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RESEARCH ARTICLE

Web-based nautical charts automated compilation from open hydrospatial data

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Abstract

Electronic navigational charts (ENCs) are specialised geospatial datasets, issued by or on the authority of a government or hydrographic office, in accordance with the International Hydrographic Organisation's (IHO) standards, specifications and symbol sets. The datasets generally comprise encoded information collected from hydrographic surveys, aimed primarily at the safety of navigation. Most ENCs are not openly available, since the encrypted datasets can be acquired through various license schemes via a centralised distribution network coordinated by two organisations operating on behalf of the coastal states that produce them. This paper describes a methodology and an integrated system developed at the National Technical University of Athens Cartography Laboratory for the generation of web-based nautical charts utilising open data and free software. The system compiles nautical charts compliant with IHO's S-101 latest standard; using open hydrospatial data retrieved from marine spatial data infrastructures (MSDI) and other qualified volunteered geographic information (VGI) sources. Open-source geospatial libraries and web-map vector technologies are used to build the system components and software scripts developed to enable automated compilation. The study also discusses how the system can be improved further by leveraging web services for end-to-end process automation and satellite-derived bathymetry for accurate depiction of seabed topography in low-depth areas.

1. Introduction

International collaboration in science and technology has been recognised as a catalyst to addressing global concerns, such as environmental protection, energy security, natural disasters mitigation, preventing and curing infectious diseases, ensuring food security (OECD, 2011) and for a long time, safety at sea. International cooperation constitutes an important means of strengthening industry understanding, providing the framework for the application of industry concepts into effect (Meyer and Kurian, 2017). It promotes, through dialogue, mutual learning, data and knowledge sharing, as well as standardisation processes, advancing the implementation of the industry best practices. In this context the International Hydrographic Organisation (IHO) for more than 100 years, has consistently worked towards achieving maximum standardisation in hydrographic surveying practices, nautical cartography and compilation of related digital products and services. This constitutes a paradigm shift compared with previous centuries of ocean navigation, in which nautical charts were classified as state secrets (Ritchie, 1972).

IHO Standard S-4 (originally published as M-4) is an exceptional example of international collaboration by IHO's Member States that has resulted in the standardisation of colours, symbols, abbreviations and overall presentation of printed nautical charts (Newson, 1984). S-4's mission is twofold, to explain the broad principles and reasons for the depiction of features on charts, including the use of text and symbols. As a result, the international paper chart series (INT Charts) have been created according to a single set of agreed-upon specifications since 1971, when the concept was introduced. This has enabled seafarers to utilise with confidence charts prepared by any hydrographic agency (IHB, 1980).

Since the 1980s, there have been numerous efforts to compile a nautical chart from digital source data and to draft the chart automatically (Evangelatos, 1989). The IHO's S-57 Transfer Standard for Digital Hydrographic Data was published in 1992, allowing nautical chart data to be transmitted digitally and in a uniform manner for the first time. S-57, along with S-52, the symbology definitions for electronic navigational charts (ENCs), is now a mature set of operational processes that has grown into a full solution for the generation and distribution of digital datasets and incremental updates for ENCs worldwide. These specifications provide datasets that are 'compact, reliable, tolerant of low-bandwidth communications and widely implemented' (Arctur, 2011).

After their inception, the demand for ENCs has constantly risen and ENCs are expected to gain even more prominence as their ability to interoperate with other navigationally relevant datasets, such as IHO's latest standard (S-100)-based products and services, become available. Moreover, despite the fact that ENCs were initially based on paper nautical charts, their production process is currently gradually diverging from the original paper chart (IHO, 2020c). Several hydrographic offices (HOs), for example NOAA[1] and UKHO,[2] run programs for rescheming ENC coverage for parts of their jurisdiction into a gridded structure. The aim is to design larger-scale ENC cells without producing the associated paper chart, differentiating the two product portfolios.

In this context, the current work presents an integrated open source-based system for web nautical chart generation, utilising open hydrospatial data (Hains, 2020; Jonas, 2021) and disseminating them through vector web maps and raster tile sets used as digital charts in a variety of navigation systems. More specifically, Section 2 provides background info on nautical charts in the digital age, cartography challenges, the evolution of the hydrographic standards and the research methodology followed for the development of the Open Nautical Chart System (OpenNCS), the experimental system of the current research. Section 3 presents a high-level architecture of the system along with the four steps for the nautical chart compilation process. Sections 4 to 7 discuss each one of the steps in more detail, meaning data acquisition in Section 4 along with the data sources used, Section 5 addresses the bathymetry compilation and generalisation processes, Section 6 describes the ENC objects packaging and portrayal preparation, and Section 7 present the chart visualisation activities, including the testbeds that facilitated the development and calibration of the system. In Section 8 technology components of the system are discussed. Section 9 discusses how the system can be improved utilising earth observation data and further automating the various processes toward achieving e-navigation capabilities.

2. Nautical cartography overview – research methodology

The nautical chart is designed for surface navigation and is an extremely important tool for sailors to navigate safely at sea, as a large percentage of accidents at sea and especially offshore relate to the collision of vessels with rocks or other fixed grounding objects (USCG, 2019). A nautical chart depicts the nature and shape of the coast, the depths of the water, the formation of the seabed, the positions of dangers, the rise and fall of the tides, the currents of the oceans, the magnetic fluctuation, the regulatory limits and the locations of navigation aids (e.g. lights, buoys, beacons). Above all, nautical charts are accurate, systematic and part of a series of charts at various scales. Sailors can easily switch from one printed chart to another to reach a destination safely and efficiently.

In recent decades, significant advances in marine research and technology have occurred. Large-scale, multinational and long-term research initiatives have evolved, providing the technological means for a variety of improvements in hydrographic and cartographic methodologies and techniques. These

[1]NOAA ENC Transformation Program: https://nauticalcharts.noaa.gov/publications/docs/enc-transformation.pdf
[2]UKHO ENC Rescheming Program: https://iho.int/uploads/user/Inter-Regional Coordination/RHC/MACHC/MACHC22/MACHC22_2021_09.4_EN_Applying a Gridded Scheme to GB ENCs.pdf

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advancements have also resulted in topographic maps (S-102), where depth data collected from multi-beam echo soundersprovide a complete seabed scan to accurately portray the seabed relief (IHO, 2019).

At the same time, the evolution of satellite positioning systems and the advent of electronic navigational charts in the 1980s triggered the automation of navigation processes, such as real-time positioning of ships. Electronic charts, particularly the vector ones, provide many advantages over traditional paper ones, since they include information from other sources, such as the course of the vessel and more advanced data-driven services, in addition to the cartographic data found in paper charts. One of the most important functions is that they enable the incorporation of automated alarms that notify the vessel's bridge when the vessel is approaching charted dangers.

2.1. *Nautical charts in the digital era*

The information that helps the navigator can be divided into two general categories, the (relatively) unchanged in time or static and the time-changing or dynamic. The first category is related to seamarks and landmarks, which are visible from the bridge of the vessel and indicate a danger or a passage or route that the vessel may follow within a channel. The second category concerns objects in motion close to the vessel's course, with data dynamically generated by navigation-supporting devices such as the automated identification systems (AISs) and the radar. Dynamic information can be either north-facing or boat-oriented. Printed nautical charts display static information and are always oriented northwards, while electronic charts with radar and AIS information usually show the course of the boat at the top of the screen and include both types of information. This difference between orientations presupposes methods of perception, which the navigator must realise in order to put the information in the field of view of the bridge, to make a decision and act based on the course and speed of the vessel (Morgere et al., 2014).

The first navigation systems using some form of electronic chart appeared in the market in the early 1980s. The main feature of these systems, also called electronic chart systems (ECS), was the graphical display of the position provided by an electronic positioning system on a computer screen combined with the simultaneous display of some form of nautical chart of the area. With this system, the mariner had constant visual control of the vessels' position. The operation of the ECS is supported by a database, which consists of the cartographic objects and nautical information that can be displayed. ENCs have significant advantages and capabilities over printed charts, such as:

- logical processing of cartographic objects to provide alerts in case of danger,
- change the scale of the displayed area,
- selective display of chart elements,
- display of additional information (e.g. sailing directions).

