FEASIBILITY OF SENTINEL-1 DATA FOR ENHANCED MARITIME SAFETY AND SITUATIONAL AWARENESS

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ABSTRACT

The ESABALT (Enhanced Situational Awareness to Improve Maritime Safety in the Baltic) project is a feasibility study of an integrated system for enhancing maritime safety, which incorporates the latest technological advances in positioning, e-Navigation, Earth observation (EO) systems, and multi-channel cooperative communications and user-driven crowdsourcing techniques. One of the core tasks of the ESABALT project is to assess the feasibility of integration of the state-of-the-art EO products, such as Sentinel-1 data, into the situational awareness platform. The objective of this article is to review alternative approaches and design system concepts based on the use of Sentinel-1 data in the experimental ESABALT maritime situational awareness system. First, the required steps to transform Sentinel-1 SAR imagery to value added data aiding navigation, situational awareness and maritime safety will be described. Second, the feasibility of two alternative methods for integrating SAR data to ESABALT system is assessed. The outcome of the study indicates that modern-day SAR data can be included into a maritime navigational system, which would clearly improve maritime situational awareness and safety.

INTRODUCTION

The ESABALT (Enhanced Situational Awareness to Improve Maritime Safety in the Baltic) project is a feasibility study of an integrated system for enhancing maritime safety and situational awareness funded by the BONUS program (Baltic Organizations Network for Funding Sciences EEIG) [1]. It incorporates the latest technological advances in positioning, e-Navigation, Earth observation (EO) systems, and multi-channel cooperative communications and user-driven crowdsourcing techniques. The objective is to assess the feasibility of providing an enhanced situational awareness solution for all ships operating in the Baltic Sea, including real-time maritime traffic monitoring and a marine environment observation system relevant for maritime transportation and accident prevention. This solution will include information for assessing sea ice, oil spread (in the case of an oil spill), wave heights, currents, as well as wind speed and direction.

EO satellites play an important role in the remote sensing of marine environment due to their capability to produce wide-area information. Sentinel-1 is SAR (Synthetic Aperture Radar) satellite constellation, and one of the core components of the European EO Copernicus programme [2]. One of its priority areas is in maritime monitoring and safety of navigation. The Sentinel EO data, as well as the Copernicus services, will be provided free-of-charge, as a public service to all users. Therefore, a huge growth in the use of EO data and its end-products can be anticipated and novel data distribution techniques are required in order for these products to be put into use. ESABALT will investigate how these data products can be integrated into the navigation systems of ships and secondly how to distribute these products widely and equitably among all maritime users.

The main existing satellite-based EO technologies are optical and microwave satellite sensors. Benefit of optical satellites are their capability to produce multi- or hyperspectral imagery with wide spectral range enabling various maritime applications, such as water color and sea surface temperature measurements and target or ship detection. However, optical sensors are dependent on solar radiation which excludes night-time imaging and they are limited by cloud cover. These can be major disadvantages in areas with high overcast or fog conditions and areas with short daylight hours, such as the northern areas of the Baltic Sea during winter. Thus, satellite-based microwave instruments which are not constrained by cloudiness or solar illumination, due to longer wavelength of microwave radiation, are considered more applicable for real- or near-real-time maritime applications. SAR imaging technology is an active microwave remote sensing technology which utilizes the motion of the antenna in satellite or airplane to create a synthetic aperture (i.e. very long antenna) enabling high spatial resolution imaging. SAR satellites produce two-dimensional images where image brightness is a reflection of the microwave backscattering properties of the surface [3]. SAR instruments are operationally used in various maritime applications that are essential for the ESABALT system, for example, to create near real-time sea ice maps, to detect oil spills and ships, to measure wave heights and the speed and sea surface currents and winds. EO technologies are already operationally utilized in several free and commercial maritime services, such as MyOcean ocean monitoring [4] and forecasting system and EMSA's (European Maritime Safety Agency) CleanSeaNet oil spill and vessel detection service [5]. Numerous previous and on-going research has been conducted to evaluate EO data in various maritime applications, such as sea ice and monitoring, oil spill detection and maritime surveillance, such as Dolphin [6], SeaU [7], MAIRES [8] and PolarView [9].

