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New Sensor Technology Integration for safe and efficient e-Navigation

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Abstract

This paper discusses the relation of new sensor technology on bridge resource management as pertaining to the integration of new information sources and types for ship navigation in a future e-Navigation environment.

An overview of several new technologies will be provided showing how systems and devices currently available in the commercial marketplace are being adapted and used to aid ship navigation planning and decision making. Examples include live Doppler radar useful for coastal navigation available from land-based sources through broadband Internet connections, imagery from unmanned aerial vehicles to aid in ice-navigation in, and forward-looking sonar for navigating in poorly charted, uncharted and other world regions where aids to navigation are not readily available. The use of such innovative methods are not yet covered in IMO Guidelines, as e.g., for Voyage Planning, the Procedures Manual of a ship's Safety Management System or any other document to illustrate the adoption of such technology, but needs to be considered and investigated.

However, the implications of introducing such new information sources in terms of bridge watchstander (Officer of the Watch - OOW) workload and training are discussed with respect to existing guidelines and regulations. Further illustration is provided in the context of how such new information sources may be integrated with existing resources to enhance overall navigation situational awareness. This includes the information itself as well as the means and methods used to interact with the OOW in terms of bridge displays, monitors and alarms.

Selected specific details of research efforts currently underway will be provided in terms of forward-looking sonar integration into the bridge environment and navigation processes. This will include results obtained from experimental studies in the laboratory as well as on a suitably equipped research vessel test bed. A description of achievements accomplished to date will be provided in terms of tasks performed; the processes and procedures employed to acquire, manage and evaluate these tasks; preliminary results and outcomes achieved; and metrics used to measure these outcomes in terms of determining whether the research goals are achievable. Comparisons between expectations and actual results will be discussed, along with an analysis of risks encountered. Lessons learned are documented regarding errors in input, process, product and/or metrics.

1 INTRODUCTION

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

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

Another assertion is that the technology needed to detect hazards to navigation in real time at and below the waterline currently exists in the form of FL-sonar and is available as commercial off-the-shelf equipment ready to be installed on vessels at the next scheduled drydocking. This does not imply, however, that this technology is sufficiently tested, capable of being integrated directly into existing navigation systems in its present form, or adequate training exists for its use. Merely adding yet another sensor and display system to an already complex bridge environment without adequate engineering, planning and training is likely to make matters worse rather than improving them, resulting in increased risks to navigation.

This is illustrated with the introduction of radar that lead to the radar-assisted collision between M/Vs Stockholm and Andrea Doria. Lack of proper training in the operation, use and interpretation of radar equipment combined with a lack of procedures for implementing corrective actions based upon radar indications created a scenario where established procedures for navigating in restricted visibility were not followed, resulting in the collision.[3]

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

2 FORWARD-LOOKING SONAR TECHNOLOGY

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

2.1 SPECIFICATIONS AND CAPABILITIES

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

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

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

FL-sonar systems, presently available on the market and each utilizing a different type of transducer, and their specifications are given in Table 1.

Table 1 – Comparison between forward-looking sonar systems

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

A. Calculation by author.

2.2 BASIC APPROACH TO ESTIMATES OF ADVANCE FLS-WARNINGS

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

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

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

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

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

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

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

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

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

2.3 INSTALLATIONS

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

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

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

Figure 1: FL-Sonar Transducer Installations (1a. Dual EchoPilot Transducers Mounted Athwartships (left) and b. Single FarSounder Bow-Mounted Transducers (centre and right)

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

3 INTEGRATED FLS BRIDGE ALERTS

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

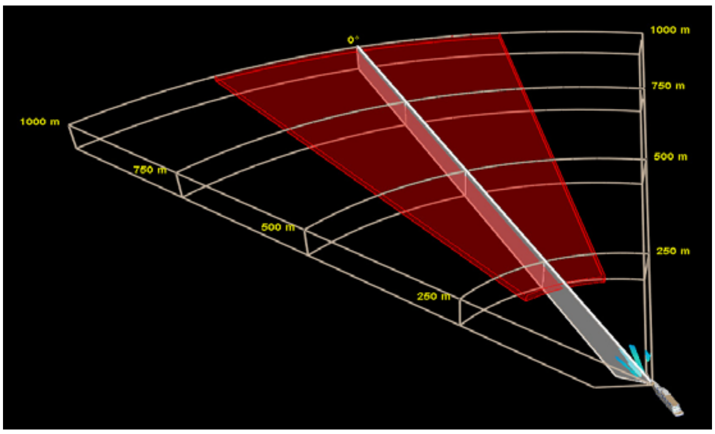

Figure 2: Forward-Looking Sonar Alarm Volume Setting

The capability to provide those warnings and alarms can be even independent of operator interpretation and be based upon analysis of the information obtained from the FL-sonar. This appears to be available only from the FarSounder system. Taking into account the characteristics of the sea area (e.g. approaching coastal waters, navigating in ice etc.) the operator can configure parameters within the area being observed by setting alarm values by depth, minimum range, maximum range, and field-of-view angle width as illustrated in Figure 2.[19] The alarm volume is shown in red. An additional setting is the number of hits detected before triggering the alarm.

