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A method of determining and visualizing safe motion parameters of a ship navigating in restricted waters

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ABSTRACT

The paper presents a method of displaying ship collision avoidance information which is based on an unconventional Collision Threat Parameters Area (CTPA) technique. The solution presented here extends CTPA's functionality from past works by supporting navigation in restricted waters and handling ship domains analytically instead of numerically. It visualizes potential navigational threats as well as possible collision avoidance manoeuvres. The proposed method provides three types of information: targets' motion parameters (typical for target tracking), combinations of own course and speed which collide with those targets (typical for CTPA displays) and combinations of own course and speed which collide with stationary obstacles (new elements). Optionally it is also possible to display only manoeuvres compliant with International Regulations for Preventing Collisions at Sea (COLREGS) for the present visibility conditions. A superposition of all these types of data enables a navigator to quickly choose an efficient collision avoidance manoeuvre. The paper includes a description of the proposed visualization technique as well as examples of visualised data for encounter situations, which demonstrate the proposed method's usefulness.

1. Introduction

Increasing traffic volume of ships imposes growing necessity to introduce new measures, tools and solutions improving safety in maritime transportation. Despite international regulations and traffic management solutions such as Traffic Separation Schemes (TSS) or Vessel Traffic Services (VTS) ship accidents still occur. As underlined in (Perera and Guedes Soares, 2015), one of the reasons is that collision avoidance actions are prone to error if based on unreliable target ship information or if a navigator is under extreme pressure. Therefore, it is essential to not only provide navigators with reliable data, but also to present those data in a manner which truly helps to make the right decisions in time. Hence the importance of target information displays.

The role of on board target information displays has been changing with their functionality. Originally, they were limited to visualizing raw data, namely, other ships' velocity vectors. Soon however they became part of more complex Automatic Radar Plotting Aid (ARPA) systems and ever since then they have also featured information about possible collision avoidance manoeuvres. Thus, with the rise in processing powers and computational techniques, the displays have been upgraded from being merely generic visualization tools to prototype decision support systems. Marine radars have then been supplemented by Automatic Identification Systems (AIS) and integration of those two technologies with Electronic Charts (EC) (Weintrit, 2009) resulted in a new generation of displays, which can now offer consolidated navigational information on a single screen. This has been emphasized by an IMO resolution (IMO, 2007) stating that Collision Avoidance Systems (CAS) functionality should be a part of Integrated Navigational Systems (INS) and should include graphical information on the risk of collision or grounding.

This technological development and necessities make it both possible and desired to further extend the decision support and collision avoidance functions of marine displays. The authors of this paper have decided to do that by re-examining an unconventional Collision Threat Parameters Area (CTPA) display technique and enhancing it by elements that were technologically unavailable when it was first introduced (Lenart, 1983). Among others, the previous works on CTPA method could not handle ship domains analytically and did not support the use of EC. Both extensions are offered in the hereby proposed new method (Sections 3.1 and 3.2 respectively). Altogether the proposed new method offers the following types of information:

1. targets' motion parameters (typical for target tracking),
2. combinations of own course and speed which would collide with

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other ships (typical for CTPA, but updated here to handle off-centred elliptic domains analytically instead of numerically),
3. combinations of own course and speed which would lead to grounding or would collide with some other stationary obstacles (new element),
4. combinations of own course and speed which are not compliant with COLREGS (IMO, 1972, Cockcroft and Lameijer, 2011) for this encounter (based on ships' motion parameters and visibility conditions),
5. "accelerated look ahead" mode in which the consequences of a proposed manoeuvre after a specified time are shown.

A superposition of the second and third types of data enables a navigator to quickly choose an effective and efficient collision avoidance action. The fourth element is an optional onscreen remainder of what COLREGS say about the particular encounter situation. Taking into account all of these information results in selecting a manoeuvre, which is safe and compliant with the abiding regulations.

The rest of the paper is organized as follows. In the next section the CTPA display technique is described, preceded by a brief history of on board ARPA systems and other related radar displays. Section 3 introduces the proposed new method, focusing on its innovative elements, while Section 4 demonstrates the method's usefulness in a series of ship encounter scenarios. Finally, the paper is summarised and briefly concluded in Section 5.

2. Collision Threat Parameters Area and related display techniques

The first marine radar displays with target information were designed in the 1960 s (Birtley, 1965), but they only offered raw data – velocity vectors of target vessels. This changed in the early 1970 s: new displays developed by Sperry Ltd. featured also Potential Points of Collision (PPC) and Predicted Areas of Danger (PADs) – areas that should be avoided by own ship so as not to collide with other ships and targets. PPC and PADs evolved with time: they were initially circles (Riggs, 1973), then ellipses (Fleischer et al., 1973), irregular shapes (O'Sullivan, 1982; Zhao-lin, 1988), polygons (Hakoyama et al., 1996) and smooth curves (Wood and Yancey, 2002). They also spawned a number of related approaches, including Predicted Capability Envelope (van Breda, 2000). The common element of various PADs and PPCs was that they indicated areas of danger and by doing this they provided data for determining collision avoidance manoeuvres. However, they did not tell directly which of the possible course and speed alterations are safe. A technique, which changed this was Collision Threat Parameters Area (CTPA), introduced in (Lenart, 1983), with an extended analysis presented in (Lenart, 2015). Similarly to PAD, a collision threat is defined there as a target for which:

$$DCPA < D_S, \tag{1}$$

where $DCPA$ is the Distance at Closest Point of Approach and D_S is minimum safe distance.

The key methodological difference between previous approaches (PPC, PAD, etc.) and CTPA is utilization of a coupled Cartesian coordinate system. In the coupled system X and Y coordinates represent both position of the ship (x, y, in NM) and coordinates of ship's velocity (V_x, V_y, in kn), all coupled by a constant time value (τ, in h):

$$x = V_x{*}\tau,$$
$$y = V_y{*}\tau. \tag{2}$$

For each target CTPA is defined as an area in the coupled system, where the tip of the own velocity vector should not be placed, because it would cause violating the safe distance between the ships (D_S). Each point in the system represents ship's course (given by its x and y positions) and velocity (given by V_x, V_y coordinates). Consequently, the own ship should perform collision avoidance manoeuvres by changing course and speed to points being outside the CTPA area. CTPA for a single target encounter is presented in Fig. 1. The target's position is denoted there by a dot and target's velocity by vector V.

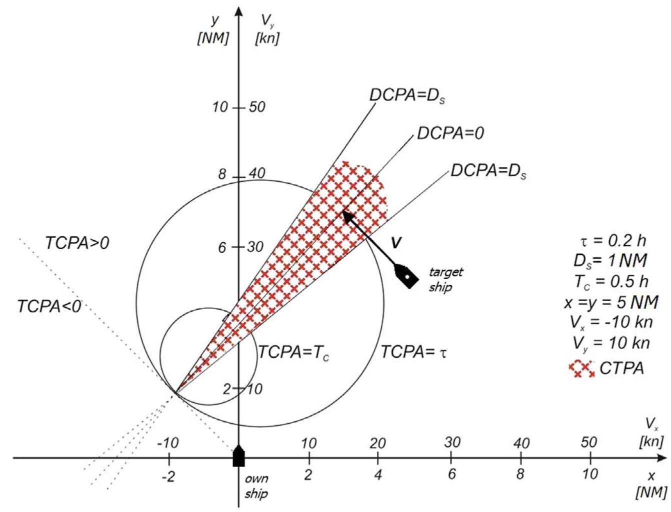

Fig. 1. The Collision Threat Parameters Area technique.

As presented in Fig. 1 the CTPA area for a single target is bounded by two straight lines of safe distance ($DCPA$=D_S). Formulas for determining these lines are provided in (Lenart, 1999). The CTPA region is limited only to future encounters with a target that is positive values of Time to the Closest Point of Approach *(TCPA)*. By widening its definition to an encounter with a group of targets the CTPA becomes a superposition of all targets' CTPA. In case of encountering many targets, the manoeuvres violating the safe distance D_S may be conditionally allowed, if *TCPA* is large enough and there is no possibility of avoiding all targets with just one economic manoeuvre. In such cases the tip of the own velocity vector may be temporarily placed within this part of the CTPA, for which *TCPA* is larger than a critical time T_C (that is between the lines of *DCPA*=*Ds* and inside the circle of *TCPA*= T_C).