The objective of this article is to study the feasibility of integrating state-of-the-art Sentinel-1 data to a maritime situational awareness system, such as ESABALT. The required steps to transform Sentinel-1 SAR imagery to value added data which can be utilized in certain functionalities aiding navigation, situational awareness and maritime safety will be described. These functionalities include, for example, route optimization and displaying sea ice and pollution reports (e.g. oil spills) and location of nearby vessels. The feasibility of the SAR data in these functionalities will be integrated optimally in the system design and assessed through case scenarios, such as ship requesting route optimization due to severe sea ice conditions or to avoid an area with a possible oil spill event; or if a ship without an AIS (Automatic Identification System) signal needs to be located. Feasibility of two alternative methods for integrating SAR data to the ESABALT system is studied. The first option is to acquire the SAR imagery directly from the Sentinel-1 data centers and process the data in the ESABALT server into value added data (e.g. sea ice maps) to aid in the decision making within a specific functionality. The second option is to utilize and integrate data from already operational marine services utilizing EO data.

MATERIAL AND METHODS

Sentinel-1

Sentinel-1 is a constellation of several satellites (in the beginning, Sentinel-1A & Sentinel-1B) carrying identical C-band (wavelength ~5.54 cm) SAR instruments. The Sentinel-1A was launched 2014 and is currently operationally delivering SAR imagery [10]. The Sentinel-1B is planned to be launch in 2015 from French Guyana. Sentinel-1 will provide imagery with four main imaging modes with varying spatial resolutions and application areas. The Stripmap (SM) mode acquires imagery with 80 km swath width with 5x5 m spatial resolution. SM mode is used only in exceptional cases to support emergency management actions. Interferometric Wide Swath (IW) mode acquires imagery with 250 km swath width at 5 m by 20 m spatial resolution. The IW mode is the main acquisition mode over land. The Extra-Wide swath (EW) mode has 400 km swath with spatial resolution of 20 m by 40 m. The EW mode is aimed primarily for use over sea-ice, polar zones and certain maritime areas, in particular for ice, oil spill monitoring and security services. EW and IW modes will be the main imaging modes over the Baltic Sea area and maritime applications. Revisit time of Sentinel-1 satellites will be approximately 1-2 days in the Baltic Sea latitudes once the constellation is completed. Currently, the revisit time with single Sentinel-1A is approximately 2-4 days. The exact repeat of one Sentinel-1 satellite orbit is 12 days. The Sentinel-1 SAR instruments are dual polarization radars, which means that it can transmit and receive signals in both horizontal (H) and vertical (V) polarization (dual polarization for all imaging modes VV+VH or HH+HV) [10]. Sentinel-1 data is currently freely distributed by Sentinel-1 open access Scientific Data Hub within 24 h from image acquisition. In the future, faster data acquisition should be possible from national data distributors (Collaborative Data Hub) or by requesting Copernicus core user status (CSC Data Access) which would provide access to the infrastructure via the user available bandwidth with guaranteed reliability and performance.

Utilization of EO Data in Maritime Applications

Route optimization and maritime situational awareness are core functionalities of the proposed ESABALT system. These functionalities require information on sea ice, possible oil spills and nearby vessels without AIS, which can be acquired using EO data from remote sensing satellites, such as Sentinel-1 SAR satellites. For navigational purposes, a major emphasis is on real-time or near-real-time information. Thus, maritime applications using satellite remote sensing are widely based on using SAR instruments which have a good spatial resolution and are not drastically affected by cloudiness or dependent on solar illumination [11], [12]. Many of the already operational maritime services utilizing EO data are using SAR imagery as their main component.

