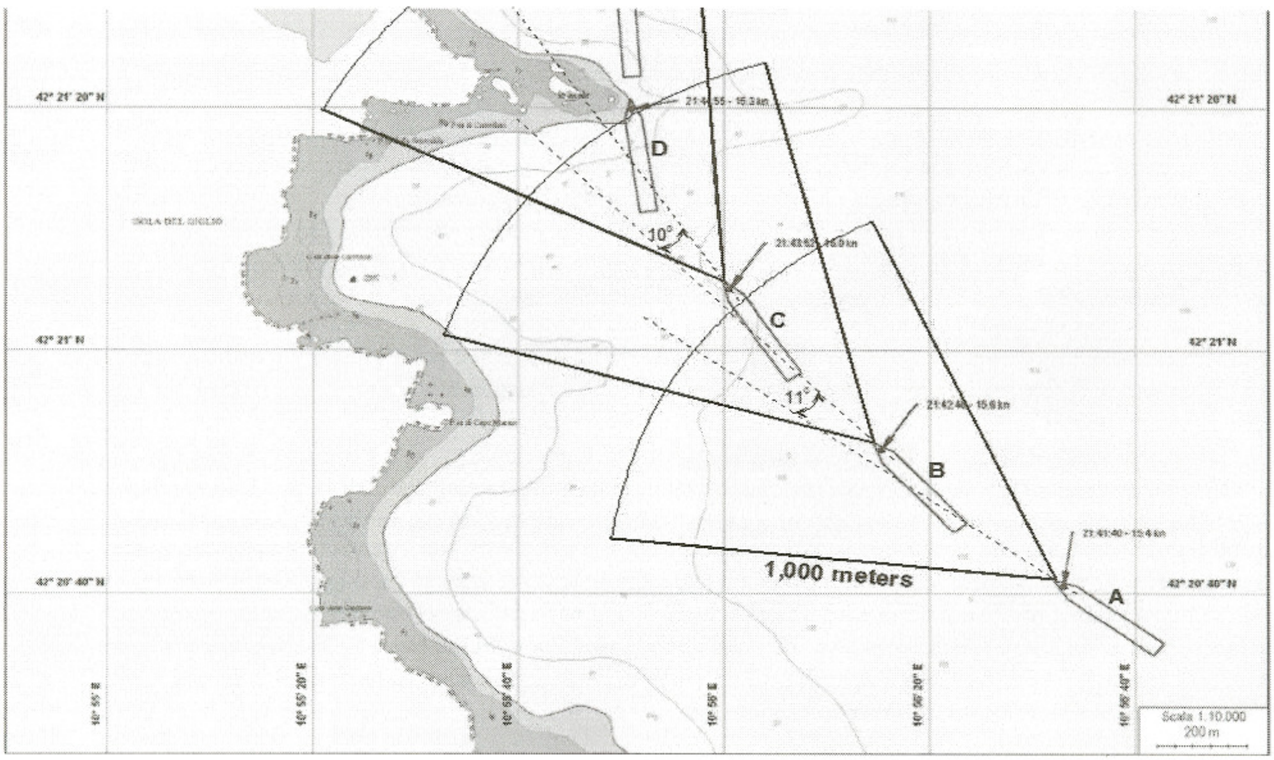
1.4.2 Segment A to B (Elapsed Time: 00:01:08, Rate of Yaw: 11°/min)

During most of this segment the bottom depth would have remained in excess of 100 meters with a mud bottom. However, just prior to arriving at Position B the maximum range of the FL-sonar would have crossed the 100 meter bottom depth contour directly ahead and to port of the centreline and it is possible that early indications of an upslope bottom may have been able to be detected. Note that during this segment the rate of turn is approximately 11 degrees per minute.

