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Presentation algorithm of possible collision solutions in a navigational decision support system

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Abstract
The article discusses an algorithm devised for presentations of acceptable solutions to collision situations of ships at sea. The solutions, course alteration ranges, are determined in compliance with the Collision Regulations. The solutions account for cases where more than two vessels are involved in a collision situation. The algorithm has been implemented into NAVDEC, a navigational decision support system. The presented results have been obtained in field research, onboard the motor vessel "Nawigator XXI".

Introduction

The competitive advantage of maritime transport over other transport modes leads to increased carriage of goods by sea. Consequently, we face a continuous rise in traffic intensity, tonnage and speeds developed by some vessels. This adversely affects the safety of people, ships, cargo and the environment. To improve the safety and enhance the efficiency and competitiveness of transport services in maritime shipping, vessels and land-based centres are being equipped with increasingly more advanced devices and systems. These, executing mainly information functions, support safe conduct of ships. However, the increasing amount of information available onboard and greater complexity of technical systems put decision makers in an extremely difficult position, as information management and decision making in case of complex situations, such as emergencies. An analysis of maritime court decisions indicates that one of the main causes of marine accidents is human error.

We can eliminate or reduce human errors, thus ensure possibly high level of navigational safety, by introducing shipboard tools that, apart from information functions, will develop and generate solutions to collision situations and supply relevant explanations. However, none of the known and implemented systems performs such functions. Therefore, the scope of decision support is significantly limited, and so is the effectiveness of collision avoidance. The safety at sea enhanced by introducing a system capable of realizing the mentioned functionalities will automatically lower the risk of marine accidents. Implied advantages include various aspects:

- social: decreased number of injured or dead crew members and passengers on sea-going ships;
- material: reduced loss of cargo, less damage to ships, fewer sinkings;
- environmental: prevention of ecological disasters that result from collisions of ships carrying dangerous goods or fuel spills.

The Navigational Decision Support System NAVDEC

NAVDEC (Fig. 1) [1, 2, 3] has been developed at the Maritime University of Szczecin as the first navigational tool worldwide that beside information functions executes tasks typical of decision support systems. These novel functionalities significantly extend the capabilities of shipboard devices installed on the bridge.

NAVDEC supplements the conventional navigational equipment of a ship. This real time system is operated by the navigator. The system observes

Fig. 1. NAVDEC, installed on the m/v "Nawigator XXI"

own ship and the area around it and records information on the current navigational situation. On this basis, NAVDEC identifies and assesses a navigational situation (processing) and generates solutions (decisions) ensuring safe navigation. For the system to run correctly, it has to co-operate with standard shipboard devices and systems (at present often found on leisure craft as well): log, gyrocompass, ARPA (*Automatic Radar Plotting Aids*), GNSS (*Global Navigational Satellite System*), AIS (*Automatic Identification System*), ENC (*Electronic Navigational Chart*). These are sources of current navigational data. Similarly to ECDIS (*Electronic Chart Display and Information System*) the NAVDEC system fulfils information functions – on a single screen it displays bathymetric data from an electronic navigational chart, image of a surface situation from a tracking radar, information on targets from an AIS system and GNSS receivers, and determines and presents to the navigator movements and parameters of approaching targets.

Effective solutions to collision situations are based on information about movement parametres of own and other ships. The accuracy of information displayed to the navigator is vital for correct assessment of the situation and for the decisions to be made and implemented. Therefore, NAVDEC carries out the fusion of data on own ship (e.g., takes into account measurements from a few GNSS receivers installed onboard) [4] and integrates data on other ships received from alternative sources (tracking radar, AIS) [5].

Another essential function performed by NAVDEC is an analysis and assessment of a navigational situation relative to all or selected targets within eight nautical miles. This is one of the decision making phases, to date carried out mainly by the navigator, because the situational assessment requires that Collision Regulations be taken into account. Thanks to NAVDEC, the navigator is currently informed on the qualification of an encounter situation in the light of the International Regulations for Preventing Collisions at Sea [6]. This provides a substantial assistance to navigators, particularly in areas of intense vessel traffic, although by a curious paradox, quite frequent are accidents of two ships away from other traffic (e.g. m/v "Gotland Carolina" and m/v "Conti Harmony" in 2009).