The first commercial digital charts were produced without official specifications and did not contain all the details of nautical charts issued by the hydrographic offices of the various states. Although ECSs made it simpler for seafarers to plan and execute a journey, they were not exempt from conventional voyage procedures, owing to lack of cartographic data. Over time, the need to establish electronic charts that would meet all the required specifications and standards for a safe voyage became apparent and in November 1995 after a thorough examination of the issue by the International Maritime Organisation (IMO), the ENCs were recognised as an official navigation aid and a replacement of paper charts (IMO, 2006).

2.2. *Nautical charts compilation challenges*

The primary function of a nautical chart is to aid navigation, and the visual aspect may be secondary, as opposed to topographic maps. Another important difference is accuracy. Most of the manmade objects on land can be measured in detail and verified relatively easily. Conversely, sea is a highly dynamic environment that is constantly changing. Reference points are more difficult to identify, as the depths and the shape of a coastline can change with the variation of tide. Underwater features cannot be easily examined and remote sensing is often the only way to detect them in shallow-depth areas.

Remote sensing techniques, in turn, are subject to measurement errors, as the medium through which the signal travels is not uniform, since salinity, temperature and density are constantly changing (NOAA, 2020). Shipwrecks and underwater dunes can be displaced by strong currents, and floating aids with strong weather conditions can rotate around their anchor. It is difficult to create a static map that takes into account these dynamics. At the same time, the navigatorhas no choice but to trust the information on the chart, as most of the depicted objects are under water and beyond visual verification.

The ENC is not just a digital version of a printed chart it introduces a new navigation culture with features that differ greatly from those of the printed charts era. The ENC loaded to the Electronic Chart Display and Information System (ECDIS) has become the legal equivalent of the printed chart as approved by the IMO, and the requirements for more specific information have led to the publication of a new generation of cartographic products (IMO, 2006). In addition, bathymetry charts created from processed hydrographic data or from multi-beam data enable the portrayal of the seabed with blue colour shades and depth contours (IHO, 2019). Similarly, lateral-scan sonar mosaic charts published in the form of diagrams or atlases depict large geomorphological structures. These charts are no longer merely about safety of navigation, as they also enable the knowledge of the environment required for underwater navigation and oceanographic research, as well as industrial uses such as cable laying, hydrocarbon mining and subsoil exploitation (IHO, 2011).

2.3. Hydrographic standards

The progress of nautical cartography, with the wide production of ENCs, gave a great impetus to the development of e-navigation. IMO recommends that ENCs be used on all merchant vessels. Specifically, the *Marine Life Safety Convention* (SOLAS Chapter V Regulation 19/2.1.4) states: 'All ships, irrespective of size, shall have nautical charts and nautical publications to plan and display the ship's route for the intended voyage and to plot and monitor positions throughout the voyage.'

The Universal Hydrographic Data Model S-100 is the latest generation of marine geographic information data modelling standard developed by the IHO. The S-100 addresses the limitations of the S-57 standard (IHO, 2000; Alexander et al., 2007) and provides a unified theoretical and application framework for modelling, coding, visualisation, exchange of nautical geographic information, and production and distribution of data products and services. The S-100 version 1.0.0 was released in January 2010, aiming to support a much wider range of hydrographic data sources, products and customers. It is compliant with international standards, especially the ISO 19100 series of geographical information standards thus allowing for the easier integration of hydrographic data and services in geospatial applications (Lovrinčević and Kljajić, 2014). Although S-100 has been updated four times since then, there are still shortcomings that must be improved. Specifications for S-100-based data products and services are still under development (IHO, 2020d).

Until 2015, IHO working groups and researchers concentrated primarily on the theoretical development of the S-100, including essential ideas such as its composition, comparison with the existing S-57 standard and the introduction of new product specifications. Since then, emphasis has been focused on S-100 applied research, such as the creation of software tools, new products and navigation services, data visualisation and correlation with the IMO's e-navigation and maritime services (Weintrit and Zalewski, 2020). This signifies that the S-100 is steadily progressing from theory to practice and from conceptual consideration and design to execution, optimisation and innovation (Duan et al., 2021).

2.4. *Depth data uncertainty*

According to S-44, the IHO standard for hydrographic surveys, the navigation of surface vessels requires accurate knowledge of depths. Where underkeel clearance is a concern, bathymetric coverage must be 100 percent, feature detection must be sufficient and depth uncertainties must be tightly monitored and understood (IHO, 2020b). It is well known that measurements have a degree of uncertainty caused mainly by two factors, the limitations of the measuring instrument -usually referred as systematic error- and the skills of the hydrographers making the measurements, referred as random error (JCGM, 2008). The IHO Working Group on Crowdsourced Bathymetry (CSBWG) has developed a publication, which defines the concept, equipment, methodology, format and uncertainty of data collection, processing and storage (Pavic et al., 2020).

According to CSBWG, metadata provide information that helps data users to determine the quality of the bathymetry data related to depth and position information (IHO, 2020a). The Quality of Bathymetric Data in S-101, or the CATZOC (CATegory Zone Of Confidence) in S-57, is an IHO classification of the level of accuracy that aims to provide qualitative indications on the uncertainties attached to the bathymetric information underlying the ENCs. The primary intention is for the users to assess how confident one should be with respect to the representation of obstacles to navigation on nautical charts. In that regard, HOs mainly rely on elements of uncertainty on the vertical and horizontal positions of the soundings, the sampling density and temporal variation of the seafloor that may have occurred since the data acquisition, or the information captured as metadata during the hydrographic surveys (EMODnet, 2021; Kastrisios and Ware, 2021).

2.5. *Research methodology*

This research approach stems from the authors' long-term involvement with subjects related to nautical cartography, particularly the standardisation of data products and services. The main driver is to study and document whether open reliable sources and open software can be considered as an applicable methodology for the composition of web-based nautical charts in compliance with the S-101 IHO product specification. During the first phase of the research, a wide variety of sources were reviewed, including open-source software repositories, for example open-source software from GitHub, IHO hydrographic standards and specifications, OGC geospatial data processing standards as well as related academic literature. Given the breadth of the research subject, it is important to note that the research work should not be considered as a niche scientific experiment by applying a proposed methodology that yields specific results, but rather as a research that addresses a number of interdependent topics ranging from hydrographic processes to state of the art cartographic applications.

Based on these factors, the research is divided into the following stages:

- detailed description of the research topic,
- review of research literature (primarily applicable IHO Standards);
- identification of important committees and working groups of the relevant international organisations (IHO, IMO, OGC, W3C) and the documentation adopted;
- observation of activities and involvement as an observer in relevant working group meetings, mostly those of IHO, such as TSMAD / S-100WG, S-101PT, DQWG, NIPWG, MSDIWG, WENDWG, and those of OGC, such as the API SWGs and the Marine DWG;
- extensive review of the reports of the aforementioned working groups and related committees (such as the IHO's HSSC);
- review of relevant open source software projects and libraries, for example OpenCPN, SMAC-M (mapserver ENC-based wms), display ENC in QGIS and other,
- experimentation with open source technologies, for example GeoPackage, gdal, mapbox gl, and Tegola;
- design of OpenNCS system components and chart compilation processes;

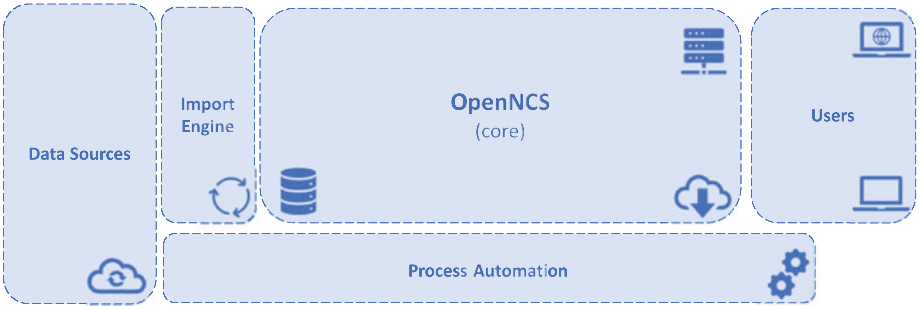

Figure 1. *OpenNCS high-level architecture.*

- development of system testbeds for charts visualisation, process enhancements and experimentation with various navigation services (route planning, optimal route finding); and
- addressing interoperability issues and discussing improvement areas for further research and development.