1.4.3 Ground Track Position B (10°56'15" E, 42°20'52" N; Speed 15.6 knots; Course 335°, approx.)

This position lies approximately 1,100 meters from Scole Rocks with depth in excess of 100 meters with a mud bottom. The 100 meter bottom contour is approximately 500 meters further along the course, with upslope bottom rising to the 10 meter bottom contour at the maximum range of the FL-sonar off the starboard bow. The bottom is also transitioning from mud to rock, with a resultant increase in acoustic reflectivity of the bottom material.

Clear indications of the approaches to Scole Rocks would have appeared on the starboard bow on the FL-sonar display. This probably would have initially alerted the Master to the existence of a problem since the appearance of Scole Rocks would have been expected off the port bow based upon his passage planning.[17] Furthermore, the depth contour displayed on the FL-sonar would clearly indicate insufficient depth in an unexpected location.



Summary of the track (extracted by the AIS data record)

Source: Marine Casualties Investigative Body, Cruise Ship Costa Concordia, Report on the safety technical investigation, Pg. 61, Ministry of Infrastructures and Transports (Italy).

Figure 2: Ground Track of Costa Concordia, Annotated with Coverage for Forward-Looking Navigation Sonar

1.4.4 Segment B to C (Elapsed Time: 00:01:04, Rate of Yaw: 10°/min)

During this segment bottom depth is steadily decreasing across the range of the FL-sonar from in excess of 100 meters to the surface. The bottom consistency also changes from mud to solid rock, resulting in a large acoustic reflection and indications of strong targets.

The appearance of a solid wall leading up to the surface and continuously decreasing in distance would have loomed prominently on the FL-sonar until it consumed two-thirds of the display from far port to starboard of centre. Despite orders from the master to turn from 330° to 350° throughout the one minute segment duration, the rate of turn appears to have been half that at 10 degrees per minute.

1.4.5 Ground Track Position C (10°56'01" E , 42°21'05" N; Speed 16.0 knots; Course 340°?)
This position lies approximately 530 meters from Scole Rocks with depth of 95 meters just past the 100 meter contour with a rock bottom. The bottom contour would reflect an upslope bottom rising to the surface around 500 meters ahead. Less than one-third of the display off the starboard bow would show clear water. There would be very little room to manoeuvre at this point.

1.4.6 Segment C to D (Elapsed Time: 00:01:03)
This is the terminal segment of the voyage. Bottom consistency is solid rock resulting in a large acoustic reflection and indications of strong targets. The appearance of a solid wall leading up to the surface and continuously decreasing in distance would have continued up to the point of impact.

1.4.7 Ground Track Position D (10°55'40" E, 42°21'21" N; Speed 15.3 knots; Course ???°)
This position lies approximately 30 meters from Scole Rocks with twelve seconds remaining before contact.

1.4.8 Hypothetic course of events - Applying FL-Sonar
Using a speed of 16 knots obtained from the chronology in paragraph 4.1 as the value for Speed of Vessel (Vs) in equation (1), FL-sonar could have provided approximately 1.8 minutes advance warning to the Master of Costa Concordia of the pending HtoN consisting of the approaches to Scole Rocks. The warning would have been issued when the vessel was just past position B shown in **Figure 2.**

Had FL-sonar been installed and operational on the bridge as discrete navigational equipment without benefit of inclusion within INS, visual indications would have shown an unmistakable wall directly in the path of the vessel. Existing alarms available both integral and external to the equipment would have also been activated, further reinforcing the severity of the situation. Consistently, at all noted positions on the final approach (Figure 2: positions A through D) the FL-sonar would have indicated clear water was present off the starboard bow.

It is assumed that the 1.8 minutes prior warning would have provided sufficient advance notice to plan and execute evasive manoeuvres that may have lessened the severity of the grounding or averted it entirely. Halting the forward momentum of the vessel would not have been possible as this would require around 1,300 meters with the vessel moving at 16 knots, and this distance was not available.[18] However, slowing the vessel combined with executing a hard turn to starboard upon receiving the warning commencing approximately 800 meters prior to Scole Rocks would have significantly reduced the damage incurred in the event of grounding such that the vessel may have remained afloat and lives may have been saved. Indeed, and even hypothetical, the accident may not have happened at all.