The CTPA technique has been further developed by other researchers. Some contemporary displays based on the CTPA have been proposed, namely cone-shaped Collision Danger Sectors (CDS) and Collision Danger Lines (CDL) presented by Qiao and Pedersen (2004) and Qiao et al. (2006). In Pedersen et al. (2003) the authors described the results of an experiment comparing the efficiency of use of a classic display and a CTPA-based display referred to as Collision Danger Presentation (CDP). Those results have indicated the superiority of the CTPA-based display for both complicated and uncomplicated traffic conditions. In (Szlapczynski, 2009) an extended CTPA version handling any convex shape of ship domain (by means of a numerical algorithm of logarithmic computational time) has been presented. Following that in (Szlapczynski et al., 2015) a CTPA-based display has been described, which included additional COLREGS-derived information and thus supported selecting collision avoidance manoeuvres in both good and restricted visibility.

3. The proposed new method

Previous versions of the method (Szlapczynski, 2009; Szlapczynski et al., 2015) have combined the general CTPA-display technique described in Section 2 with ship domains (Coldwell, 1983) and COLREGS. Instead of using classic approach parameters of *DCPA* and *TCPA*, still popular in collision avoidance research (Mou et al., 2010; Li and Pang, 2013; Zhang et al., 2015), a domain-based approach factor f_{min} (Szlapczynski, 2006) has been applied there. However it was done by means of a numerical algorithm of logarithmic computational time, which was robust enough for simple scenarios, but seriously slowed down the method in case of multi-ship encounters. Another limitation of these past versions was that it did not support the use of EC, thus only working for open waters. The current paper, presenting continuation of the authors' work introduces the method addressing both these issues: it features handling off-centred elliptic ship domains analytically as well as visualization of interpreted geographical data on landmass and other constraints limiting sea room. Interpreted geographical data mean that an unconventional approach to visualizing them is used here. Normally these data would be simply imported from EC and displayed onscreen as a background for other information. Instead of such policy, in this work combinations of own course and speed, which would lead to collision with landmass within a predefined time, are displayed as "groundings" (Section 3.2). Handling this comes at an additional computational cost, because it is not enough to simply check whether a given course would lead to grounding (in restricted waters practically any course sooner or later would). Instead we are interested whether it would result in grounding within a given time and this depends on the ship's speed. Therefore, given a predefined timespan, for each combination of own course and speed information about potential grounding is displayed. To keep the computational cost of the whole method acceptable despite this additional feature, the computational complexity of the method's main past feature (visualizing combinations of own course and speed, which collide with other ships) – has been reduced to a constant one. This has been done by already mentioned analytical solution to the problem of determining violations of ships' domains (outlined in Section 3.1). The summary of the current method's contribution, when compared with past CTPA-based methods, is given in Table 1.

3.1. Domain-based approach factor

The domain-based approach factor f_{min} reflects the fact that collision risk varies depending on bearings and thus it is not always the same for targets in the same distance. For a given ship, the approach factor is equal to the scale factor of the largest domain-shaped area that remains free from other ships throughout the encounter situation. In Fig. 2 the predicted approach factor f_{min} for an example encounter situation is shown in the relative coordinates system, with V_t and V_r denoting true and relative speed of a target, respectively. As can be seen in this example, the target's domain will be violated. The own ship will appear at the boundary of an ellipse of about half the length of the original domain, so the approach factor f_{min} will be about 0.75.

Determining the precise values of approach factor values is done as follows. Let us assume an elliptic domain with a target displaced from its centre and denote:

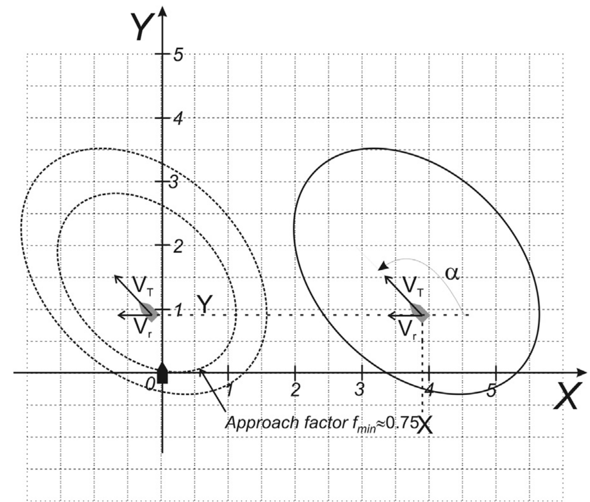

Fig. 2. Predicted value of the approach factor f_{min} in the relative coordinate system.

a –semi-major axis,
b – semi-minor axis,
Δa – a ship's displacement from the ellipse's centre towards aft along the semi-major axis,
Δb – a ship's displacement from the ellipse's centre towards port along the semi-minor axis,
(X,Y) – relative position of a target,
(X_e, Y_e) – relative position of an ellipse being the target's domain,
(V_x,V_y) – relative velocity of a target,
α – the rotation angle of the target's domain (being equal to course angle of the target).

The coordinates of the rotated ellipse's centre are:

$$X_e = X + h \tag{3}$$

$$Y_e = Y + h \tag{4}$$

where

$$h = \Delta a \cos \alpha + \Delta b \sin \alpha \tag{5}$$

$$k = \Delta a \sin \alpha + \Delta b \cos \alpha. \tag{6}$$

For an f-scaled domain, that is one, whose semi-axes and displacement dimensions are multiplied by scale factor f, Eqs. (3) and (4) have a form of:

$$X_e = X + hf \tag{7}$$

$$Y_e = Y + kf \tag{8}$$

The elliptic domain moves with the relative speed of a target:

Table 1
A summary of new elements featured in the proposed method.

	Lenart (1983)	Szlapczynski (2009)	Szlapczynski and Szlapczynska (2015)	Current method
Safe combinations of own course and speed displayed in the coupled coordinate system	√	√	√	√
Ship domain handling	–	√	√	√
Good and restricted visibility taken into account	–	–	√	√
"Look ahead" mode	–	–	√	√
Time-based filtering of navigational threats	–	–	√	√
Ship domains taken into account analytically (analytical solution of constant computational complexity does not affect computational time of the whole process)	–	- *	- *	√
Restricted waters supported	–	–	–	√
Geographical data taken into account and displayed in the coupled coordinate system	–	–	–	√

*- Numerical solution of logarithmic computational complexity seriously slowed down computations for multi encounter scenarios.

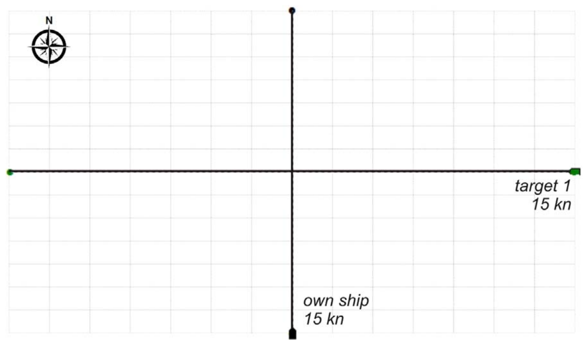

Fig. 3. Ships' positions and courses for the example encounter situation.

$$X_e(t) = X + hf + V_x t \tag{9}$$

$$Y_e(t) = Y + kf + V_y t \tag{10}$$

The parametric equation of a moving, α −rotated and f-scaled ellipse with a centre in $(X_e(t), Y_e(t))$ as a function of time t is:

$$\frac{(X_e(t)\cos\alpha + Y_e(t)\sin\alpha)^2}{f(t)^2 a^2} + \frac{(X_e(t)\sin\alpha - Y_e(t)\cos\alpha)^2}{f(t)^2 b^2} = 1 \tag{11}$$

Solving (11) gives a formula for $f(t)$, whose minimum over time t is the approach factor f_{min} we are interested in. The above described approach factor makes it easy to apply elliptic domains of various dimensions so as to support COLREGS: if starboard sector is much larger than port sector and bow sector much larger than astern sector then the domain favours manoeuvring to starboard and crossing astern instead of ahead.