3. System for web-based nautical charts compilation

The term 'compilation' in nautical cartography is defined (IHO, 1994) as 'the selection, assembly and graphic presentation of all relevant information required for the preparation of a chart'. This process entails a variety of tasks that are frequently repetitive, time intensive and error prone (Kastrisios et al., 2019). The automation of the compilation process has been a long-term aim of the hydrographic community due to the undeniable benefits of automation for product accuracy, process repeatability and continuous testing at lower production costs.

3.1. System overview

Figure 1 depicts a high-level architectural design of the logical units of the OpenNCS system developed in the context of the research.

The system essentially consists of five logical units:

- the data sources, which include the reference digital seabed model, coastline and marine markings among other objects;
- the import engine, which includes tools and software code (scripts) for converting data into a common format and importing data into the system database;
- the main part of the system, which consists of the database and the services for providing the nautical charts to the users;
- the process automation, that consists of geoprocessing tools and scripts that automate the data import, the compilation process and the system services; and
- the users part, which includes the devices of the users that can be a web browser on a personal computer or tablet as well as smart mobile devices.

3.2. Compilation process

The compilation process of the web-based nautical charts that is adopted in the OpenNCS consists of four main phases: data acquisition, bathymetry features compilation, chart features packaging and chart visualisation, as shown in Figure 2.

Data acquisition is the process of identifying and automating the import of the open hydrospatial data that will be used for compiling the objects of the chart. The main sources selected are the EMODnet as well as the OpenStreetMap coastline and seamarks. The selection of charted soundings and the

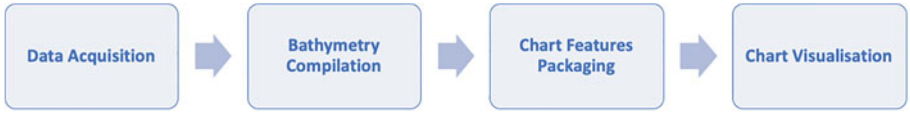

Figure 2. *Web-based nautical charts compilation and generation phases.*

generation of depth contours are the tasks that receive the main attention of automation efforts. Both contribute to retaining and displaying the morphological characteristics and differentiating elements of the seabed on the charts (Skopeliti et al., 2021). Chart features packaging includes the tasks for the preparation of the database layers for the various objects and the symbols library, as well as the lights sectors and labels. For chart visualisation, web-mapping libraries and techniques are used to compile vector tiles, in both static and dynamic modes depending on the chart scale. Relevant test beds were prepared to facilitate development and quality assurance activities. The next sections discuss the four process steps in detail.

4. Data acquisition – open hydrospatial data

The quality of a nautical chart depends on the quality of the data sources used for its compilation (Manzano, 2021). Bathymetric data collection in hydrographic and marine geophysical surveys is mostly achieved by utilising vessel-mounted multibeam echo sounders (MBES) resulting to Digital Terrain Models (DTMs) of the seafloor and derived products. One research (Cordero Ros and Kastrisios, 2021) demonstrates the use of the EMODNET-harmonised Bathymetric DTM for the European sea regions and Free and Open-Source Software for Ocean Mapping (FOSSOM), with the aim to improve hydrographic procedures. The capabilities of FOSSOM can reduce processing time and overall production costs, thus enhancing the overall planning-to-product process.

On the other hand, Marine Spatial Data Infrastructures (MSDIs) can facilitate the continuous recording of data from spatiotemporal natural phenomena and human activities in marine and coastal areas, their transformation, and dissemination to achieve continuous improvement of marine related applications, including nautical cartography (Contarinis et al., 2020). The recent European Open Data Directive and the reuse of public sector information, known as the 'Open Data Directive', is a key driver in establishing 'open' MSDIs among other spatial data infrastructures. Moreover, the scientific community has put in great effort to develop and make publicly available bathymetric models of the seafloor, such as that by the European Marine Observation and Data Network (EMODnet) and other tools for application specific requirements. These data and software resources have the potential to improve the workflow from data acquisition to chart visualisation.

4.1. EMODnet bathymetry

The EMODnet bathymetry portal provides open and free access to bathymetry of European seas and is being developed within the scope of the EMODnet, established by the European Commission. EMODnet bathymetry intends to improve access to bathymetric data maintained by a variety of organisations, including hydrographic offices, academic institutions and enterprises. The portal (www.emodnet-bathymetry.eu) provides access to the EMODnet DTM with a grid resolution of 1/16 arc minute × 1/16 arc minute (approximately 115 m width and 60 to 90 m height, depending on the latitude). It contains approximately 12·3 billion grid nodes organised in 64 tiles, where 3 tiles where used for the Mediterranean testbed of the research (see relevant section below). The DTM is available for viewing, downloading and sharing through OGC web services (Schmitt et al., 2020).

The EMODnet DTM has been created using the best available bathymetry from a variety of sources using various methods. The data coverage is still incomplete and some data were collected several years ago, however as new data and other composite DTM datasets are made available, the gaps will be

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filled and the grid will be updated. The information contained in the grid is believed to be trustworthy. However, its accuracy and completeness cannot be guaranteed. Four indicators have been defined and described in the EMODnet high-resolution seabed mapping (HRSM) document 'Completing metadata elements for the generation of the quality index for the EMODnet DTM', known as 'Quality Indices':

- Horizontal accuracy (QI Horizontal)
- Vertical accuracy (QI Vertical)
- Purpose of the survey (QI Purpose)
- Age of the survey (QI Age)

Improvements in the latest EMODnet DTM include the quality index provided at the grid node level (EMODnet, 2021). However, it is clearly mentioned by the EMODnet producers that whilst every effort has been made to ensure its reliability within the limits of present knowledge, no responsibility can be accepted by those involved in its compilation for any consequential loss or damage arising from its use. The EMODnet DTM for European seas is not to be used for navigation or for any other purpose relating to safety at sea.[3]

4.2. The General Bathymetric Chart of the Oceans (GEBCO)

The General Bathymetric Chart of the Oceans (GEBCO) intends to provide the most authoritative, publicly available bathymetry datasets for the world's oceans. GEBCO's current gridded bathymetric dataset, the GEBCO_2021 Grid, is a global terrain model for ocean and land, providing elevation data, in meters, on a 15 arc-second interval grid, a resolution that is useful for the compilation of charts for sea areas where bathymetric data without the accuracy required are not available. It is complemented by a type identifier (TID) grid which provides information on the types of source data that the grid is based. The GEBCO_2021 Grid has been developed through the Nippon Foundation-GEBCO Seabed 2030 Project. It is a collaborative project with the Nippon Foundation of Japan and intends to compile all available bathymetric data in order to create the definitive map of the entire ocean bottom by 2030 and make it available to everybody (Mayer et al., 2018; GEBCO Bathymetric Compilation Group, 2021). GEBCO is essentially a deep-ocean product and does not include detailed bathymetry for shallow waters. Even to the present day, most areas of the world's oceans have not been fully surveyed and, for the most part, bathymetric mapping is an interpretation based on random tracklines of data from many different sources. The quality and coverage of data from these sources is highly variable and similarly to EMODnet's disclaimer; the GEBCO's data sets are not to be used for navigation or for any purpose relating to safety at sea.[4]