Sea Ice Mapping Using SAR Technology

In SAR imagery the brightness of ice surface backscattering intensity is influenced by the ice surface characteristics, volume structure, and dielectric properties. The ability of SAR to image different sea ice properties depend on the frequency, polarization and incidence angle of the SAR pulses [11], [13]. Sea ice drift estimation using SAR is based on tracking the sea ice drift from consecutive images which means that imagery with good temporal sampling (one to two days) is required. [11], [12]

Oil Spill Detection Using SAR Technology

SAR based oil spill detection is based on detecting lower backscattering areas than its surroundings in SAR imagery caused by dampened Bragg scattering induced by oil film on the sea surface [14]. In addition to oil spills, microwave backscattering from sea surface can also be dampened due to natural phenomena. Thus, the main disadvantage of satellite based SAR is the relatively high tendency to false targets, induced for example by low wind areas, rain cells, algae blooms etc. [15]. Consequently, additional procedures, such as airborne surveillance, are usually required to verify the oil spill and to identify the polluter [16]. Currently, most operational oil spill detection services rely on manual detection where human operators are trained to analyze images for detecting oil spills. However, a lot of research has been conducted to implement automatic or semi-automatic oil spill detection methods.

Vessel Detection Using SAR Technology

In SAR backscattering images, ships typically appear as very bright objects compared to the surrounding sea water surface. This enables automatic detection of ships from SAR data. However, the backscattering signal from ships is highly affected on the geometric situation, that is the orientation of the ship relative to the satellite location. The ability of SAR to detect ships is hindered by strong winds, heavy rain and rough sea state that cause sea clutter. In addition, strong winds cause the ships to pitch and roll which blurs the ship in SAR image and the location of the ship in SAR image can be distorted in azimuth direction if the ship is moving. However, this can also be used to detect the direction and speed of the ships movement. [17]

Sea Ice Services

MyOcean is an EU FP7 (European Union Seventh Framework Programme) project which aims to establish ocean monitoring and forecasting system of the Copernicus marine service users. The system will operate in all marine applications, including maritime safety, marine resources, marine and coastal environment and climate, seasonal and weather forecasting. The main products currently available in the MyOcean service are sea surface temperature, ocean color, ocean salinity, ocean currents, sea level, sea ice, surface winds and fluxes, and in-situ data. The products include forecast, near real time, multi-year and time invariant products that have been produced using models utilizing EO observation data from both satellite and in situ measurements. The sea ice coverage, thickness and drift maps of MyOcean are produced by the Ice Service of the Finnish Meteorological Institute (FMI). The sea ice products are also available directly from the FMI open access database [18]. The sea ice information is based on a manual interpretation of satellite and ground truth data. Currently, the satellite data consists of RADARSAT-2 SAR and MODIS (Moderate Resolution Imaging Spectroradiometer) and NOAA (National Oceanic and Atmospheric Administration) satellite data. Sentinel-1 data will be integrated to the FMI ice service products in the near future. [4]

Oil Spill and Vessel Detection Services

CleanSetNet is an European Near Real Time oil spill monitoring and vessel detection service. It has been operated by the European Maritime Safety Agency (EMSA) since April 2007 and it is a recognized Copernicus service. The CleanSetNet service is based on radar satellite imagery, covering all European seas. CleanSetNet provides information about possible oil spills, pollution alerts and related information to the operational national maritime administrators within EU states 30 minutes after satellite image acquisition. Vessel traffic information, such as AIS data, is included in the CleanSeaNet systems, which enable the detection and identification of discharging vessels. Vessel detection using SAR imagery is also a regular feature of the CleanSeaNet service. CleanSeaNet users are mainly national organizations responsible for national oil spill detection. However, there is also possibility for other European organizations and services to request access rights to the CleanSeaNet system [5]. There also exist commercial service providers for sea ice, oil spill and vessel detection, such as Konsberg Satellite Services (KSAT). It is a Norwegian commercial company providing services utilizing Earth observation data. KSAT offers services especially within maritime sector using data from several optical and radar satellites.