The main innovation of the NAVDEC system is that it determines (accounting for the rules of the road, good sea practices, and criteria used by expert navigators) and presents to the navigator solutions of a collision situation, in relation to all vessels or a selected vessels with the right of way. This capability extends the set of system functions beyond provision of information, and makes NAVDEC a decision support system. Apart from a specifically suggested solution, other alternative solutions complying with the regulations in force are generated (possible range of course alteration or speed changes). Additionally, the navigator receives a justification of the proposed manoeuvre. The NAVDEC system also incorporates a track optimization algorithm, which may operate in its classical version or fuzzy environment [7]. The latter, instead of one manoeuvre, determines a series of manoeuvres (optimal trajectory) solving a collision situation and, ultimately, leading the vessel back onto its preset course.

The proposed solutions, and their explanations, do not do navigator's job – they facilite it, suggesting a right decision. Ship control can be automated by direct connection of NAVDEC with implemented control algorithm, as in [8], with the autopilot, steering gear, main engine, telegraph and controllable pitch propeller.

Presentation of solutions by NAVDEC

For practical reasons, this article is limited to the demonstration of the presentation algorithm for acceptable collision solutions, given in the form of specified course alteration ranges.

When a situation is qualified as a risk of collision and another ship (target) has the right of way (stand-on vessel), the system has to determine a safe manoeuvre, one that will indicate a solution to the collision problem. The solution may consist in determining a safe course, assuring passing a target at a preset distance, considered as safe by the navigator. Formulas for the calculation of course alteration such that the target will be passed at a pre-established minimum distance, referred to as the closest point of approach (CPA_{LIMIT}), have these forms [9, 10]:

$$\mathrm{tg}\frac{\psi}{2} = \frac{A_{DCPA} \cdot V \pm \sqrt{(A_{DCPA}^2 + 1)\, V^2 - \left(B_{DCPA}\right)^2}}{B_{DCPA} - V} \quad (1)$$

$$A_{DCPA} = \frac{X_{wz} \cdot Y_{wz} \pm CPA_{\mathrm{LIMIT}} \sqrt{D^2 - \left(CPA_{\mathrm{LIMIT}}\right)^2}}{X_{wz} - \left(CPA_{\mathrm{LIMIT}}\right)^2} \quad (2)$$

$$B_{DCPA} = A_{DCPA} \cdot V_x - V_y \quad (3)$$

where:
V – own ship speed;
X_{wz}, Y_{wz} – distance between ships calculated along the axes x and y;
V_x, V_y – components of the own ship speed vector;
D – distance between the ships;
ψ – a new course that will allow to pass the target at CPA_{LIMIT}.

The above equations yield up to four propositions of course alteration (γ_1, γ_2, γ_3, γ_4) while maintaining the current speed. Angles with the negative sign stand for alteration of the course to port side. One of the propositions, requiring least departure and satisfying the rules, may be given as a minimum-time solution. The formulas given do not determine ranges of allowed course alteration, though. To find them, we should use the function written in the pseudo-code below:

```
y = range(gamma1,gamma2)
if gamma1>gamma2
     calculate CPA and TCPA for 0
if CPA>=CPALIMIT or CPA<CPALIMIT
  and TCPA<0
          y = 1
else
          y = 0
end
else
     calculate CPA and TCPA for
     (gamma1+gamma2)/2
if CPA>=CPALIMIT or CPA<CPALIMIT
  and TCPA<0
          y = 1
else
          y = 0
end
end
```

Input data for this function are pairs of solutions of the equations (1)–(3), which are proposed extremes of intervals of acceptable course alterations, the solution pairs being selected via the following procedure:

- all different solutions of equations (1)–(3) are standardized to bring them to the interval $\langle 0, 360°\rangle$ and sorted in a rising order;
- the looked-for pairs are two adjacent solutions (first and second, second and third, etc.) and a pair composed of the first and last solutions.