4.3. Voluntary geographical information (OpenStreetMap)

The beginning of the 21st century brought the rise of crowdsourced geographic information-collection projects. A number of major technological developments, such as online maps, the proliferation of mobile positioning devices and open access to satellite imagery, allowed citizens to become key players in production and exchange of geospatial information (Foody et al., 2017). This process is known as voluntary geographic information (VGI) (Goodchild, 2007), although a number of similar terms have been coined in the literature (See et al., 2016). The number of such initiatives is constantly increasing thanks to emerging technologies, and covers a large number of applications, disciplines, communities and tools with a huge volume of literature already produced. VGI has become an important source of geoinformation and describes collaborative and voluntary spatial data collection (Goetz and Zipf, 2013). Users can join voluntary communities and share their data with other members of the community free of charge. The data are based on personal measurements or personal knowledge, as well as processing from available aerial images that can be made available freely by various entities (e.g. European Copernicus

[3]EMODnet disclaimer for use: https://www.emodnet-bathymetry.eu/data-products/disclaimer
[4]GEBCO disclaimer for use: https://seabed2030.org/disclaimer

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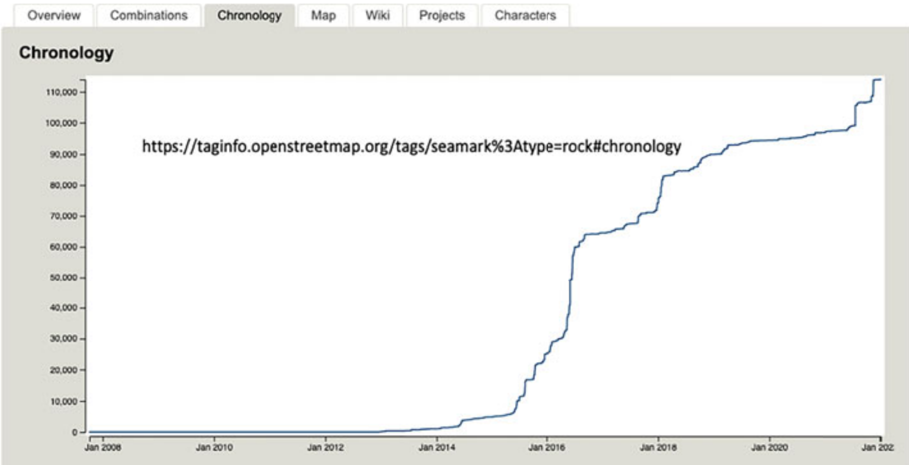

Figure 3. *Chronology of rock seamark type. Source OSM taginfo service.*

Sentinel). Initially, data collection was about 2D data, but lately more and more users are contributing 3D data, which include height and depth information. Using such data, one can create digital terrain and seabed models.

Among such initiatives, the most popular infrastructure is OpenStreetMap (OSM), a vector database of multiple geospatial sources with global coverage and available under the Open Database (ODbL) License (Mooney and Minghini, 2017). OSM has attracted data contributions from millions of users thanks to the simplicity of its data model, which is based on just three types of objects accompanied by a list of any number of key-value pairs. This makes it extremely easy to search, access and use OSM data using common geographical information system (GIS) software as well as to create applications. There is significant research on the quality of VGIs, and in particular OSM (Senaratne et al., 2017), which confirms that despite the nonprofessional nature of the sources and the possible lack of quality metadata, VGI data can be used as a valid alternative, or complement government and private data sources. An OSM tag schema called Seamark[5] is based on elements defined in IHO's S-101 feature catalogue. Seamark tags have risen significantly during the last decade, with more than 500 K tags recorded as of January 2022. Moreover, important seamarks for the safety of navigation such as rocks, are recorded with very high rate, as depicted in Figure 3.

5. Bathymetry compilation – generalisation process

The compilation process, as stated in S-4 (IHO, 2021), shall start with the largest scale possible, as the seafarer anticipates charts to be consistent across scales, at least for the most important data objects, a practice which is referred as 'vertical consistency'. As a result, the initial compilation and subsequent updating of charts should be from the largest scale of the series to the smaller scales (ladder approach). This practice is followed in OpenNCS by creating first the Approach ENC scale (level 4) being the largest scale chart possible from the original source data, and then creating the next smaller scale chart using the Approach level scale as a source, and so on until the smallest scale relevant for the data type compiled. In addition, to depict the seabed relief without cluttering the chart, it is required to generalise the bathymetric information, as indicated in IHO S-4, by removing the least essential information. Generalisation is defined as 'the omission of less important detail when compiling a chart. Its purpose is to avoid over-loading charts where space is limited' (IHO, 1994). Nautical charts objects generalisation is based on rules and constraints extracted from IHO standards, best practices adopted by hydrographic offices and nautical cartography literature (Skopeliti et al., 2020).

[5]List of S-57/S-101 Objects – https://wiki.openstreetmap.org/wiki/Seamarks/Seamark_Objects

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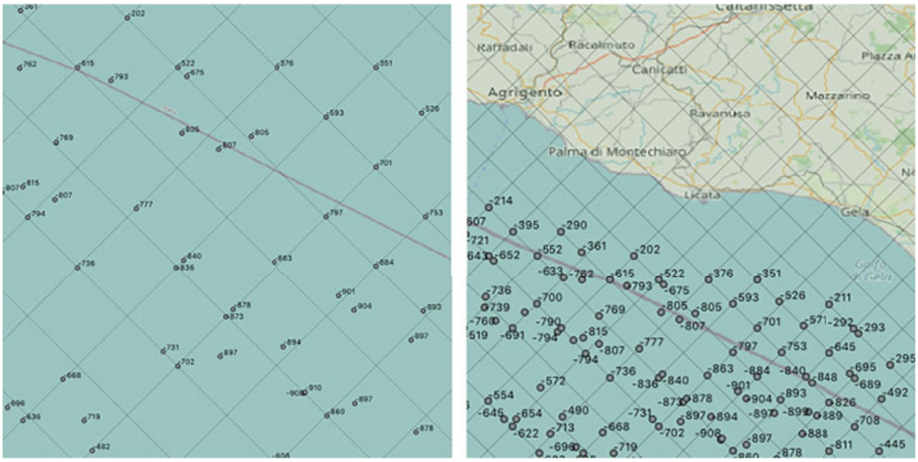

Figure 4. *Results from sounding selection methodology.*

5.1. Sounding selection

Water depths (soundings) are numerically displayed on nautical charts and sounding selection is ‘the process of choosing individual water depths from a hydrographic survey in the compilation of a chart’ (IHO, 1994). For OpenNCS, a well-defined methodology, as proposed by Skopeliti et al. (2020), is used for soundings selection. Based on this methodology, a rhomboidal fishnet is used as a reference structure (Figure 4), where the cell size depends on the compilation scale.

The input dataset is a high-resolution DTM, and the output is a dataset with soundings appropriate for portrayal on the various ENC scales. The sounding selection process is implemented using python geo-processing libraries. The generalisation procedure adheres to the ‘ladder principle’, which is important for the depiction of soundings on nautical charts, that is every sounding displayed on a smaller-scale chart should also be shown on larger-scale charts. The method successfully produced generalised soundings for Overview, General, Coastal & Approach ENC scales, as shown in Figure 4.

5.2. Depth contours generation

Depth contours generation, according to S-32 (IHO, 1994) is ‘the process of establishing lines representing equal values of a quantity on a map or chart’. Depth contours generation has been identified as the most challenging task (Manzano, 2021). Another challenge is the generalisation and smoothing of depth contours (e.g. removing or merging small rings, fixing contours intersections, or modifications according to soundings out of depth contours) to achieve an outcome that meets the safety and morphology constraints stated by IHO S-4 (IHO, 2021). Depth contours generation is performed using Geospatial Data Abstraction Library (GDAL). The gdal_contour program generates vector contour file (Figure 5) from the input raster terrain model (DTM). Depth contours generalisation is performed using an Open-Source Geographic Information System (QGIS) plugin called Geo Simplification that contains a processing script named Reduce Bend, a geospatial simplification and generalisation tool for lines and polygons.