3.2. Modelling and visualizing information

An example of displaying the data for a given encounter situation (Fig. 3) is shown in Fig. 4. The time value τ from (2) is set to one hour. The target's relative velocity vector crosses own ship domain, which means that own domain would be violated within τ time. The own ship is in the centre of the display, surrounded by solid grey circles, which mark 8, 16 and 24 NM distances from the own ship. A dashed black circle marks the own speed. A combination of own course and speed is safe and COLREGS-compliant if the tip of own velocity vector is in the white area. The outer borders of the pink area (domain violations) are equivalents of lines *DCPA=Ds* from Fig. 1. The red colour represents critical domain violations: situations when a target would violate the inner half of the central ship's domain. The light blue background represents manoeuvres not recommended by COLREGS (in case of a crossing encounter with a target on starboard: course alterations to port). The dark blue stands for speed values, at which ship cannot be operated safely or speed values, which are not feasible. It is assumed that maximum value of speed is a configurable parameter set by the system's operator.

Neither the abovementioned display nor any of the previous CTPA-based displays included support for avoiding grounding and avoiding collisions with stationary obstacles. In practice, it limited the potential use of those displays to open waters only. It must be noted here, that the majority of ship accidents occur on restricted waters rather than open waters as shown by a number of research projects carried out for Gulf of Finland (GoF) (Kujala et al., 2009; Montewka et al., 2010, 2014), Shanghai harbour area (Hu et al., 2007) and other sea areas. First of all, groundings which for obvious reasons nearly always happen on restricted waters, have been reported to be one of the most common causations of accident, about twice as frequent as ship-ship collisions (Guedes Soares and Teixeira, 2001; Kujala et al., 2009). As for ship-ship collisions they are also much more likely to happen on coastal (inner or outer) waters than on outer waters (Kujala et al., 2009). The latter can mostly be attributed to higher traffic density and limited sea room for manoeuvring on restricted waters. All this considered, collision-threatening encounters on restricted waters are arguably more common, more complex and more difficult to handle. Consequently, they are also much more important and interesting for collision avoidance research. Therefore it is this aspect that is thoroughly dealt with in this section.

There are two possible approaches to integrating CTPA-based display with data from EC, necessary to operate on restricted waters. The first, more obvious approach is to simply incorporate the raw map data to the display: to visualize the own ship and targets with the area's map in the background. The example of this is shown in Fig. 4. The other, more complex way, is to treat the EC-derived data the same way that data on targets are used, that is, instead of simply showing navigational obstacles and landmasses' contours, to indicate own courses, which lead to collisions with those objects. The second approach is depicted in Fig. 6.

As can be seen in Fig. 5, direct incorporation of landmass data could lead to interpretation problems due to the coupled coordinate system that is used here. CTPAs are after all not a geographic area, but a representation of dangerous speeds and courses. And, consequently, any area outside CTPAs represents speeds and courses, which are safe. Therefore a display's user may intuitively assume that any white area on the screen stands for safe manoeuvres. As a result, they could opt to choose a course alteration manoeuvre of 30 or more degrees (white part of an own speed's circle in Fig. 5). This would lead to grounding, since such a course alteration collides with the nearby landmass. Therefore the authors have decided to visualize not raw, but interpreted geographical data, as shown in Fig. 6. Here the yellow area does not represent landmass as such, but grounding sectors. Grounding sectors are combinations of own ship's course and speed which lead to a grounding within a predefined time τ. The algorithm for determining

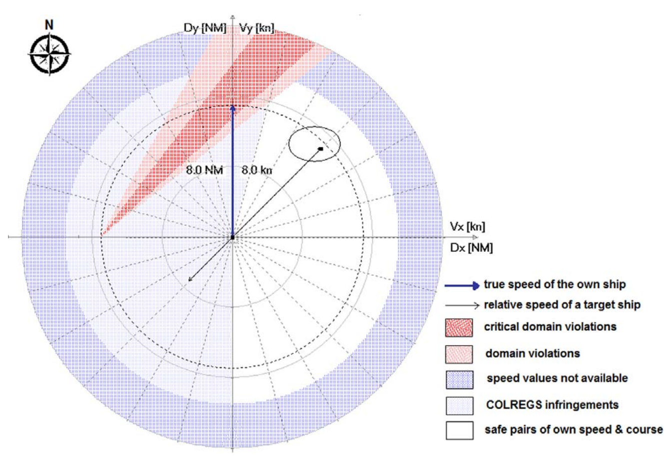

Fig. 4. The display view for the example encounter situation.

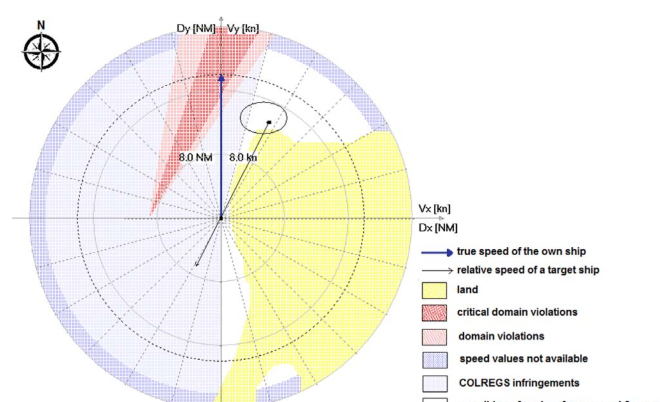

Fig. 5. The display view with incorporated raw EC data.

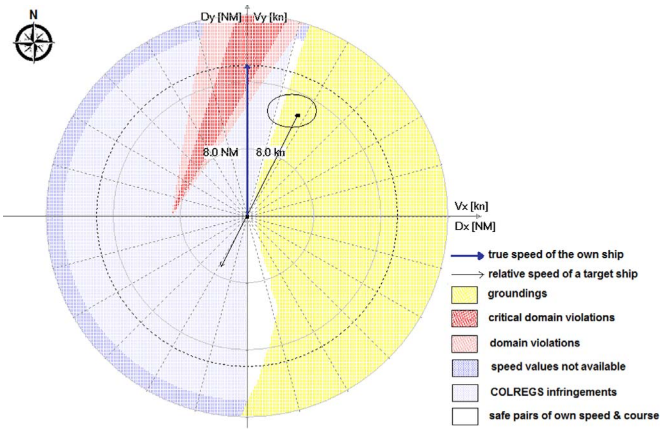

Fig. 6. The display view with interpreted EC data.

