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Correlation of Virtual Aids to Navigation to the Physical Environment

R.G. Wright
GMATEK, Inc., Annapolis, MD, USA
World Maritime University, Malmö, Sweden

M. Baldauf
World Maritime University, Malmö, Sweden
Hochschule Wismar – University of Applied Sciences: Technology, Business and Design, Rostock, Germany

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.

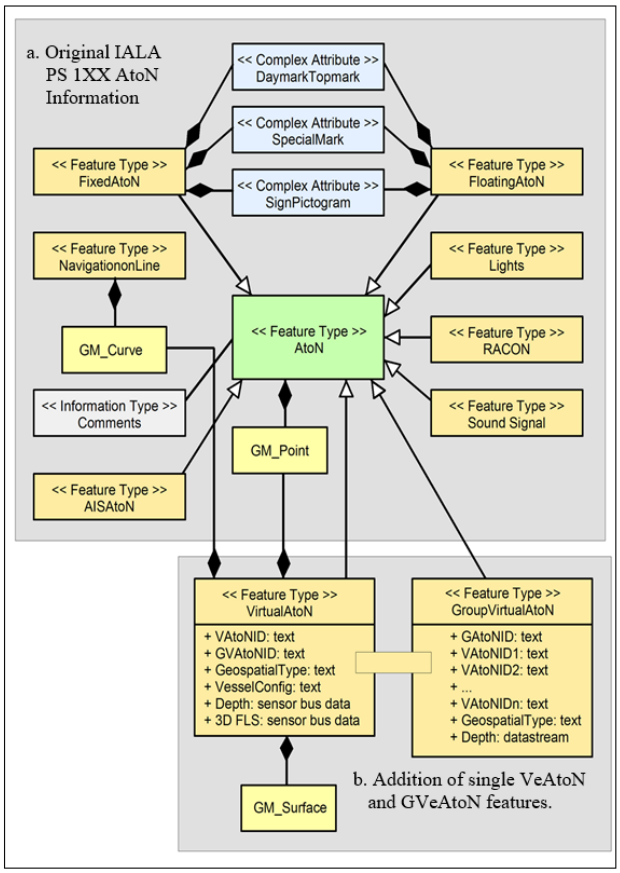

Figure 1. Virtual eAtoN application schema embedded within the IALA AtoN Information Product Specification 1XX, draft 0.0.5 – June 2013.

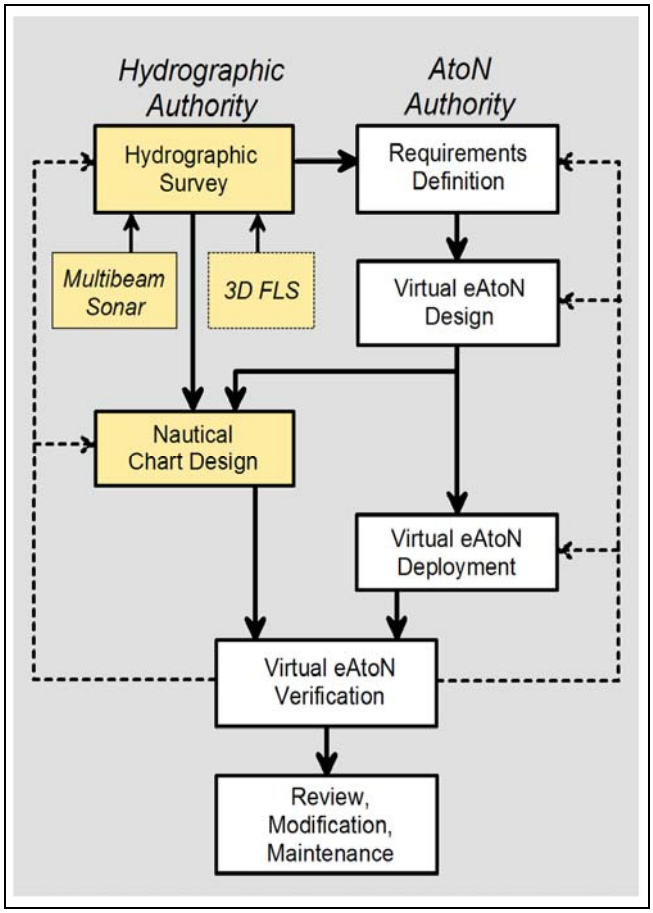

Figure 2. Virtual eAtoN life cycle representing roles of national hydrographic and AtoN authorities.

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.

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.