Reduce Bend is an improved implementation of the Wang and Müller (1998) algorithm, often known as ‘Bend Simplify’[6] or ‘Wang Algorithm’. It can simplify lines but also polygons, while preserving topology within and between features of the same layer. The algorithm for each line analyses its curves and decides which one must be simplified, trying to emulate what a cartographer would do manually to simplify a line. Simplification is a line generalisation operator for removing vertices along a line while trying to keep the maximum number of details within the line at the level of the screen’s scale.

[6]This term is used for the version of the algorithm incorporated in ESRI’s ArcGIS generalization tools.

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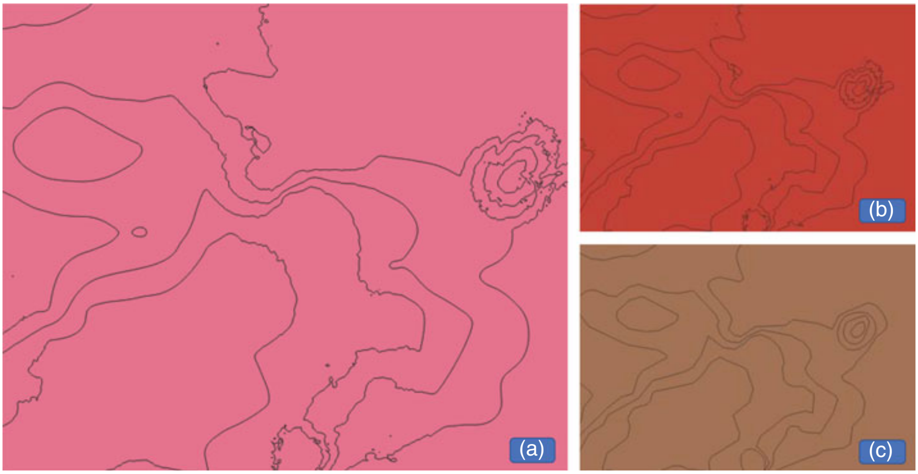

Figure 5. *Depth contours generation process in QGIS. (a) Contours as produced through DTM processing. (b) Elimination of very small rings. (c) Line simplification.*

Table 1. *ENC features in NOAA ENCs vs OSM Seamark vs OpenNCS.*

Layer	NOAA ENC	OSM Seamark	OSM Seamark (%)	OpenNCS	OpenNCS (%)
Base	25	13	52%	15	60%
Standard	63	50	79%	43	68%
Other	57	26	46%	33	58%
Total	**145**	**89**	**61%**	**91**	**63%**

Reduce Bend falls more in the category of line generalisation tools, the process of removing meaningless (unwanted) details of a line usually for scaling down, where the well-known Douglas and Peucker (1973) algorithm is another good example of line simplification tool. Both algorithms can be complementary, since Reduce Bend does not remove unnecessary vertices in the case of very high densities of vertices and it is good practice to use Simplify before Reduce Bend in the case of very dense geometries.

6. Chart features packaging

IHO S-100 defines a universal data model with standardised objects, subgroups of objects (called categories of objects), attributes with value lists and value formats. The S-100 standard is the basis for further product specifications, including S-101 for ENCs. IHO grants free access to related documents in a Geospatial Information Registry, a repository that allows to browse and search as a data dictionary. The relationship between features, attributes and enumerants is specified in S-101 by a single-feature catalogue. For the chart features packaging, the GeoPackage data format is chosen. GeoPackage is an SQLite database container, with a nonproprietary, platform-independent data format standardised by Open Geospatial Consortium (OGC). The objects for each chart layer are stored in a separate database container for performance reasons. In terms of ENC features, the S-101 portrayal catalogue provides 185 features divided into three groups called ViewingGroupLayers, which are labelled Base (always on display), Standard (ECDIS default display) and Other (displays all features available).

Table 1 summarises the ENC features found (a) in NOAA ENCs (freely available), (b) as OSM Seamarks and (c) used in OpenNCS, in relation to the three viewing group layers. Moreover, Figure 6 demonstrates the current global distribution of seamark tags, with a noticeable emphasis on more available data in Europe.

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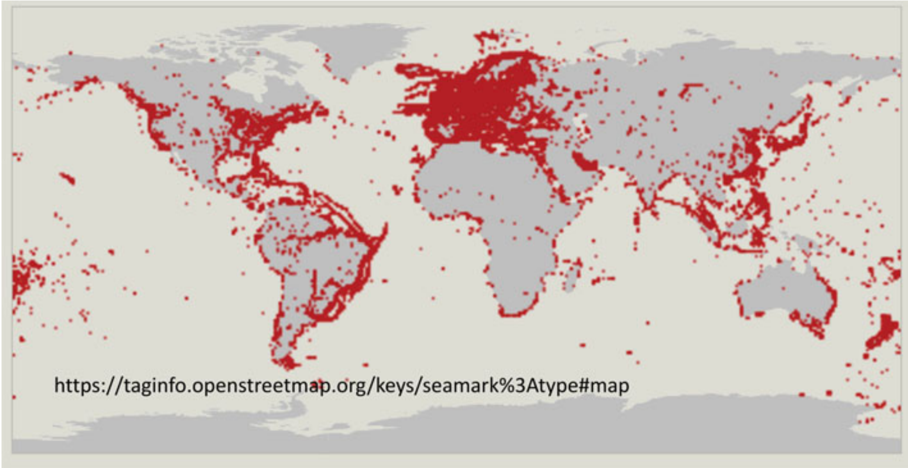

Figure 6. *Seamark tags distribution. Source OSM taginfo service.*

Table 2. *Seamark object example.*

Parent object	Seamark object
seamark:type=buoy_lateral	seamark:buoy_lateral:category=port seamark:buoy_lateral:shape=pillar seamark:buoy_lateral:colour=red seamark:topmark:shape=cylinder seamark:topmark:colour=red seamark:light:colour=red seamark:light:character=Fl seamark:light:period=5

6.1. OSM seamark tags

The OSM Seamark tags[7] are based on elements defined in the S-57 & S-101 feature catalogues. For human readability, the six-letter mnemonics used in the S-57 standard have been replaced in S-101 by words or underscore-separated English phrases. The format of seamark tags is *seamark:<object>:<attribute>=<value>* where <object> is the object key, <attribute> is the attribute key and <value> is the attribute value, where the *seamark:type= <object>* is the parent object. Any given node or way can be tagged with more than one S-57/S-101 objects – for example, a buoy with a light and top mark is tagged with three objects and their attributes. These objects are structured as a parent–child relationship (hierarchical model) with one parent object and zero or more child objects. The parent object is indicated with a tag in this scheme form, with a value corresponding to a valid object key. An example of the tagging scheme – a buoy with top mark and light – is presented in Table 2.