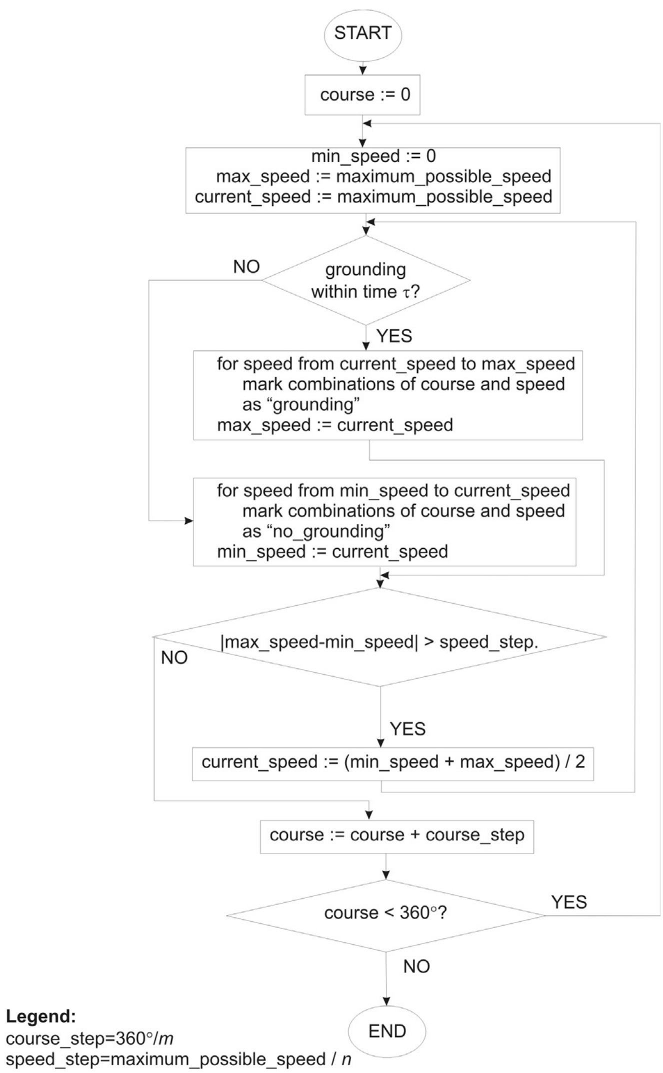

Fig. 7. Algorithm for determining grounding sectors of own course and speed.

them is presented in Fig. 7.

The algorithm's computational complexity is *O(m*log(n))*, where m is the configured resolution of the own course and n – resolution of the own speed. It is worth noting, that due to the time horizon equal to τ from (2), grounding sectors will always include and slightly expand beyond landmass, as shown in Fig. 6. The fact that they always include landmass results from the nature of τ parameter, which couples position and speed coordinates (for a speed of k knots, the own ship will reach an object distanced by $k*\tau$ nautical miles in time τ). Depending on the user's preferences, it is possible to alter default settings and set grounding time horizon to values larger or smaller than τ. Larger values would result in larger and closer grounding sectors, greatly expanding beyond landmass (groundings more distant in time would be taken into account so proportionally smaller speeds would also be considered dangerous). Smaller time horizon values would limit grounding sectors to the nearest future, making grounding sectors proportionally smaller and more distant from the own ship (proportionally larger speeds would also be considered safe).

After marking grounding sectors, domain violations and other limitations, the remaining white area on the display will represent truly safe combinations of own course and speed. This enables a navigator to choose a collision avoidance manoeuvre much quicker (no further analysis is necessary) and reduces the risk of a wrong decision in situations when fast reactions are needed.

If the areas resulting from various types of threats overlap, the following order of coloured layers is used:

1. Groundings possible within a configured time.
2. Major and minor domain violations.
3. Speeds which are not feasible.
4. COLREGS-derived limitations.

The reason for this order is that groundings are sure to happen if the navigator chooses wrong course and keeps it too long, so the information on them should usually be on top. As for feasible and infeasible speeds, their borders may be blurred in practice as the experienced navigator knows best whether it is possible to increase own speed in extreme situation. Finally, COLREGS-derived limitations are rather a hint for the navigator than a blocking limitation, so they are beneath other layers in case of overlapping. The operator however may switch between those layers to have a full picture of various navigational threats and limitations. Apart from the normal view, the visualization method offers an additional "look ahead" view mode, where a navigator may check the consequences of a considered manoeuvre: motion parameters of all ships and updated sectors of own speed and course after a specified time from performing this manoeuvre. This mode is shown in Section 4 in each scenario's last figure (two separate figures in case of Scenario 6).

3.3. The algorithm determining safe manoeuvres

If ship domains, manoeuvre's dynamics and EC-derived data are taken into account (as is the case here), then it is impossible to determine CTPAs analytically the way it was done in the original method by Lenart (1983). Therefore, they are determined numerically in this work. In brief, the method works as follows.

1. Each pixel on the display is associated with a combination of course and speed values. For these combinations of course and speed values it is determined for all targets if the own ship would violate their domains or not. If it would, a degree of domain violation is computed. In case of multiple domain violations, the largest domain violation is taken into account. A degree of domain violation is determined based on the approach factor value, presented in Section 3.1.
2. If the current course and speed collide with one or more targets, violations that would occur within predefined time (30 min by default) are taken into account and COLREGS-forbidden sectors are determined for them based on visibility conditions and encounter type (head-on, crossing or overtaking in case of good visibility; target's relative position in case of restricted visibility).

All danger sectors are displayed, including CTPA-based domain violation sectors, COLREGS-forbidden sectors and grounding sectors. Domain violations potentially leading to a crash (approach factor below 0.5) are marked in red, while other domain violations (approach factor between 0.5 and 1), probably leading to close quarter situations, are marked in pink. COLREGS-forbidden sectors are marked as light blue, impossible values of speed in dark blue and grounding sectors in yellow. The remaining white area (safe combinations of own course and speed) represents possible collision avoidance manoeuvres. In case of course alterations, it is assumed that a navigator chooses a rudder angle that allows for the fastest possible turn form the current course to the new safe course in the white area. It is also assumed that all manoeuvres are initiated within a specified time from showing them onscreen. By default this time is set to one minute, meaning that a one minute decision time is taken into account by the method when visualizing potential manoeuvres.

Based on the designed method, a computer demonstrative application has been developed. Examples of encounter situations are presented and discussed in the next section. For all situations a decentralised, elliptically-shaped domain has been used with the domain parameter values (from Section 3.1) a =3NM, b =2NM, Δa =0.75NM, Δb =0.5NM. Domain dimensions are method's configurable parameters and can be scaled down, according to environmental conditions, vessel's manoeuvrability and navigator's own preferences.

In general, the domain used here is similar in shape to the one proposed by Coldwell (1983), but larger so as to compensate for considerable distance and speed errors in Target Tracking systems (Pedersen et al., 1999; Lenart, 2005). The other way of compensating for these errors would be to use pre-processed data instead of those directly returned by radar and Automatic Identification System (AIS). The input data for the proposed display would be a result of data fusion operations (Stateczny and Kazimierski, 2011; Zhao et al., 2014a; Zhao et al., 2014b; Kazimierski and Stateczny, 2015). In case of a strong correlation between the radar and AIS data, the assumed accuracy would be higher and consequently – smaller ship domains could be used for those high-accuracy targets.

4. Examples of the method's usefulness

The scenarios in this section include one overtaking encounter, one head-on encounter, three crossings (with 45, 90 and 135° differences between the course of the own ship and the course of the potentially colliding target) and one multi encounter scenario. The motion parameters of the ships for all scenarios are provided in Table 2.

For each scenario, an overview of the situation is shown first with the own ship marked in black in appropriate figure. This is followed by a display look at the start of the situation (with a user-selected manoeuvre marked as a green dot) and the display look after the selected manoeuvre has been performed. It must be emphasized here that all scenarios have been purposely designed to maximally limit possible manoeuvres of the own ship while keeping the number of targets relatively small (to make them easier to follow and to avoid interactions between targets). As a result, based on the overview figures solely, it is hard to tell at first, which (if any) manoeuvre guarantees safe passage. However, a look at the figures presenting display view reveals that actually there is a solution to each of these cases.

4.1. Scenario 1: overtaking

Despite the fact that relative speeds of the ships approaching during overtaking are lower than in case of crossing and head-on encounters, overtaking encounters produce significantly more collisions (Goerlandt and Kujala, 2011; Hanninen and Kujala, 2012). This can be mostly attributed to two facts. First, the areas with high traffic density often include Traffic Separation Schemes (TSS), where crossings are rare and head-on encounters should not normally take place. Second, the navigator of the overtaking ship may occasionally classify the encounter as crossing and not take any action if the target is on port. However, as the example shows, there are also possible other cases of overtaking encounters, where making the right decision can be difficult.