Figure 3 below shows an example of FLS information integrated as an ECIDS overlay. For this prototype HMI of integrated of FLS information, the three major requirements valid for display of radar information in ECDIS are applied with respect to the new technology.

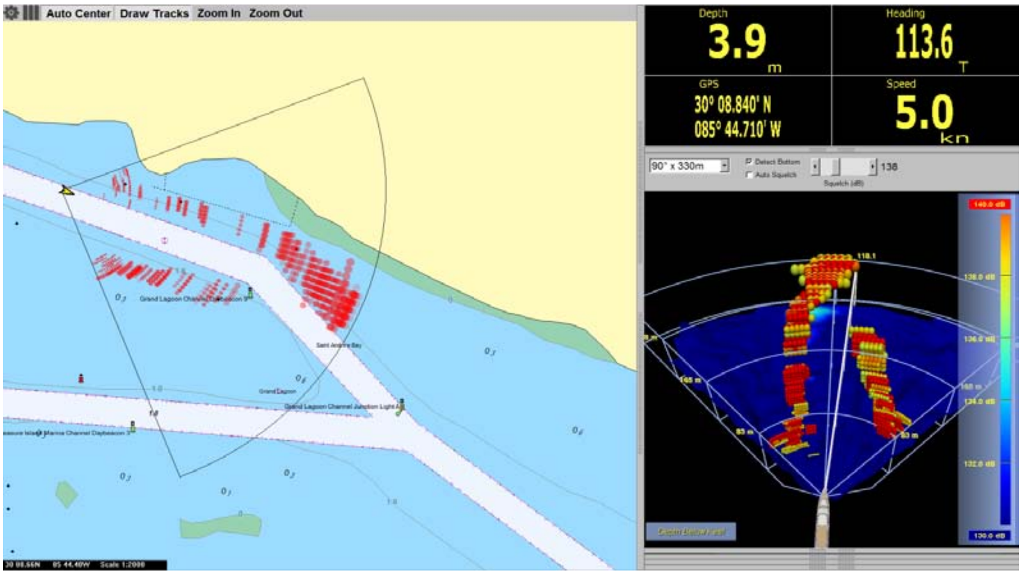

Figure 3: FL-Sonar ENC Overlay

Taking the potentials of FLS technology and results from first experimental implementations it is concluded that watchstanders are provided both visual and audible notifications e.g. announced via the centralized CAM-HMI and supported by presentation in FL-sonar target overlay in an ECDIS as suggested in the figure 3.

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

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

Finally even an alarm could be triggered, characterizing conditions requiring immediate action e.g. the ship is approaching the lower manoeuvring limit (e.g. an emergency, hard rudder action would be required) in order to avoid the contact with an FL-sonar detected object/HtoN. This last stage of an alert could be connected to the actual ship status and the ship's actual manoeuvring capabilities. That information can be provided by dynamic predictions of the ship's future path for an emergency evasive manoeuvre and check of the predicted track, for instance, against the available water depth.

4 FLS INFORMATION AND WARNINGS – A CASE STUDY

For the purposes of visualisation and discussion of FLS based warnings simulation of the circumstances encountered in during a real grounding accident is used as a hypothetical case. Data are taken from official accident investigation report [15] and simulation is attempted through extraction of the ground track using the AIS data record, then overlaying FarSounder 1000 FL-sonar cone coverage onto the ground track to identify key events that may have provided opportunities to enhance situational awareness. Four noteworthy positions in the transit just prior to grounding identified as A, B, C and D are illustrated in Figure 4 and recorded into the above chronology.