6.2. Lights labels and sectors

In the case of lights, there are two possible objects (light_major & light_minor) in OSM, both of them are treated similarly, differentiated only by the range of visibility across the ENC scales. Special scripts were developed to prepare the light labels for the characteristics of their circle of visibility as well as the curves for those lights that have sectors. The former circle of visibility is defined (IHO, 1994) as the

[7] List of S-57/S-101 Objects – https://wiki.openstreetmap.org/wiki/Seamarks/Seamark_Objects

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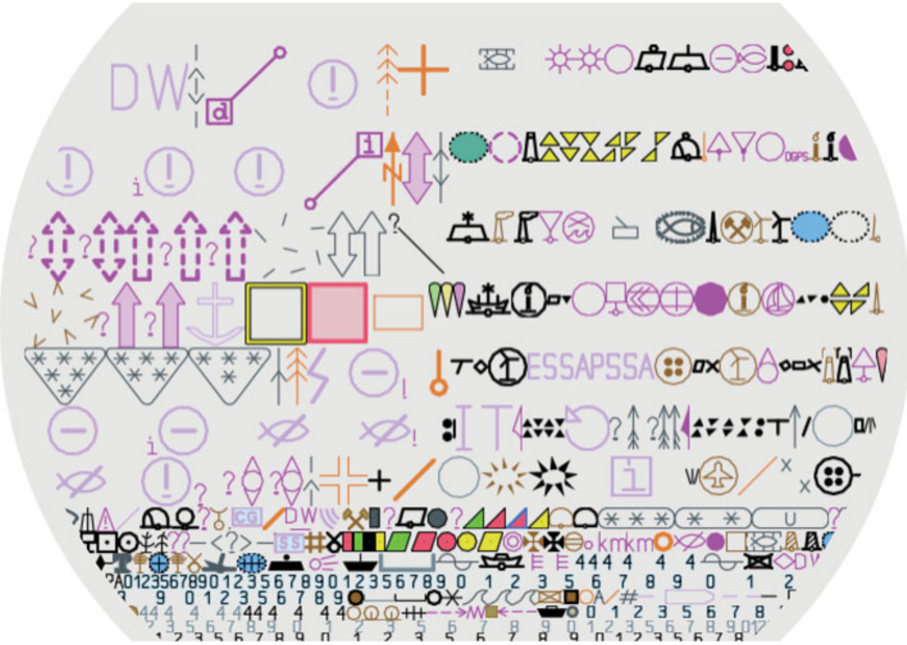

Figure 7. *S-101 portrayal symbols used in OpenNCS.*

'circle surrounding an aid to navigation and in which the aid is visible' while the latter as 'a sector of the circle of visibility of a navigational light in which a specific color light is exhibited'. Such sectors are designated by their limiting bearings as observed at some point other than the light. Red sectors are often located so that they warn of danger to vessels'.

6.3. Portrayal

Along with the S-57 (the S-101 predecessor), IHO developed the S-52 standard for presenting ENC content on an Electronic Chart Display and Information System (ECDIS) used for navigation that complies with IMO regulations. The purpose of S-52 is to contribute to the secure operation of ECDIS systems by providing a base as well as complementary display levels for ENC data, symbol patterns, colours and their standard correlation with objects and their features, the appropriate compatibility with printed chart symbols as standard on IHO specifications, ensuring that the screen is clear and there is no uncertainty about the meaning of colours and symbols on the screen. In addition, the introduction of an acceptable pattern for the presentation on ECDIS becomes familiar to mariners and can be recognised immediately without creating confusion. The IHO Geospatial Information Registry includes the so-called portrayal register, which contains chart symbols including their SVG and XML origin. The elements of the portrayal catalogues relate the elements of the feature catalogues to their graphical representation. Figure 7 depicts the S-101 symbols file that was compiled and used in OpenNCS.

7. Chart visualisation

The visualisation component of OpenNCS is essentially a cartographic subsystem based on web map technologies. Web maps are a means of data distribution and visualisation with the ability to integrate information from different sources that enables the connection of space and time during geospatial exploration, which in turn facilitates provision of automated services. Web cartography's emergence is closely related to the development of the internet as a medium of communication and web-mapping services like Google Maps that were introduced in 2005, have transformed the mapping experience on

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Table 3. *Mapping of zoom levels, chart scales and navigational purposes.*

Zoom level	Chart scale[8]	Navigational purpose
0	1:591·657·527	
1	1:295·828·763	
2	1:147·914·381	
3	1:73·957·191	
4	1:36·978·595	
5	1:18·489·297	
6	1:9·244·649	
7	**1:4·622·324**	**Overview**
8	**1:2·311·162**	
9	**1:1·155·581**	**General**
10	**1:577·791**	
11	**1:288·895**	**Coastal**
12	**1:144·448**	
13	**1:72·224**	**Approach**
14	**1:36·112**	
15	**1:18·056**	**Harbour**
16	**1:9·028**	
17	**1:4·514**	**Berthing**
18	**1:2·257**	
19	1:1·128	
20	1:564	
21	1:282	
22	1:141	
23	1:71	

the World Wide Web (Steiniger et al., 2012). Despite the fact that web applications have evolved since then, tile mapping technology is being used in much the same way. Various tile formats have been developed in order to generate dynamic tiles that alter considerably in size and resolution; nevertheless, the techniques have not seen substantial improvement.

7.1. Web vector-based cartography

Recent advancements in web map applications have had a significant impact on how cartographic backgrounds are presented. Raster tiles are currently considered a standard method, whereas vector tiles are gaining popularity. Raster tiles are based on the production of an original data set that incorporates custom symbols and style, and all tiles are made in accordance with a standard scheme (Netek et al., 2020). With vector tiles, the principle of dividing the maps/charts into squares, is still used, but instead of images vector objects are loaded. Only vector geometry is stored on the server, while symbolisation, rendering and zoom levels are performed by the client device. This method simplifies the change of symbols or topology, as the objects on a map/chart can be manipulated using libraries and scripts of the JavaScript programming language, their symbols can be changed and more features can be portrayed. It is important to note that when developing internet maps, the capabilities and limitations of the online environment must be considered. OpenNCS operates on the principles of internet cartography

[8]The sources for creating the table beyond IHO S-4 and S-11 are the following articles: https://www.esri.com/arcgis-blog/products/product/mapping/how-can-you-tell-what-map-scales-are-shown-for-online-maps/- https://www.esri.com/arcgis-blog/products/product/mapping/web-map-zoom-levels-updated/

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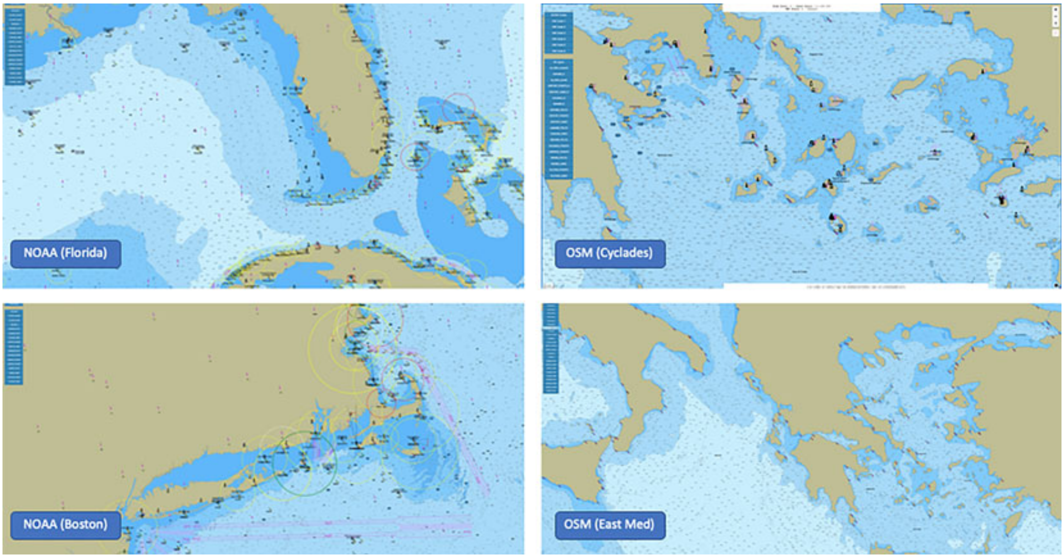

Figure 8. *OpenNCS testbeds with NOAA (ENC) data and EMODnet & openStreetMap (OSM) data.*

applications and has the capability to display beyond the six scales for navigational purposes provided in S-101, with smaller and larger zoom levels (see Table 3).