In the situation depicted in Fig. 8 the own ship must choose a manoeuvre to safely overtake target 1. COLREGS definition of overtaking is used here, though some authors in their research (Montewka et al., 2010) limit overtaking to difference between courses not exceeding 10°. Manoeuvres to both starboard and port are allowed when overtaking and, considering target 2 on port and the fact that target 1 is steering away from landmass, the own ship may be inclined to choose a manoeuvre to starboard (towards landmass). However, a view at the proposed display (Fig. 9) tells us that such a manoeuvre would not be safe: it is impossible to avoid violating target's domain and avoid grounding with a single course alteration manoeuvre. Instead (as seen in Fig. 9) it is much safer to alter course to port by 15°. The results of choosing such a manoeuvre are shown in Fig. 10, presenting display's view after 43 min from performing this manoeuvre. The own ship passes both targets safely, without any of the

Table 2
Positions and motion parameters of the ships for all scenarios.

		X	Y	Course [deg.]	Speed [kn]	Course alteration [deg.]		Speed reduction [kn]
Scenario 1	Own ship	0	0	86.82	15	15° to port		–
	Target 1	1	9	96.34	5	–		–
	Target 2	−4	18	266.82	10	–		–
Scenario 2	Own ship	0	0	90	10	15° to starboard		–
	Target 1	−0.2	18	270	10	–		–
	Target 2	−3	15	270	10	–		–
Scenario 3	Own ship	0	0	90	15	–		from 15 to 9
	Target 1	−4	18	270	10	–		–
	Target 2	4	6	135	8.5	–		–
Scenario 4	Own ship	0	0	90	20	15° to starboard		–
	Target 1	6	12	180	10	–		–
	Target 2	−3	17	270	10	–		–
	Target 3	−11	19	293.96	6	–		–
Scenario 5	Own ship	0	0	225	14	15° to starboard		–
	Target 1	−10	−5	0	10	–		–
	Target 2	−12	−3	26.56	15	–		–
Scenario 6	Own ship	0	0	229.09	10	Option 1	15° to starboard	from 10 to 7
						Option 2	20° to starboard	–
	Target 1	−10	−5	12.09	16	–		–
	Target 2	−16	−7	33.02	5	–		–
	Target 3	−13	0	6.71	10	–		–

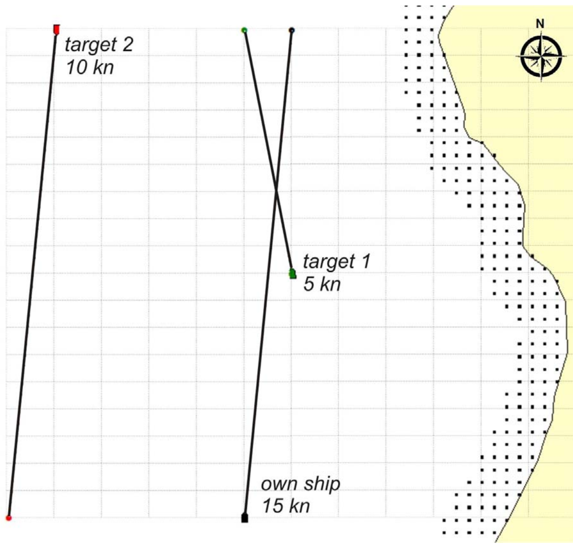

Fig. 8. Ships' positions and courses for scenario 1.

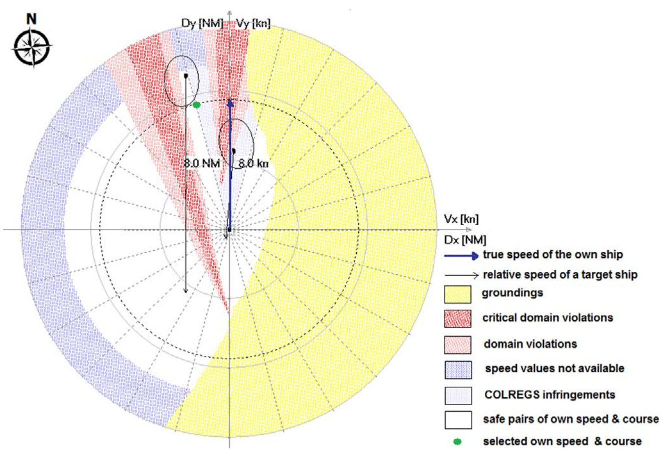

Fig. 9. The display view for scenario 1.

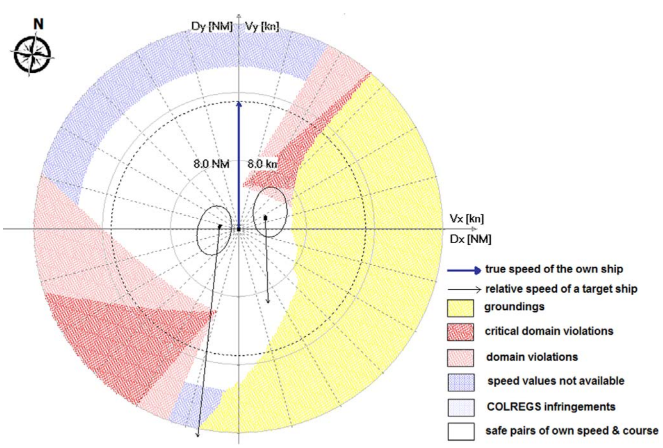

Fig. 10. The display 'look ahead' view for scenario 1; 43 min from turning to port by 15°.

ships' domains being violated: domains of the own ship and both targets slightly overlap, which is acceptable as long as the ships themselves remain outside each other's domain.

4.2. Scenario 2: head-on encounter

Although head-on collisions are relatively rare it is partly because head-on encounters do not occur very often. However, once such an encounter occurs, the risk is considerable due to high relative speed and little time for manoeuvring. According to the research presented in (Hanninen and Kujala, 2012), the sheer fact of altering course is usually enough to avoid collision. But, if there is more than one target involved and there is little sea room, the head-on situation can still be problematic, as shown in the following example.

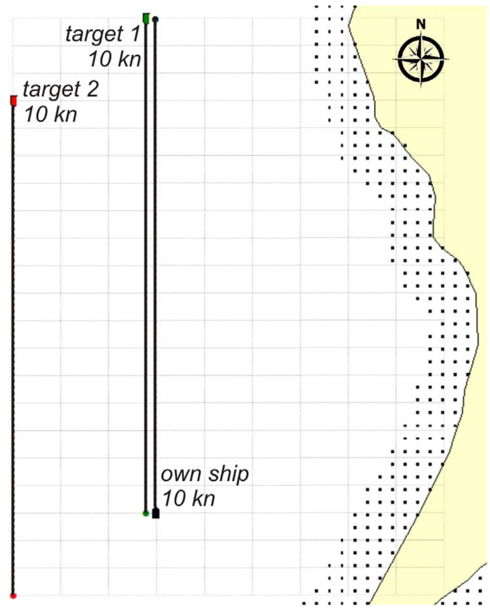

Fig. 11. Ships' positions and courses for scenario 2.