The output of the function is the value:

- 1, when its arguments determine an interval of acceptable course alterations;
- 0, when its arguments do not determine an interval of acceptable course alterations.

The ranges of acceptable, or allowed, course alterations will be a sum of all determined intervals, for which the function output equals 1. To calculate *CPA*, the closest point of approach and the time to *CPA* (*TCPA*) we should use these formulas [9, 10]:

$$CPA = \frac{X_{wz}\, VY_{wz} - Y_{wz}\, VX_{wz}}{V_{wz}} \quad (4)$$

$$TCPA = \frac{X_{wz}\, VY_{wz} - Y_{wz}\, VX_{wz}}{V_{wz}^2} \quad (5)$$

where:
VX_{wz}, VY_{wz} – components of relative speed vector;
V_{wz} – relative speed.

So far we have considered a collision situation involving two ships, own ship and a target. If more ships happen to participate in a collision situation and at least one of them has the right of way (stand-on vessel), to find global solutions of such situation, we have to calculate the product of the ranges of allowable course alterations in relation to all ships concerned.

The determined ranges of course alteration, that is acceptable solutions of a collision situation, are presented in the form of a circle graph (Fig. 2).

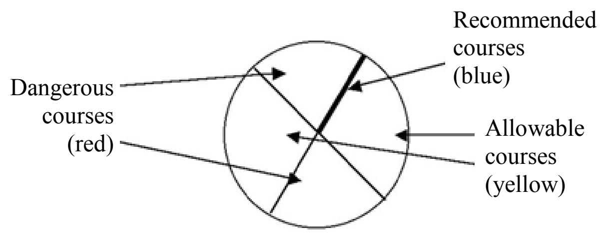

Fig. 2. Presentation of acceptable ranges of ship's course alterations

Field research results

The presentation algorithm of allowable collision situation solutions implemented in the navigational decision support system NAVDEC has been verified in real conditions, onboard the motor vessel "Nawigator XXI". Field tests have been carried out on the Szczecin-Świnoujście fairway and in the southwest waters of the Baltic Sea. Some results of the tests are herein demonstrated.

Figures 3, 4 and 5 show a collision situation involving m/v "Nawigator XXI" and three other targets (ship 1, ship 2, ship 3). Relative to the "Nawigator XXI", all the other ships have the right of way. The bottom right-hand circle graphs illustrates ranges of allowable course changes in respect to single defined targets, while the top circle graph, presenting the product of the three, shows a global solution.