7.2. ENC & open data testbeds

Two OpenNCS testbeds were set up to facilitate the chart visualisation phase of the web nautical charts' generation process. The first testbed displays vector tiles compiled from NOAA's ENC data while the second displays vector tiles compiled from open hydrospatial data sources. Figure 8 depicts the two OpenNCS test-beds tested, with the NOAA (ENC) data shown on the left, and with EMODnet & OSM data shown on the right. This figure provides evidence that the outcome of the methodology described gives similar results for both free ENC and open hydrospatial data. Each testbed includes tools to zoom, select scales and choose individual objects from vertical menus on the left side of the screen, for testing and troubleshooting the inclusion of objects, as shown in Figure 9.

8. OpenNCS system architecture – interoperability

Figure 10 depicts a more detailed OpenNCS system architecture, presenting the various components and providing the primary technologies employed per component.

As discussed, the data sources include the EMODnet digital seabed model, coastline and seamarks from OSM, freely available ENC datasets (e.g. from NOAA) and in the future offshore satellite imagery (e.g. EU Copernicus program). OpenNCS's import engine includes python scripts based on GDAL and OGR libraries for converting source data to GeoPackage format. The database, considered as the core of the system, consists of individual GeoPackage files, one per ENC scale. The webserver hosts the vector tiles that are created for the smaller four ENC scales, while the Tegola tileserver is used for producing dynamic vector tiles for the larger two scales, meaning the harbour and berthing. The users part includes the devices of the users, which can be a web browser on a personal computer or tablet as well as smart mobile devices. Figure 11 revisits the compilation process as waterfall model, mapping input or output datasets per step.

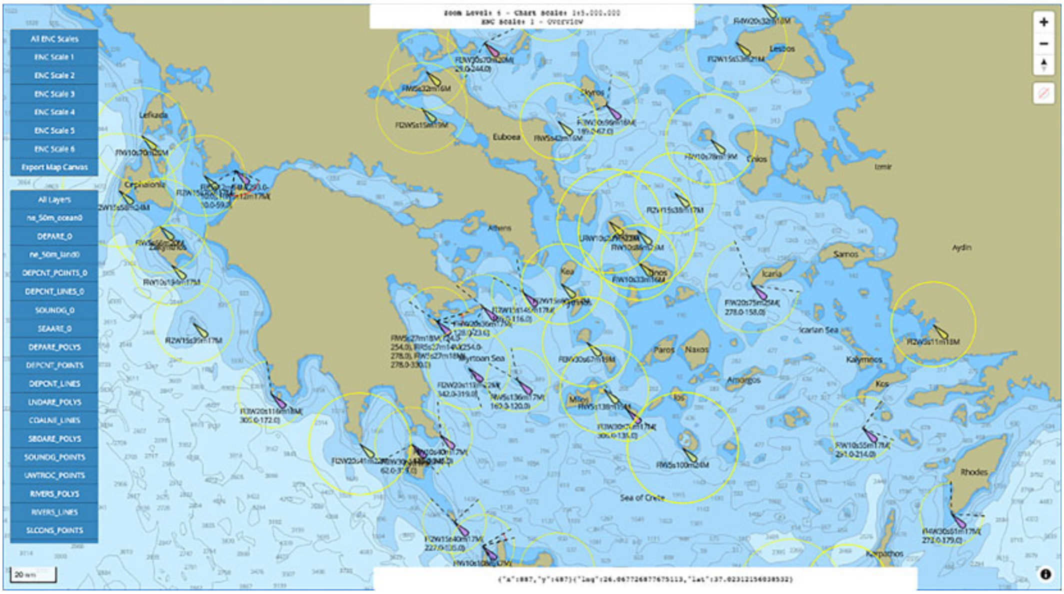

***Figure 9.** OpenNCS visualisation testbed.*

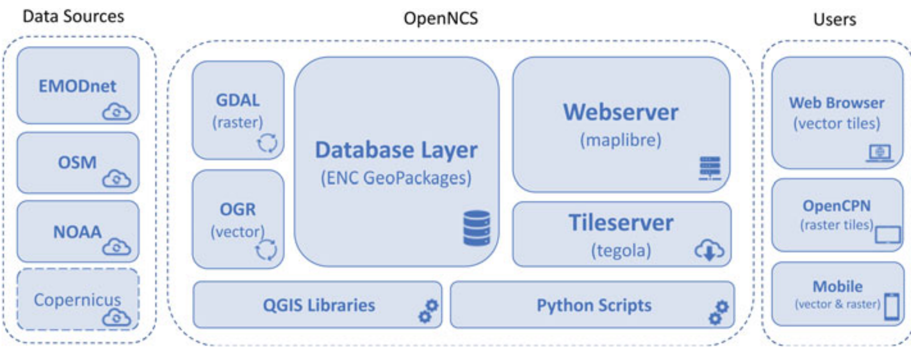

***Figure 10.** OpenNCS system architecture.*

To test the interoperability of the nautical charts produced, the open source navigation system OpenCPN[9] was chosen that works also offline, using installed charts. OpenCPN generally supports S-57/S-63 (vector charts), BSB/KAP (raster charts) and MBTiles (raster tiles). Simple functionality developed to export charts for different zoom levels in image files (png). The images are then geo-referenced and converted to mbtiles using the GDAL library. The MBTiles are uploaded as charts to OpenCPN and the result is shown in Figure 12. It should be emphasised that OpenNCS may be utilised offline using cached vector or raster tiles, which is essentially how it will be used on mobile devices.

9. Discussion

Users seeking information and navigation services on land may easily find them through a range of free online sources, as well as through smart-device applications. However, nonspecialist maritime users' access to (open) data and electronic navigational charts services is not easy for most of the world's seas (excluding the US coastlines, where NOAA charts are freely available on the internet). The reason is that official electronic navigational charts are created by national hydrographic agencies of the

[9] Free Open Source Chartplotter and Marine GPS Navigation Software (https://opencpn.org/)

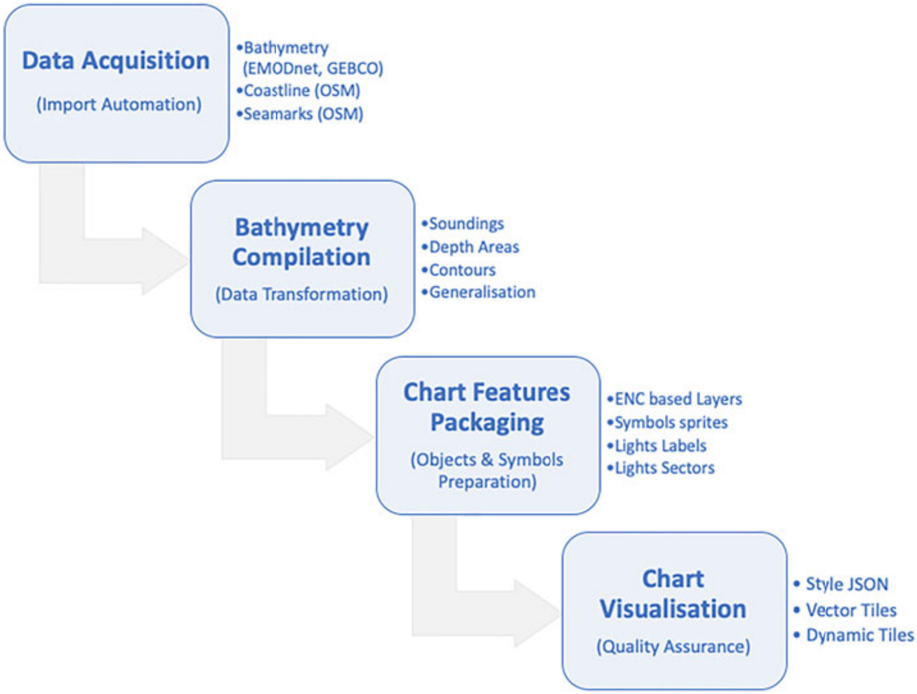

Figure 11. *Web nautical charts compilation process.*

various coastal nations and contain encoded information that can be used efficiently through specialised navigation systems. These charts are compiled from the hydrographic agencies, usually being member states of the IHO. They are made available to maritime operators via two distribution networks, known as Regional ENC Coordinating Centers (RENCs) (Hecht, 2000; Hecht et al., 2017).