In Fig. 11 a head-on encounter is shown, with the own ship facing target 1. A manoeuvre to starboard should be chosen according to COLREGS, but the navigator may have doubts whether there is sufficient space for that and might be tempted to manoeuvre to port instead. As indicated by Fig. 12, manoeuvring to port would be wrong: not only because of disobeying COLREGS, but also because the turn would have to be by about 45° and thus resulting in a huge way loss. Additionally, there is a significant probability that target 1 will manoeuvre to starboard and any manoeuvres to port by the own ship may lead to collision. The manoeuvre to starboard by about 15° is the safe choice here as it avoids collisions with both targets without the risk of grounding. The suggested combination of a new course and unchanged speed (marked with a green dot) is outside the yellow area, which means that there is at least 1 h to a potential grounding on that course. As shown in Fig. 13, after passing both targets (50 min from the manoeuvre), the available time is shorter than 1 h (the tip of the own speed vector is already in the yellow area) but it is still sufficient to

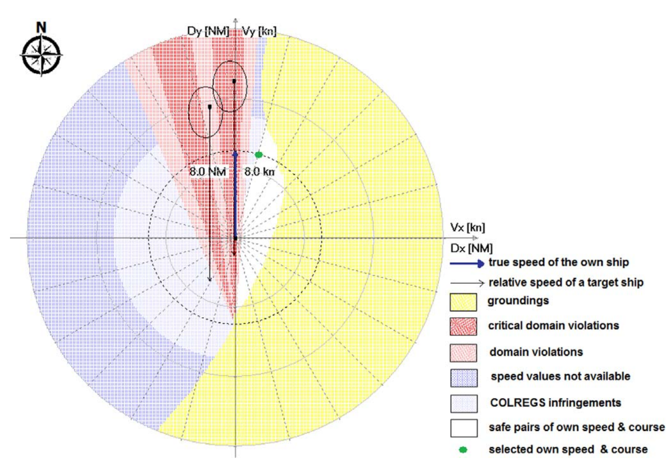

Fig. 12. The display view for scenario 2.

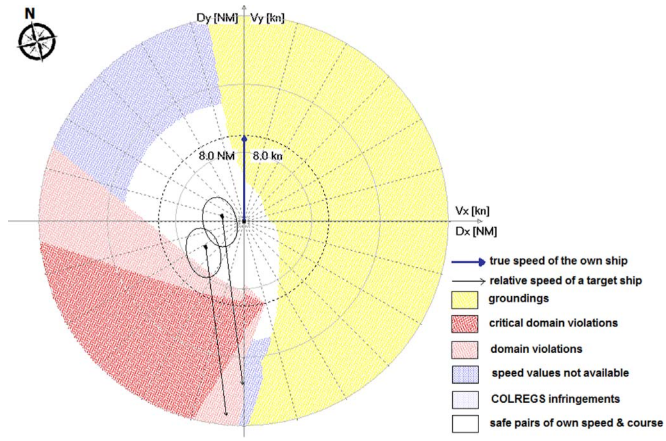

Fig. 13. The display 'look ahead' view for scenario 2; 50 min from turning to starboard by 15°.

return to the original course – turning back to port by 15° is enough to avoid grounding.

4.3. Scenario 3: crossing encounter (45° difference between ships' courses)

Crossing encounters differ from head-on and overtaking ones in that their probability does not strictly depend on the distribution of traffic on the route (Talavera et al., 2013), the encounters usually being the result of intersection of traffic. Theoretically, making decision in encounter situations should be easy: only one of the ships is supposed to manoeuvre and the direction of a turn is specified by COLREGS. However, as the following three examples show, it becomes harder if other targets and grounding risk have to be taken into account.

In Fig. 14 the first of the three crossing encounters is presented. The own ship would collide with target 1 had none of them change their courses. Since target 1 is on starboard, it is the own ship that should manoeuvre, if possible – to starboard. It may seem hard, as the space on starboard is limited by a nearby landmass and thus manoeuvres to port would probably also be taken into account. As shown in Fig. 15, the turn to port would have to be about 45° (significant loss of way) not to mention that it would mean disregarding COLREGS and passing ahead of both targets, including privileged target 1. Instead, as Fig. 15 informs us, it would be safe to reduce own speed by about 6 knots or combine a reduction of speed with turning to starboard. The results of

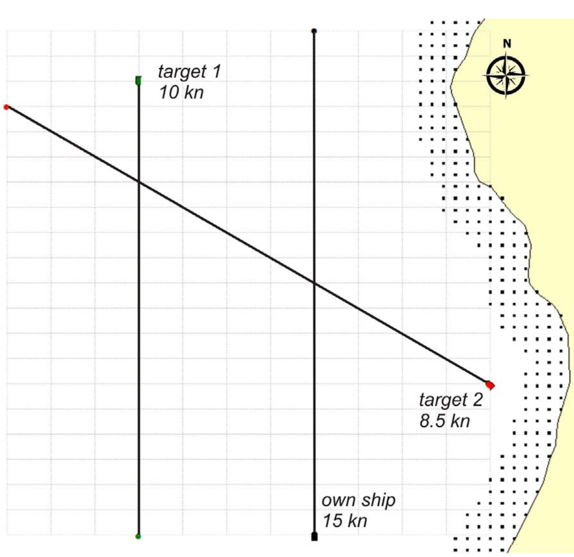

Fig. 14. Ships' positions and courses for scenario 3.

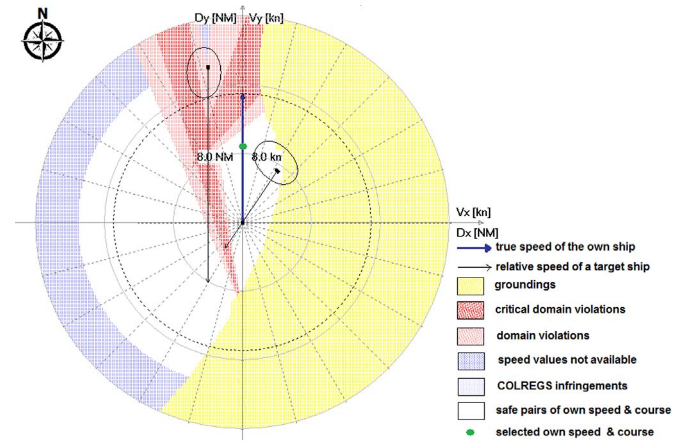

Fig. 15. The display view for scenario 3.

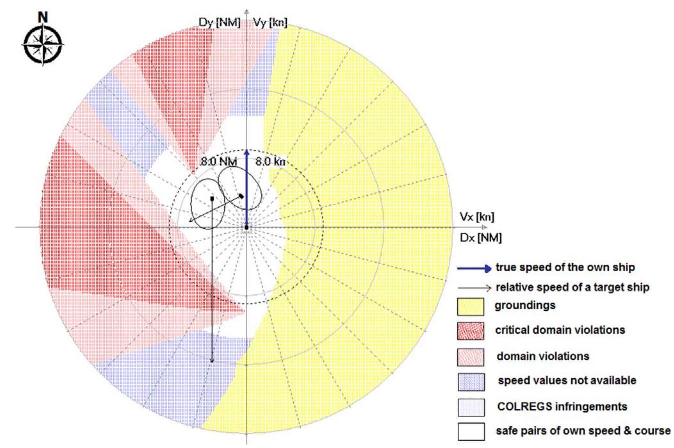

Fig. 16. The display 'look ahead' view for scenario 3; 45 min after reducing own speed from 15 to 9 kn.

reducing the own speed by 6 knots (from 15 to 9) are depicted in Fig. 16, where the own ship passes astern of target 1 without violating target's domain.

4.4. Scenario 4: crossing encounter (90° difference between ships' courses)

In Fig. 17 another crossing encounter is presented, but this time the own ship and target 1 are on perpendicular courses. Again target 1 is on starboard and own manoeuvre is necessary. It is also yet another example of a situation where limited space on starboard may cause an

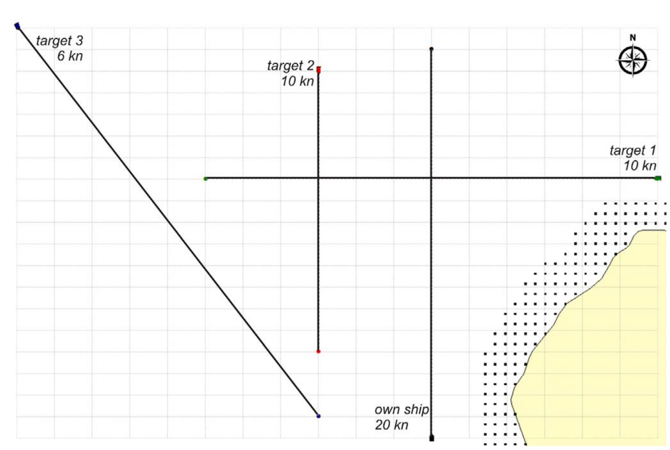

Fig. 17. Ships' positions and courses for scenario 4.