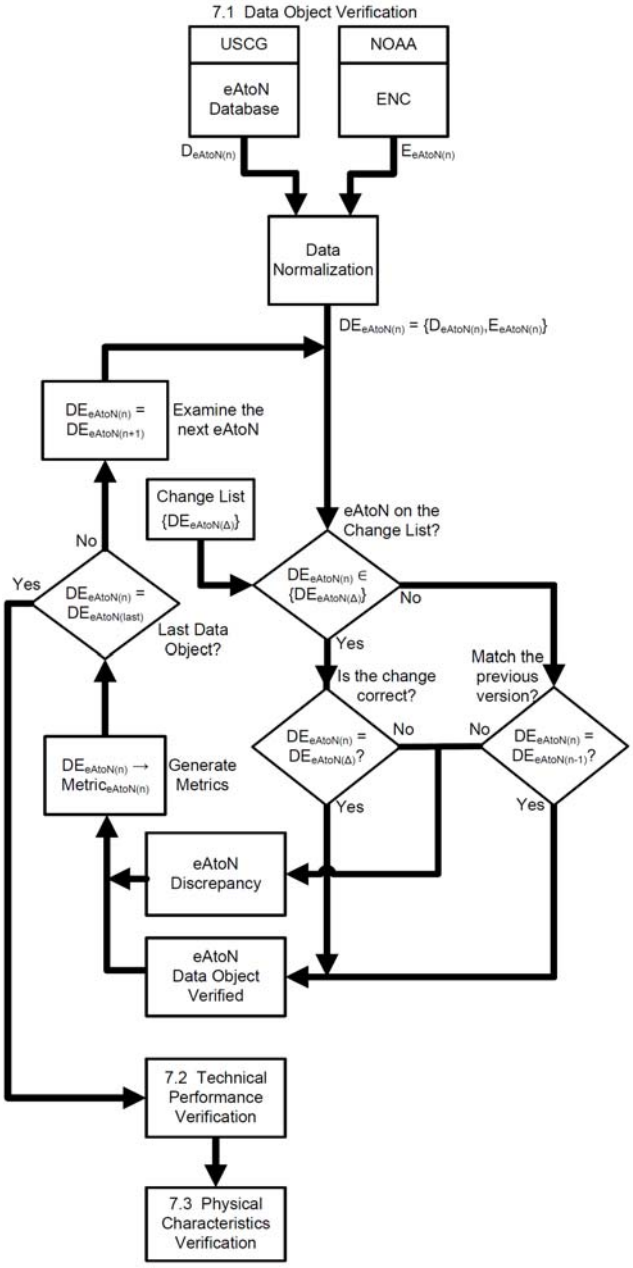

Figure 3. eAtoN Data Object Verification Process.

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.

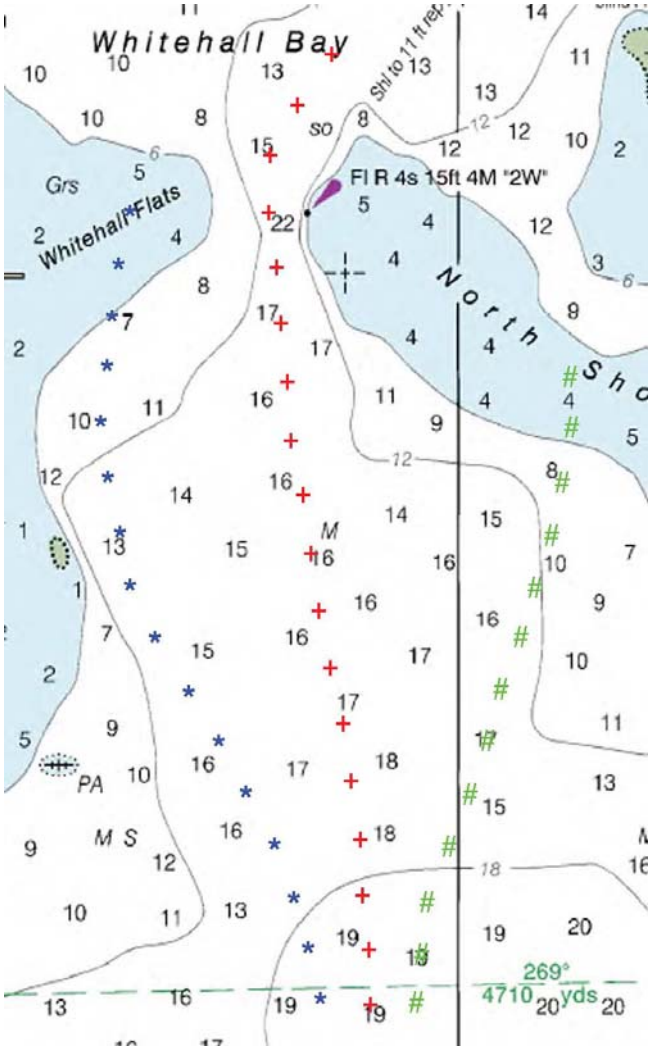

Figure 4. Divergent Ground Tracks 1 and 3 Compared to the intended Ground Track 2.

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
	d D/t	0	2	4	2	2	1	2	1	2	3	4	9	14	8	11
	d D/*d* t		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**
	***d* D/*d* t**		**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		
	d D/t	0	0	0	0	3	0	0	0	4	6	9	15	18		
	d D/*d* t		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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