5.0 BRIDGE ALERTS AND ALARM GENERATION

The information available from the FL-sonar can be useful in alerting watchstanders as to potential HtoN present in the path directly ahead of the bow. Visual indications seen on the FL-sonar display are one form of alerting mechanism. However, this data may also be shared as part of an integrated approach using ECDIS as well as the Alert management, module C of an INS according to latest IMO Performance Standards. This coincides with existing STCW training requirements and could utilize existing alarm mechanisms with which watchstanders are already familiar.

Analysis of information available from FL-sonar can be used to trigger alerts with different levels of priority. In accordance with the definitions provided by IMO performance standards the lowest level of such an alert is a caution to just raise awareness of the bridge team to a certain unusual situation. In respect to the integrated use of FL-sonar information this could be a situation, where an obstacle is detected at a larger distance ahead, e.g. due to a cross track error.

Triggering warning, the second priority level of alert and requiring immediate attention by the bridge team, could be linked to criteria within the usual Maneuvering range of the ship to avoid contact to any detected HtoN. The time frame is to be configured as to allow the OOW to additionally check the FL-sonar display but also match with available ECDIS information (e.g. to proof approaching a shallow waters area, a wreck or rock, island).

Finally even an alarm could be triggered, characterizing conditions requiring immediate action e.g. the ship is approaching the lower Maneuvering limit (e.g. an emergency, hard rudder action would be required) in order to avoid the contact with an FL-sonar detected object/HtoN.

The capability to provide those warnings and alarms can be even independent of operator interpretation and be based upon analysis of the information obtained from the FL-sonar. This appears to be available only from the FarSounder system. Taking into account the characteristics of the sea area (e.g. approaching coastal waters, navigating in ice etc.) the operator can configure parameters within the area being observed by setting alarm values by depth, minimum range, maximum range, and field-of-view angle width as illustrated in **Figure 3**.[19] The alarm volume is shown in red. An additional setting is the number of hits detected before triggering the alarm.