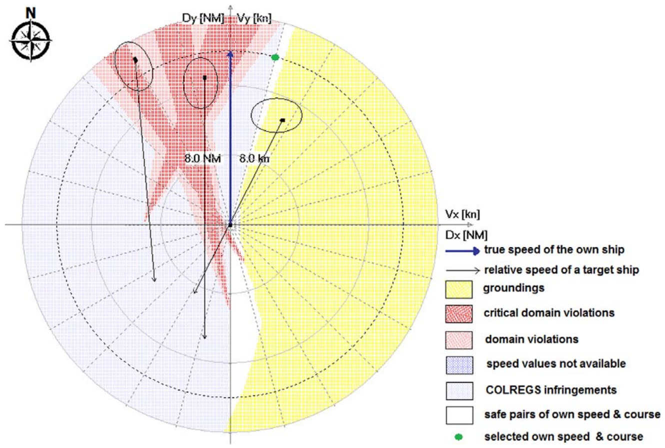

Fig. 18. The display view for scenario 4.

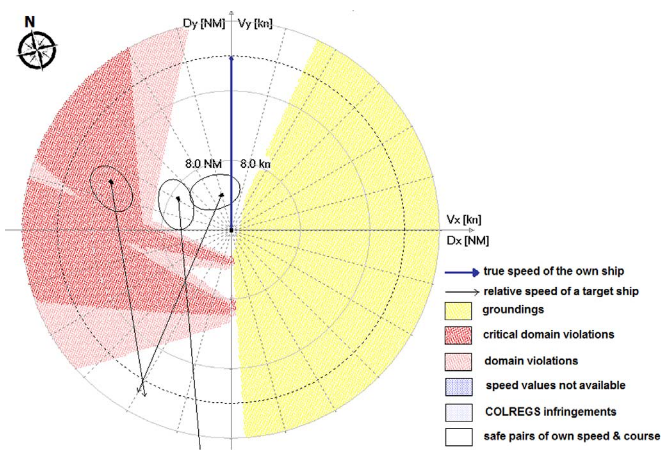

Fig. 19. The display 'look ahead' view for scenario 4; 23 min from turning to starboard by 15°.

inexperienced navigator to turn to port. However, as Fig. 18 shows, a safe manoeuvre to starboard is actually possible – changing course by about 10° is enough to avoid collisions with targets and an even smaller manoeuvre would be sufficient if smaller ship domains were applied. However, arguably, a navigator may choose a larger alteration to make the manoeuvre "readily apparent" (as dictated by COLREGS). A display view after 23 min from turning to starboard (by 15°) is shown in Fig. 19, where the own ship passes astern of target 1 and target 1 in turn passes astern of target 2.

4.5. Scenario 5: crossing encounter (135° difference between ships' courses)

The last of crossing encounter involves the own ship and target 1, whose course differs by 135° from the own course (Fig. 20). This time manoeuvres to port are limited not by a landmass, but by another ship (target 2). The manoeuvring space on port seems relatively large in comparison, which again could theoretically lead to a wrong choice. However, the display view shown in Fig. 21 informs the navigator that it is impossible to select a sufficient manoeuvre to port: the COLREGS-compliant turn to starboard by about 15° is the right solution. Indeed, the situation after 28 min from turning to starboard by 15° (Fig. 22) is safe: both targets are just being passed, their domains not violated.

4.6. Scenario 6: multi encounter

The last of the scenarios features the own ship encountering three targets, as shown in Fig. 23. The targets and the proximity of a

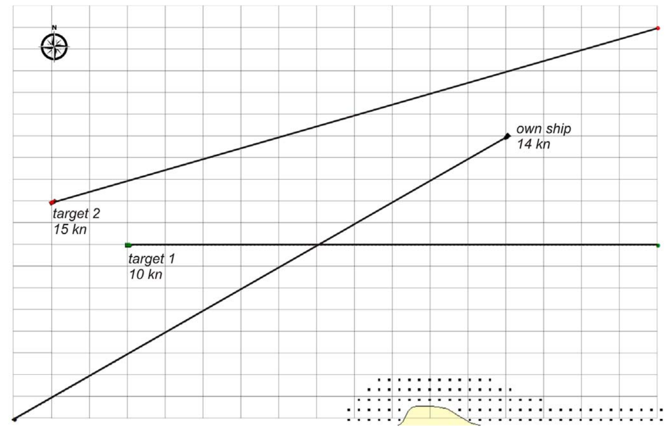

Fig. 20. Ships' positions and courses for scenario 5.

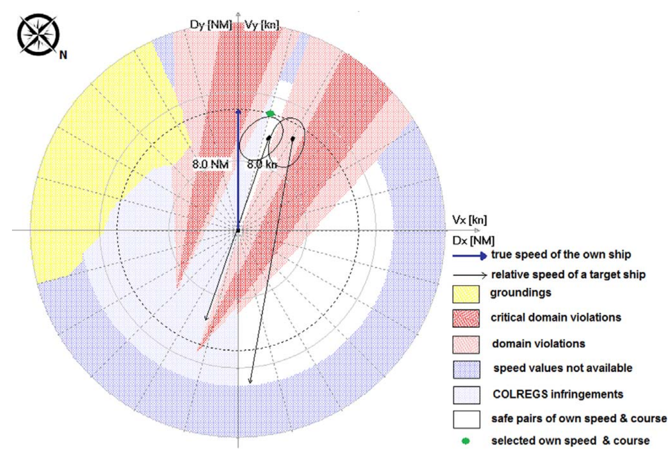

Fig. 21. The display view for scenario 5.

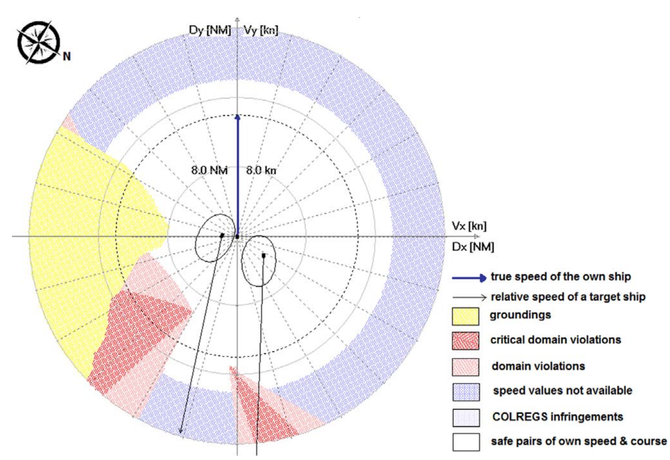

Fig. 22. The display 'look ahead' view for scenario 5; 28 min after turning to starboard by 15°.

landmass make it hard to find a collision avoidance manoeuvre to starboard and the navigator may be tempted to turn to port where the situation is seemingly safer. This could result in a collision, especially if any of the targets on port manoeuvred to their starboard. However, there are possible safe manoeuvres. The first solution, as Fig. 24 (option 1 – green dot) informs us, lays in a combination of course alteration to starboard (by 15°) and speed reduction (by 3 knots). The results of such action are shown in Fig. 25, where the own ship passes safely the closest target while avoiding grounding (the tip of the own speed vector is in the white area).

Another possible solution shown in Fig. 24 (option 2 – purple dot)

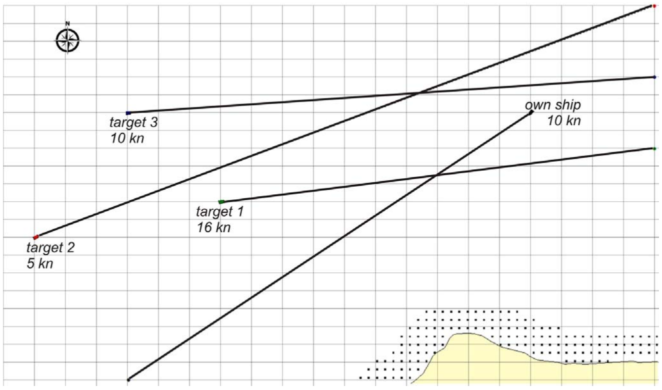

Fig. 23. Ships' positions and courses for scenario 6.