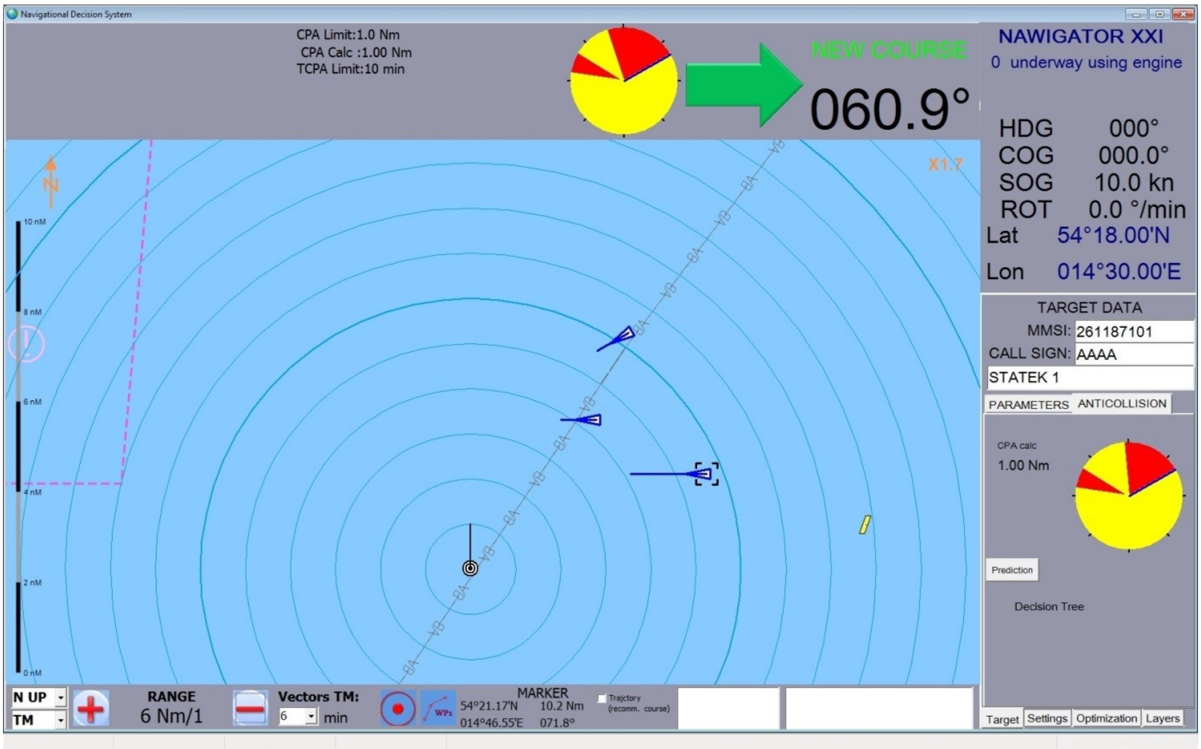

Fig. 3. Presentation of a global solution of an example collision situation and solutions relating to one selected target (ship 1) – screen one