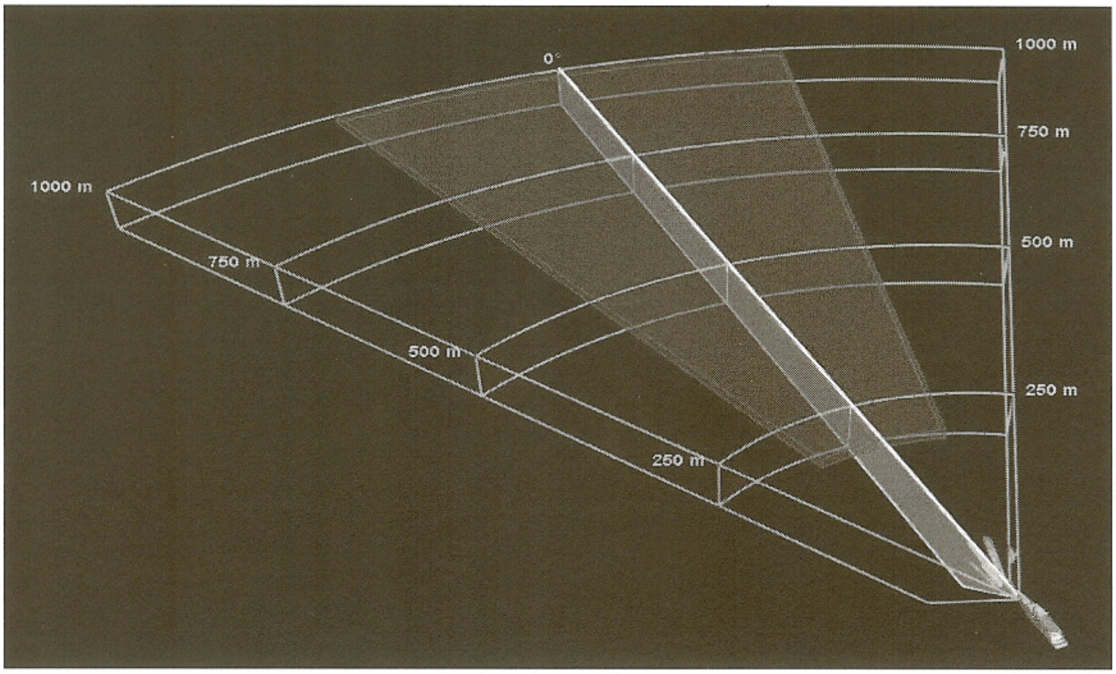


Figure 3: Forward-Looking Sonar Alarm Volume Setting

Watchstanders are provided both visual and audible notifications e.g. announced via the centralized CAM-HMI and supported by presentation in FL-sonar target overlay in an ECDIS as suggested in the following figure, which takes into consideration and applies requirements and standards similar to integration of information and radar overlays.

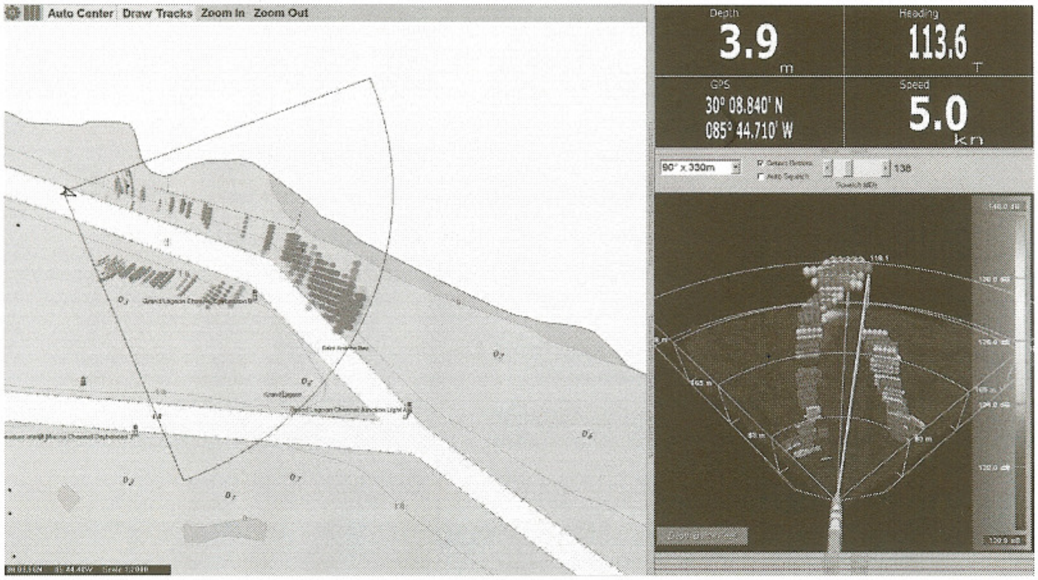


Figure 4: FL-Sonar ENC Overlay

Fulfilling these requirements is accomplished through the fusion of data acquired directly through standard NMEA-0183 interfaces with external navigation sensors that include the vessel's GNSS, heading sensor and echo sounder via the host computer's COM ports.[20] A number of 3rd party manufacturers have implemented their own FarSounder client capabilities as part of their ECDIS/ENC software products.

6.0 SIMULATION PRIOR TO INTEGRATION

The use of simulation to accomplish testing, verification and validation to assimilate FL-sonar into the INS environment is a vital factor towards ensuring systems are properly integrated and mariners are adequately trained prior to the introduction of the technology into widespread use and as IMO carriage requirements.