Integration of EO Data to ESABALT

Two alternative methods for integrating SAR data to the ESABALT system have been considered. The first option is to acquire the SAR imagery directly from the Sentinel-1 data centers and process the data in the ESABALT server into value added data (e.g. sea ice maps) to aid in the decision making within a specific functionality. The second option is to utilize and integrate data from already operational marine services utilizing EO data. EO data products will be downloaded and processed in the ESABALT servers to valued added information as soon as new EO data or EO-data based service product is available from the data or service distributor. The new value added information is updated to the ESABALT server where it can be utilized in other ESABALT functionalities. The processing flow both options are presented in Fig. 1 and Fig. 2.

Option I

The first option is to implement own automatic data acquisition and processing chain for Sentinel-1 data in the ESABALT server. The data would be acquired from the Sentinel data hub as soon as new imagery is available from the Baltic Sea area. The Sentinel-1 data will be distributed with different data hubs depending on the user needs. If ESABALT will be implemented as an operational service, ESABALT should try to request Copernicus service core user contract in order to get access to new data as soon as possible. It would also be possible to acquire the date from the national data centers distributing Sentinel-1 data (Collaborative Data Hub), but currently these services are not yet operational. Currently, open access Sentinel-1 data can be queried and downloaded from Scientific Data Hub using Open Data Protocol (OData) or Open Search (Solr) protocols. After Sentinel-1 data is downloaded, standard SAR pre-processing steps are automatically carried out in the ESABALT server. The pre-processing steps include georeferencing, radiometric calibration and land area masking. Then, SAR images will be processed as value-added ocean data products using specific algorithms developed for each target application, such as sea ice thickness, coverage and drift estimation, oil spill and ship detection. Finally, value added products are updated to the ESABALT server to be used in other ESABALT functionalities.

The most significant sea ice parameters for marine navigation and situational awareness are ice coverage, thickness and drift. There are several automatic algorithms utilizing SAR data that could be used in the ESABALT server to extract various sea ice parameters. Algorithms to extract sea ice coverage and thickness information have been developed for example by [19] and [20]. The most relevant oil spill parameters are spill coverage, drift and thickness. Automatic oil spill detection algorithms have been developed for example by [21], [3], [22]and [23]. In addition, to spill coverage, thickness and drift estimates, the result of oil spill detection algorithms should include information on the alert level and confidence of the detected potential spill [14]. The most relevant information that vessel detection algorithms utilizing SAR data can produce include vessel location, size, heading and velocity. In addition to SAR imagery, reliable vessel detection and identification requires additional information, such as AIS data and information on the static infrastructure and objects in the sea, such as buoys and light houses. If vessel that is not transmitting AIS signal is detected the detected vessel will be marked as a possible unidentified vessel. Vessel detection algorithms that could be implemented in the ESABALT system have been developed, for example, by [24] and [25].

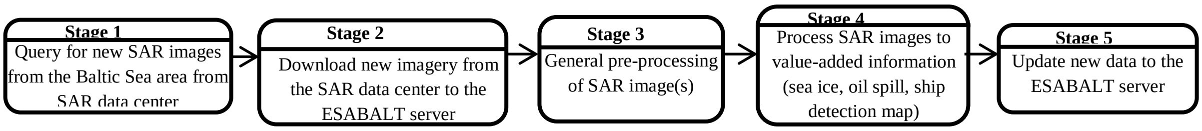

Fig. 1 Integrating SAR data to ESABALT system: Option I functional diagram

Option II

The second option is aimed to utilize already available open access or commercial maritime services utilizing EO data in the ESABALT system. The concepts would be to use products of various service providers for specific functionalities. For example, the FMI Sea Ice service or the MyOcean open access data could be used for navigation requiring sea ice information. Currently, there are no open access maritime services providing ship and oil spill detection services. However, it might be possible to apply for access to EMSA's CleanSeaNet system.

Sea ice information from the FMI could be acquired using WFS (Web Feature Service) and WMS (Web Map Service) and from the MyOcean using HTTP (Hypertext Transfer Protocol) or FTP (File Transfer Protocol). However, it is still unclear how oil spill and vessel detection data could be acquired from service providers, such as CleanSeaNet. First, the data from service providers would be downloaded to the ESABALT server. Second, data would be transformed to new format that can be utilized in other ESABALT functionalities. These transformations could include operations such as transforming raster to vector data, coordinate system or some data type transformations. Finally, the value added products are updated to the ESABALT server to be used in ESABALT functionalities.