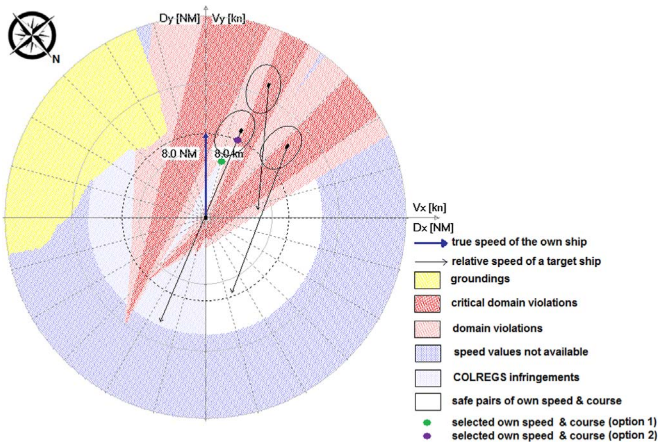

Fig. 24. The display view for scenario 6. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

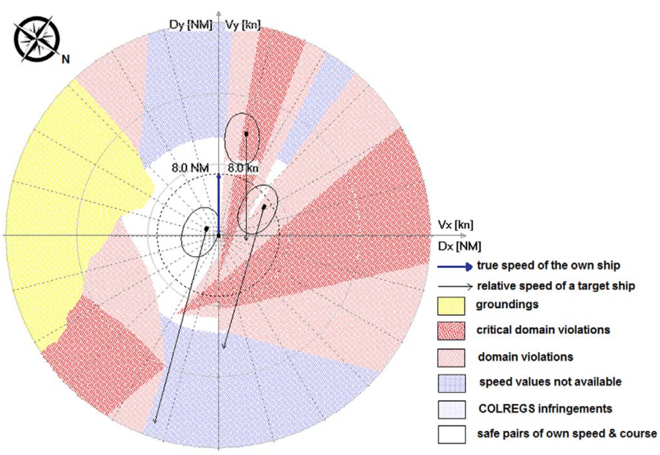

Fig. 25. The display 'look ahead' view for scenario 6; 27 min after turning to starboard by 15° and reducing speed by 3 knots (option 1).

is a sequence of course alterations, which may be performed e.g. if the navigator does not want to reduce speed. The tip of the own speed vector may be temporarily placed in the red area and the consequences of such manoeuvre may be viewed in the "look ahead" mode. As can be seen in Fig. 26, after turning to starboard by 20° and keeping the new course for 25 min the first target is safely passed. The own course can be then changed again so as to avoid minor violation of the second target's domain – there is still time for the second manoeuvre as evidenced by the white area.

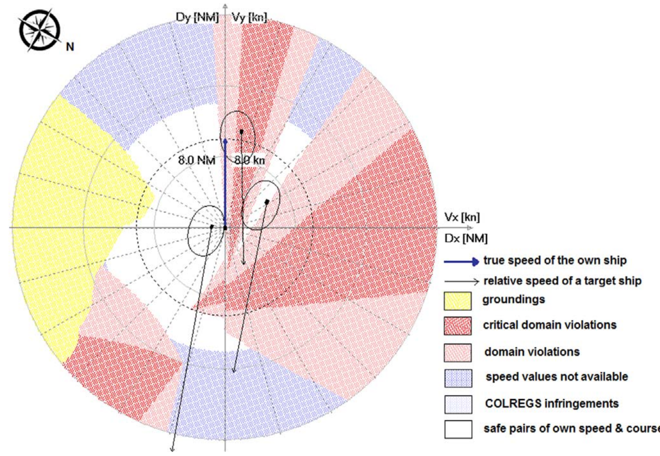

Fig. 26. The display 'look ahead' view for scenario 6; 25 min after turning to starboard by 20° (option 2).

4.7. A comparison of results

As have been shown in Figs. 10, 13, 16, 19, 22 and 25 the manoeuvres that have been chosen from the display's white are safe: ships pass each other without violating the domains. A summary of this is given in Table 3, where approach factor values and *DCPA* values are given for all targets that the own ship encounters in each scenario.

Indeed, all of the computed approach factors f_{min} are larger than 1, which confirms that ships' domains remain free of targets. Additionally, approach factor values can be compared with *DCPA* values. It is worth noting that sometimes largely differing *DCPA* values may accompany roughly similar approach factor values: e.g. for targets 1 and 5 in Scenario 5. These differences are best seen in the quotients of *DCPA* and approach factor, which range from 1.42 to 2.52. It is a consequence of applying a ship domain shown in Fig. 2. Varying the domain's dimensions in various directions naturally results in different *DCPA* values for targets on different bearings. In such a way a navigator's safety preferences can be directly applied in the method. This is the first of the two improvements offered by the proposed method, when compared with the existing works described by Lenart (1983), (1999), Pedersen et al. (2003), Qiao and Pedersen (2004) and Qiao et al. (2006). Additionally, the fact that it is done analytically greatly speeds up the method, when compared with (Szlapczynski and Szlapczynska, 2015). The second improvement is incorporating EC-derived data which makes it possible to apply this kind of visualization method for restricted waters. Up to date this feature has not been offered neither in works by the researchers listed above nor in works by these authors (Szlapczynski and Szlapczynska, 2015), which practically limited the method's functional scope to open waters only.

Table 3
Approach factor values (f_{min}) and *DCPA* for all encounters.

		f_{min}	*DCPA*	$DCPA/f_{min}$	*TCPA*
Scenario 1	Target 1	2.75	4.00	1.45	45 min 46 s
	Target 2	1.60	2.27	1.42	43 min 7 s
Scenario 2	Target 1	1.54	2.51	1.62	52 min 43 s
	Target 2	3.01	4.89	1.62	42 min 37 s
Scenario 3	Target 1	2.67	4.00	1.5	55 min 35 s
	Target 2	1.71	3.50	2.04	54 min 30 s
Scenario 4	Target 1	1.49	2.62	1.76	31 min 1 s
	Target 2	3.47	5.82	1.68	31 min 29 s
	Target 3	5.74	12.91	2.25	41 min 14 s
Scenario 5	Target 1	1.19	1.68	1.41	27 min 25 s
	Target 2	1.23	3.11	2.52	23 min 34 s
Scenario 6	Target 1	1.07	1.92	1.79	27 min 17 s
	Target 2	1.08	2.68	2.48	82 min 18 s
	Target 3	1.53	3.63	2.37	39 min 9 s

5. Summary and conclusions

The paper introduces the authors' approach to visualizing information for ship collision avoidance purposes. The presented method offers both direct physical data (ships' motion parameters) and interpreted data (dangerous combinations of own course and speed) with an emphasis on the latter. It is based on CTPA display technique, which is here combined with new elements: grounding sectors and handling off-centred elliptic ship domains analytically, thus offering a complete picture of the navigational threats and ways to avoid them, while keeping computational time acceptable. The method also features a manoeuvre simulation mode, in which the navigator is able to see the results of a planned manoeuvre in advance: future motion parameters as well as target-colliding and landmass-colliding combinations of own course and speed after a specified time. Owing to this, the navigator can easily verify the results of any considered manoeuvre. Additionally, if an efficient single collision avoidance manoeuvre is not possible, the navigator can choose a sequence of manoeuvres instead. In the paper a set of examples covering typical encounter situations has been used to illustrate the benefits of the presented approach, which are especially evident in complex ship encounter situations on restricted waters. As these examples show, visualizing integrated and interpreted information on navigational threats and collision avoidance manoeuvres should enable navigators to make safe decisions faster. It is especially important in cases when those decisions are not intuitively obvious and the time for making them is strictly limited.

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