Beside technical aspects, simulation trials are also to be designed and to be conducted to specifically address and study the impact of new technologies on the human operators. Therefore simulation trials are also especially aiming at gathering information about good practice to properly familiarize users with the handling of equipment to safely and reliably handle such innovative systems during routine operations but also in case of safety-critical situations.

The following table provides an example for a simulation scenario firstly to be used for the purposes of researching the effects of integrated FL-sonar on the situational awareness of OOW. Secondly, the framework can be further developed to also make use in training exercises related to ice navigation too.

Simulation studies will be conducted to collect and analyse data in order to support that system requirements and specifications are properly defined at the level of the FL-sonar (component level) as well as the INS (system level). Human Element related studies are to define optimal Human machine interface (HMI) and adapt alert management to end users' needs and requirements.

On the other hand, properly implemented simulations can also serve as a means to mitigate future training lag times through the parallel development and integration of training curricula with new system technology. Data available can be useful to assist in marine casualty investigations especially in the cases of grounding, allision, collision and evasive maneuvers that comprise some of the top marine casualty events. Indeed, the same hardware deployed on ships for navigation can be used for training. The entire suite of test criteria and test cases used in system verification, validation and test can comprise a foundation for future comprehensive training tool and simulator scenario development. Involvement of training personnel in the technology development process can also help to ensure navigation system feature development is accomplished with appropriate consideration given to ultimate end-user experience, requirements and needs.

Draft sample exercise scenario	
Identifier	**Efficient navigation support by FL-sonar** Alert Management and grounding avoidance
Training objective	i.a. / e.g. • Use of integrated FL-sonar information for route monitoring and grounding avoidance • Use of Integrated Navigation System for safe, efficient and environmentally friendly shipping • Configuration of alert settings • Route monitoring using all available means
Simulator tool	Desk-top Ship handling simulator
Standard of competence	Navigational watch officer, Master, chief mate (management level)
Configuration	e.g. Cruise ship (L_{oa} = 210 m; draught = 6,8 m; service speed = 18 kts)
Duration	Long, > 45 min
Area	Coastal area
Environment / Traffic	Moderate environmental conditions (low states) and traffic situation (low density)
Event-description	• Passenger vessel (i.a. equipped with modern two propellers, bow thruster system) is navigating in a coastal area following the planned route including a number of course changes, • Communication with shore-based company control and VTS stations • Passage includes several rudder/engine maneuver • Navigational warnings about sunken container ship and drifting containers in the concerned sea area • Change to alternative route • Engine problems to be discussed with engineers • Effects of "squat" on under keel clearance power, speed and fuel consumption in shallow water • Situation assessment in respect to collision and grounding avoidance

Table 2: Draft framework for a suggested simulation scenario

7.0 CONCLUSIONS

Vessel groundings and collisions with HtoN can and do cause untold suffering, loss of life and property, often resulting in devastating environmental damage. Costs incurred as a result must include property and liabilities arising from the accident itself as well as the cleanup. Such costs escalate as vessels increase in size and cargo capacity, especially for cargos that include toxic chemicals. Larger passenger vessels with greater carrying capacity create even greater risk. The effects of such accidents are amplified in areas that are remote where search and rescue and salvage efforts are problematic at best.

FL-sonar can provide a means to directly detect HtoN that are not present on navigation charts as well as supplement existing methods to effect greater urgency to adverse circumstances and heighten situational awareness. The technical capabilities exist to make a substantial difference now. The establishment of carriage requirements as well as fusion into INS still needs to take place. The costs involved are minimal, especially in light of the consequences of not having FL-sonar available for navigational use. The salvage cost of Costa Concordia amounts to over $2 billion US.[21] This amount by itself would cover the costs to purchase and install FL-sonar equipment on 75% of the world's merchant fleet greater than 25,000 gross tons.[22]

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9.0 AUTHORS' BIOGRAPHIES

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