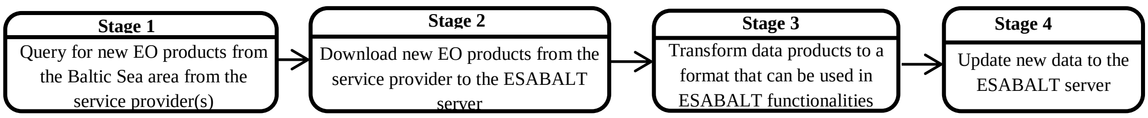

Fig. 2 Integrating SAR data to ESABALT system: Option II functional diagram

Use of SAR and EO Data in ESABALT Functionalities

One of the primary functionalities of the ESABALT system requiring sea ice and oil spill information is route optimization. Route optimization functionality queries ESABALT server for optimized route based on user input criteria. The functionality returns and displays the optimized route to the user based on a particular cost model defined by user needs (speed, efficiency of fuel, distance between source and destination, risk of besetting in ice etc.). The route optimization utilizes information such as sea ice and oil spill information to optimize the route. The functional diagram of route optimization functionality is presented in Fig. 3. The functional diagram for the Stage 4.0 Query ESABALT server for optimized route is presented in Fig. 4.

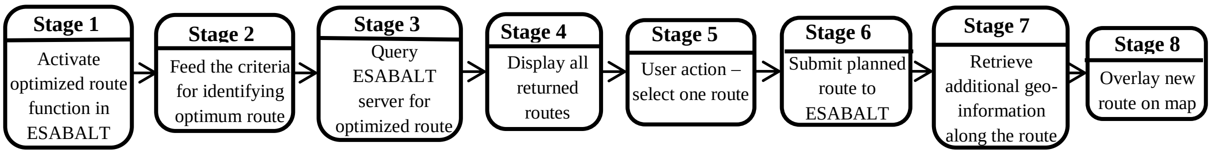

Fig. 3 The functional diagram of route optimization functionality

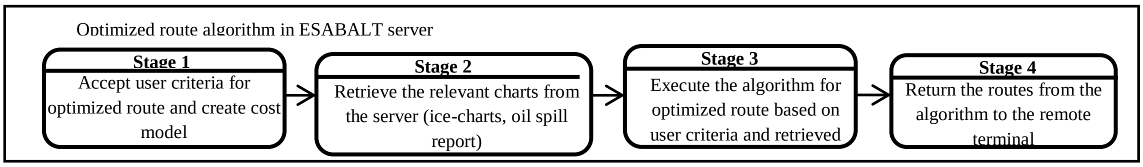

Fig. 4 The functional diagram for the stage "Query ESABALT server for optimized route"

One of the primary functionalities of the ESABALT system utilizing SAR based vessel detection is to display position and basic information about nearby ships. Crowdsourcing will enable ships to locate, identify and submit to the ESABALT server information about vessels not visible on AIS (ships with their AIS transponder off or damaged). When such data on a particular 'invisible ship' is submitted by multiple vessels, the data (ship type, approximate location etc.) will be considered as 'widely reported' (reported by multiple sightings but not yet authenticated) in the ESABALT server. Such a ship can also be displayed as a nearby ship through this functionality. In addition, vessels detected from SAR imagery and invisible to AIS, which are marker as a possible unidentified vessel, will also be displayed as a nearby ship. The functional diagram of this functionality is presented in Fig. 5.