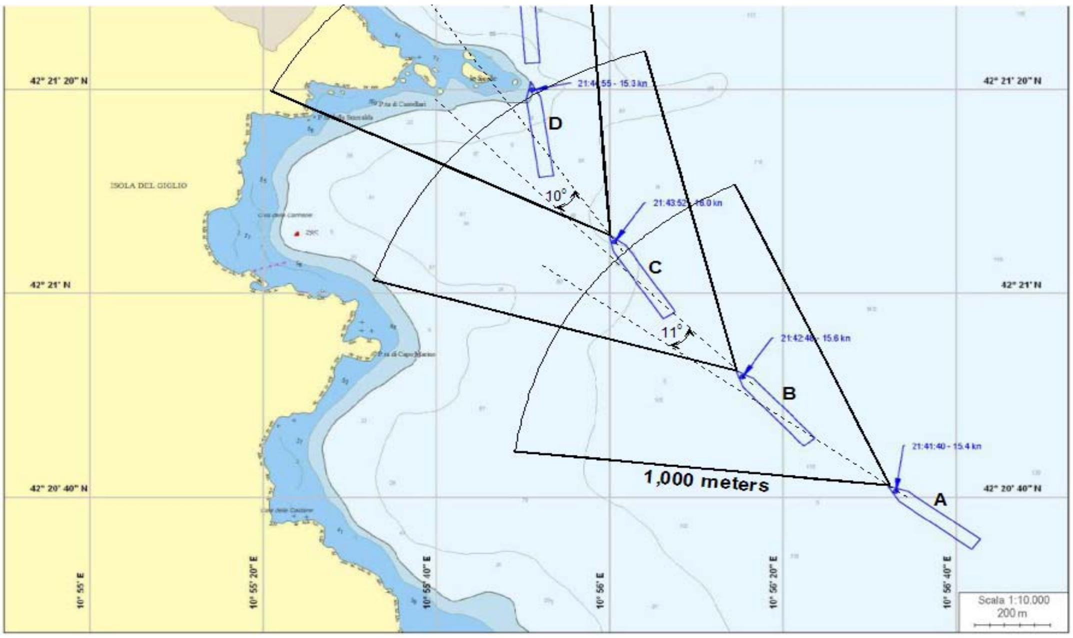

Figure 4: Ground Track of Costa Concordia, Annotated with Coverage for Forward-Looking Sonar Navigation (Source: Marine Casualties Investigative Body, Cruise Ship Costa Concordia, Report on the safety technical investigation, p. 61, Ministry of Infrastructures and Transports (Italy).

Ground Track Position A (10°56’32” E, 42°20’41” N; Speed: 15.3 knots; Course 325°)
This position lies approximately 1,600 meters from Scole Rocks with depth in excess of 100 meters with a mud bottom.[16] This location is outside the range of FL-sonar to detect bottom information and is not likely to have provided any information of significance to navigation.

Segment A to B (Elapsed Time: 00:01:08, Rate of Yaw: 11°/min)
During most of this segment the bottom depth would have remained in excess of 100 meters with a mud bottom. However, just prior to arriving at Position B the maximum range of the

FL-sonar would have crossed the 100 meter bottom depth contour directly ahead and to port of the centreline and it is possible that early indications of an upslope bottom may have been able to be detected. Note that during this segment the rate of turn is approximately 11 degrees per minute.

Ground Track Position B (10°56'15" E, 42°20'52" N; Speed 15.6 knots; Course 335°)
This position lies approximately 1,100 meters from Scole Rocks with depth in excess of 100 meters with a mud bottom. The 100 meter bottom contour is approximately 500 meters further along the course, with upslope bottom rising to the 10 meter bottom contour at the maximum range of the FL-sonar off the starboard bow. The bottom is also transitioning from mud to rock, with a resultant increase in acoustic reflectivity of the bottom material.

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

Segment B to C (Elapsed Time: 00:01:04, Rate of Yaw: 10°/min)
During this segment bottom depth is steadily decreasing across the range of the FL-sonar from in excess of 100 meters to the surface. The bottom consistency also changes from mud to solid rock, resulting in a large acoustic reflection and indications of strong targets.

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

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

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

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

Hypothetic course of events - Applying FL-Sonar
Using a speed of 16 knots obtained from the chronology in paragraph 4.1 as the value for Speed of Vessel (Vs) in equation (1), FL-sonar could have provided approximately 1.8 minutes advance warning to the Master of Costa Concordia of the pending HtoN consisting of the approaches to Scole Rocks. The warning would have been issued when the vessel was just past position B shown in Figure 4.

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

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

5 SUMMARY AND CONCLUSION

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

FL-sonar can provide a means to directly detect HtoN that are not present on navigation charts as well as supplement existing methods to effect greater urgency to adverse circumstances and heighten situational awareness. The technical capabilities exist to make a substantial difference now. The establishment of carriage requirements as well as fusion into INS still needs to take place. The costs involved are minimal, especially in light of the consequences of not having FL-sonar available for navigational use. The salvage cost of Costa Concordia amounts to over $2 billion US [20]. This amount by itself would cover the costs to purchase and install FL-sonar equipment on 75% of the world's merchant fleet greater than 25,000 gross tons [21].

6 Acknowledgement

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