Moreover, some unofficial nautical charts that are freely accessible on the internet do not adhere to the norms of standard-based electronic charts (e.g., OpenSeaMap, which lacks also soundings information), and various nautical chart suppliers (e.g. Navionics) often utilise proprietary symbology and cartographic representation. This research aims at the compilation of web nautical charts based on open data and rendered through commonly available cartographic representation tools and in compliance with IHO's S-101 standard, that is in a more comprehensible and standardised fashion. It is emphasised that the proposed system and the underlying methodology cannot be considered as a replacement of the official electronic navigational charts produced by the coastal states' hydrographic offices, as ENCs are based on official hydrographic data and include the necessary quality assurance that the international maritime community requires for the safety of navigation (IMO, 2006).

The primary function of nautical charts is to provide the information needed by the mariner to plan and execute a safe voyage. It is consequently critical to understand the mariner's needs for sufficient, relevant, accurate and clear information while creating charts and selecting content. Special care must be taken to avoid mistakes and the emergence of conditions in which the mariner is exposed to too much information (chart cluttering) or irrelevant information that may create distress or distraction. In addition, information to suit non-navigational requirements, for example: subsurface operations (military, research, fishing; natural resource exploitation; recreation; port development; international boundaries and national limits) may also be included on nautical charts if considered useful or necessary by the producing authority. However, additional information must not be added at the expense of clear portrayal of navigationally significant information (IHO, 2021).

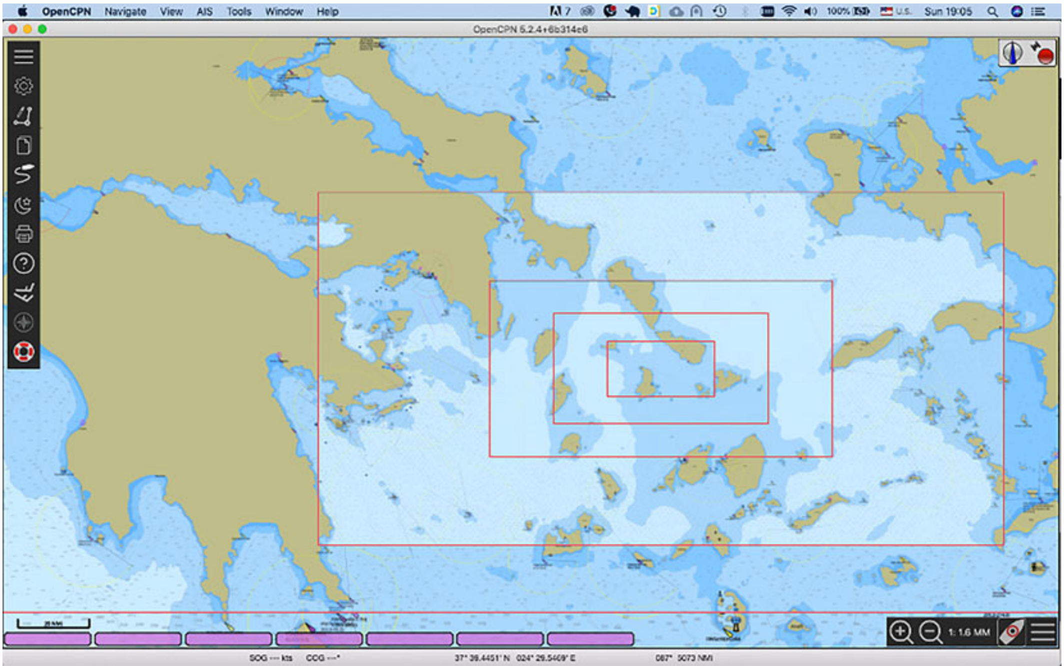

Figure 12. *OpenNCS raster tiles on OpenCPN.*

Along with the research activity, the evolution of S-100 has been observed. S-100 took more than 15 years in development before it could be widely utilised. There are several reasons why this was not previously achievable and the authors consider the following to be the most important:

- the breadth and the complexity of the application field, including the ISO compliant registry, tools to generate feature and portrayal catalogues, the machine-readable presentation rules, the interoperability and the complementary nature between different S-100 products;
- the initial rather-general and sometimes vague requirements for product specifications (other than nautical charts), which are being specialised gradually while they are considered by the relevant IHO working groups together with other international bodies and industry experts;
- potential industry conflict of interest, aiming to keep the successful existing 'closed' standard (S-57) for ECDIS systems in place as long as possible; and
- the HOs need to set up parallel production lines for S-57 and S-101 ENCs for another decade, but this requires additional resources.

In recent years, the IHO's relevant working group (S-100WG) has been methodically endeavouring to achieve the aim of completing the S-100 design by expanding the working groups and establishing groups per product specification (S-101, S-102, etc.). Hence, the plan from the recent Hydrographic Services and Standards Committee (HSSC) meetings is to have the standard in production mode by 2025.

The emergence of new technologies, alternative data sources and increased user demand has led to the creation of completely new architectures that provide flexible and scalable solutions for data access and consumption. For example, the rise of the Internet of Things (IoT), even if it is fragmented in terms of infrastructure, contributes to a huge amount of spatiotemporal data. Likewise, application programming interfaces (APIs) enable developers to easily create value-added products. APIs manage to hide the complexity of infrastructure and offer a set of well-defined and documented methods for using and processing data in various fields. APIs in traditional SDIs (e.g. WMS, WFS, WCS and WPS)

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are supported by a number of applications and provide access to geospatial data. Modern web APIs go one step further (Kotsev et al., 2020) as:

- provide a simple approach to data processing and management functions;
- offer different data encodings;
- can be easily integrated into different tools; and
- can facilitate data discovery through mainstream search engines.

Adopting RESTful architectures simplifies access to the functionality offered by APIs, while minimising bandwidth usage. Two recent developments from the OGC, namely the 'OGC API Features' and the 'SensorThings API' provide standard APIs to ensure synchronous access to spatial and observational data. Similarly, leveraging OGC API processes, this study (Pakdil and Çelik, 2021) explores a system design and architecture for handling complicated geographic data processing activities with minimum human interaction. Moreover, the widely used OpenAPI specification not only allows for standalone, portable and open API documentation, but it also integrates an effective testing environment.

Future developments of the system shall target not only the incorporation of state-of-the-art technologies for end to end automation, but also the inclusion of bathymetry information with higher resolution for low-depth areas. Satellite remote sensing has a long tradition in providing raw observation data to support many geospatial applications. In an area characterised by the presence of major industry players (Kotsev et al., 2020), developments have emerged that revolutionise the way we view our environment. Among them, (i) small satellites, (ii) low-cost unmanned aerial vehicles (UAVs) and (iii) Copernicus Sentinel missions play a prominent role. Copernicus data products are provided by default free of charge and through an open license. In that sense, satellite-derived bathymetry (SDB) has significant potential to improve knowledge and data about Earth's coastal areas and enhance nautical cartography processes. However, SDB still has limitations when applied to cloudy but visually shallow areas covering large areas of the world's coastal zone (Caballero and Stumpf, 2020), which must be tackled to achieve cartography automation potential.

10. Conclusions

This paper describes an experimental methodology for the development of an integrated system for web nautical charts compilation/generation, based on the new IHO S-101 ENC portrayal standards, open source data and open source software. In contrast to the IHO S-57 standard, where the use of symbols and display rules require the purchase of relevant libraries, the new hydrographic data standard makes the symbols and rules for the display of electronic nautical charts available through the portrayal catalogue, which is freely available. Furthermore, essential information on depth and maritime navigation points of interest are gathered and made accessible as open data over time, such as the EMODnet Bathymetry DTM and the OpenStreetMap seamarks. In addition, the developed OpenNCS can also be employed for the dissemination of time varying geospatial information for web-based navigation services, such as updated piracy charts, weather charts, ice charts and other vessels' routing information.

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