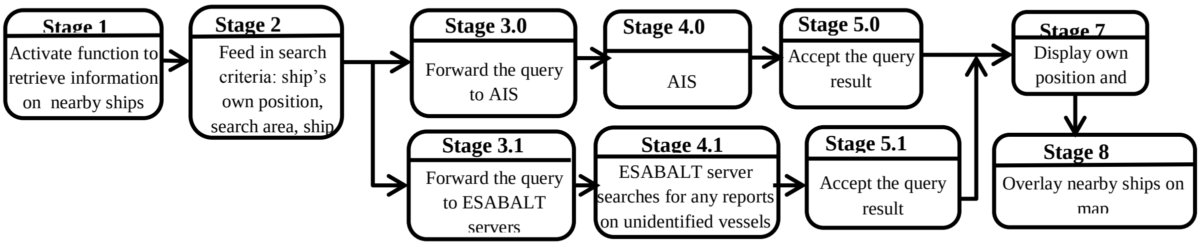

Fig. 5 The functional diagram of the display nearby ships functionality

RESULTS & DISCUSSION

Feasibility of Sentinel-1 Data

The Sentinel-1 SAR is one of the core components of the European Earth Observation system, Copernicus. Resolution and polarization capabilities of the Sentinel-1 SAR are not notably advanced compared to already operational state-of-the-art SAR systems, such as TerraSAR-X or COSMO-SkyMed. For example, there are already operational SAR satellites capable of measuring four polarization combinations, whereas Sentinel-1 will only measure two polarization combinations. However, dual polarization measurements are more than adequate for most maritime applications, where the most importance is in revisit time, areal coverage and spatial resolution. The major benefit of the Sentinel-1 is the free data policy and short revisit time after the constellation is completed. Sentinel-1 satellites are especially planned for European users, and thus the revisit times of the satellites are the best in Europe. In addition, the imaging modes and the observation scenarios have been developed with Baltic Sea monitoring in mind. When both Sentinel-1 satellites are operational, they will enable daily coverage for the Baltic Sea, improving the quality and confidence of the real-time, near-real-time and forecasting maritime products. The goal of Sentinel-1 data distribution is that new imagery would be available within one hour after the image acquisition (3h in worst case) for near-real-time services. Data delivery from archive will be 24h.

SAR data are beneficial in sea ice monitoring [11]. IW and EW modes of Sentinel-1 operating in dual polarization will be well-suited to sea ice surveillance [26]. The spatial resolution of Sentinel-1 imagery is enough to detect larger ships with EW and IW imaging modes, but detection of smaller vessels would possibly require higher spatial resolution, which can be achieved with Sentinel-1 using SM (Stripmap) mode. IW mode has better spatial resolution than EW mode which makes it more suitable for most ship monitoring scenarios, whereas EW mode is more suitable for wide-area ship surveillance [26], [27]. In case of emergency, Sentinel-1will offer SM mode with 5 m spatial resolution, which will enable detection smaller ships and identification of even individual ships, for example in ports [27]. SAR instrument have also been operationally used in oil spill detection, although false alarms using satellite based SAR RS has been a problem. The dual polarized (HH+HV or VV+VH) EW and IW mode is adequate for oil spill detection. However, imaging mode with HH+VV dual polarization or quad-polarized imagery, would improve oil spill detection [28], [29].

Feasibility of Maritime Services Using EO data

Sea ice information produced by the FMI Ice Service is highly advanced and reliable product that utilizes both satellite and in situ EO weather data. The sea ice products utilize SAR data from the RADARSAT-2 satellite which is not openly available. The Sentinel-1 data is not yet integrated to the FMI sea ice products, but they will be during 2015. In addition to sea ice information, FMI also provides other marine weather data, such as wave height and wind speed, which could be acquired with almost the same amount of effort as sea ice data. The data provided by the FMI is open access and available to all users.

If the oil spill and vessel detection data of, for example CleanSeaNet service, could be accessed, it would be beneficial. Especially, if it were possible to integrate the ESABALT and CleanSeaNet systems to exchange data, which could enable, for example, confirmation of possible oil spill detected by CleanSeaNet by ESABALT crowdsourced user data (e.g. reported possible oil spills), or identification of polluter by ESABALT user data. However, currently there are no free and publicly available maritime services providing ship and oil spill detection services.

Advantages and Disadvantages of the EO Data Integration Options

Implementing own automated processing chain for SAR images into the ESABALT server would require great amount of development, perhaps more work than by utilizing already available services. The amount of work needed is much dependent on the complexity of the algorithms and models used to derive the value-added products. For example, implementing models and algorithms including *in situ* measurement or other data sources in addition to SAR would require more work. However, there are several algorithms and models already developed for maritime applications that could be utilized and implemented for the ESABALT system. In addition, development of own automated processing procedures would make the ESABALT system independent from third-party systems and the system could be more flexibly modified for changing demands or user needs.

The major benefit of utilizing already operational services providing maritime services is that the methods and models used have typically been widely developed and tested. In addition, free operational maritime services might use EO data that would otherwise be chargeable or not openly available. The disadvantage is that the data formats might not be the optimal for ESABALT functionalities which could require development and implementation of good data transformation procedures.

If the ESABALT ends up preferring open access data sources, we suggest using sea ice information from already operational open access maritime services, such as the FMI Ice Service, which offers free reliable and accurate sea ice products. Achieving sea ice information with the same quality with own implementation would probably require a lot of resources. ESABALT should also further investigate if access to the CleanSeaNet would be possible and how well the service could be integrated to the ESABALT system. Otherwise, the solution would be to implement own ship and oil spill detection procedures. If chargeable services will not be an issue for the ESABALT system, commercial services could be utilized.

Case-Scenarios

ESABALT user requires route optimization due to severe ice conditions or oil spill event

1. There is severe icing in the Baltic Sea and ESABALT user wants to avoid thick ice or there has been oil spill event in the Baltic Sea and the user wants to avoid the spill area
   - In addition to EO data, oil spill might have been detected by other ESABALT users or authority vessels
2. ESABALT user requires route-optimization with ice- or oil spill-aware criterion as input
3. The ESABALT server performs route-optimization using the most recent ice or oil spill charts and forecast or oil spill and user vessel characteristics
4. The ESABALT server returns several route alternatives that avoid the areas with thick ice or oil
   - The route information includes the latest ice sheet and oil spill maps and EO imagery if available
   - The route information includes information on the confidence levels of the forecasts
5. ESABALT user selects the most suitable route and sends information of this route to the ESABALT server

Benefits: The user can navigate more safely to the destination and avoid worsening the environmental detriments of possible oil spill.

Display position and information about nearby ships

1. There is severe fogginess and poor visibility in a narrow water way and the ESABALT user wants to get information and possible location of all nearby ships.
2. The user requests the ESABALT system to show all nearby vessels.
3. The ESABALT system shows all nearby vessels transmitting AIS signal. Contact information to these vessels is also provided.
4. The ESABALT system requests ESABALT server information about vessels without AIS
5. The ESABALT server returns information of possible unidentified vessels using EO techniques including vessel size, heading and speed if available. Information includes the time when the unidentified vessel has been detected. The information is displayed on map.

Benefits: The user can use this information to navigate more safely through the water way and possibly try to contact other vessels without AIS. The user can send additional information to the ESABALT server of the situation that could be helpful to other ESABALT users

CONCLUSION

The evaluation presented in this paper indicates that SAR satellite data can be integrated to a maritime navigational system, which would to our understanding improve maritime situational awareness and safety. However, a major challenge is that real-time navigation requires short revisit times from the satellites. For Sentinel-1 SAR data, this is somewhat inadequate at the moment, but will be improved by the launch of Sentinel-1B satellite in late 2015. The first option in the ESABALT service is to acquire data directly from the SAR data centers and perform data processing in the ESABALT server. This option would require development and implementation of new automated data processing chain. The benefit of this option is that the ESABALT system would be independent of third-party systems and data products and could be more flexibly modified to new requirements. Whereas, in the second option, using EO data products from already operational services, the usability and modifiability of the third-party data for ESABALT functionalities might be limited. A major benefit of utilizing already operational services is that they might utilize data sources that would otherwise chargeable or not openly available, although the service itself is free. Current suggestion for ESABALT is to use sea ice information from already operational maritime services and implementing own ship and oil spill detection methods for the ESABALT system.

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