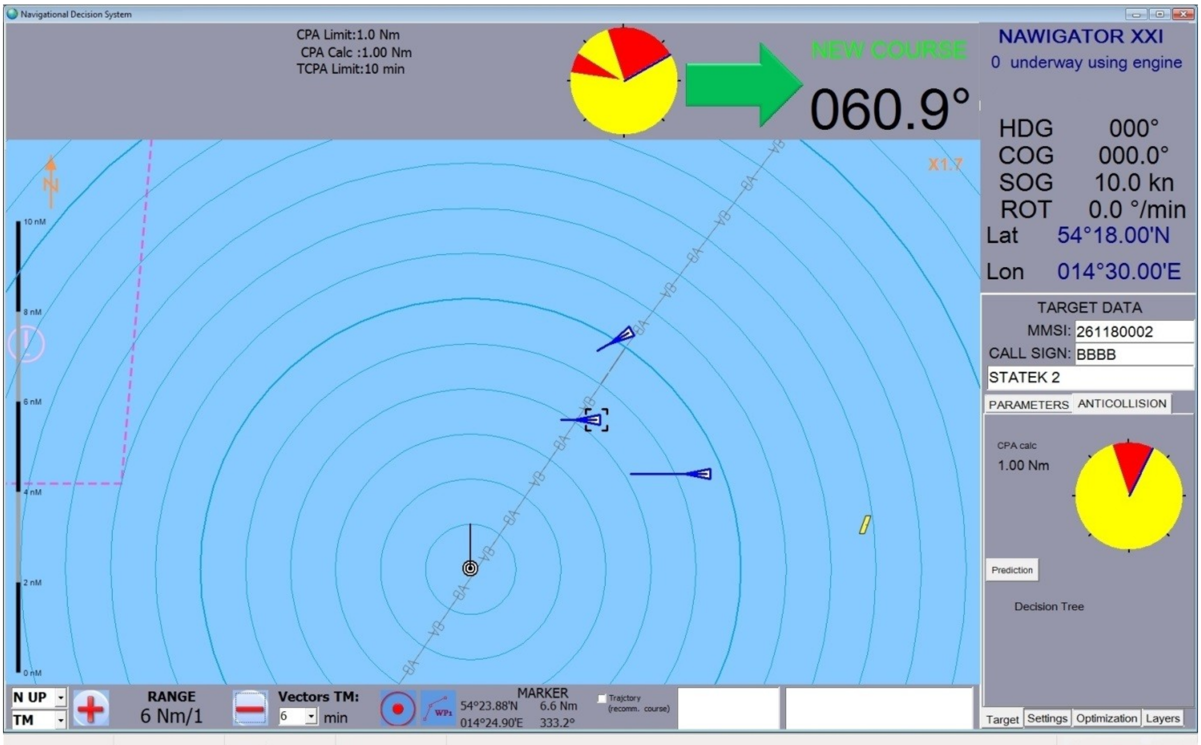

Fig. 4. Presentation of a global solution of an example collision situation and solutions relating to one selected target (ship 2) – screen one

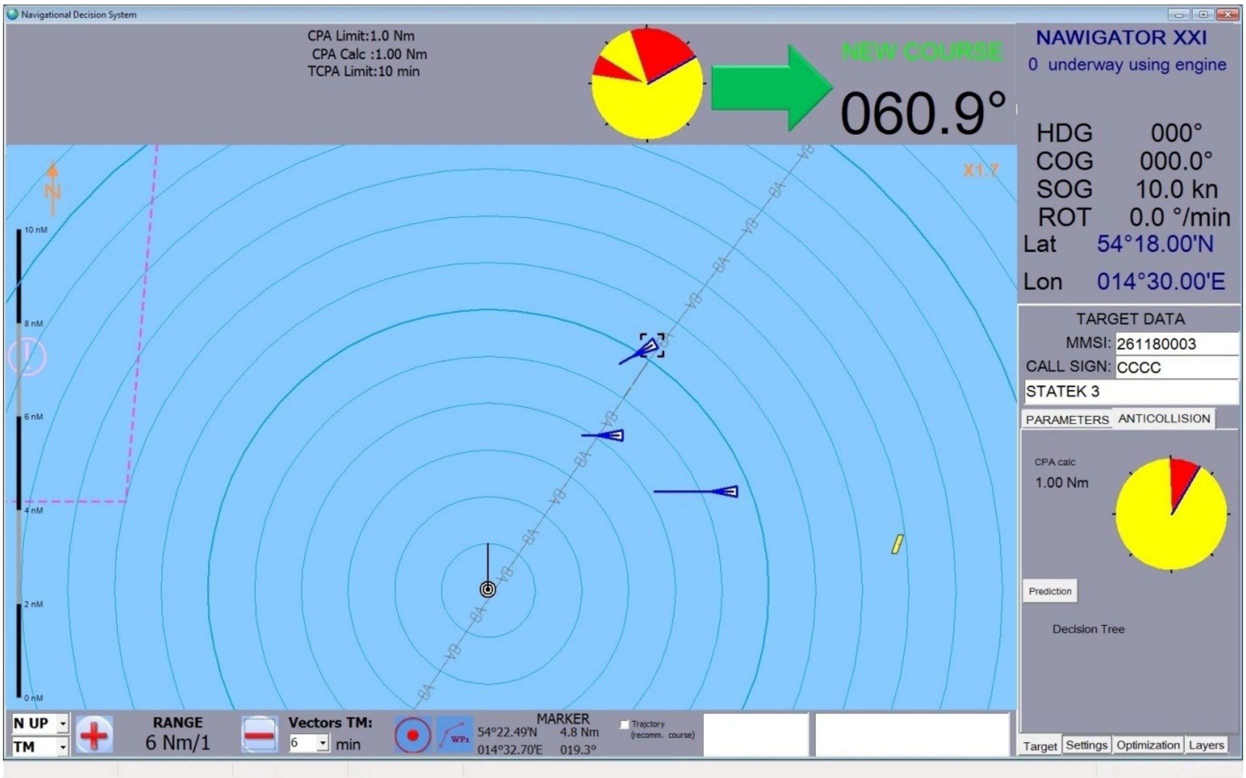

Fig. 5. Presentation of a global solution of an example collision situation and solutions relating to one selected target (ship 3) – screen one

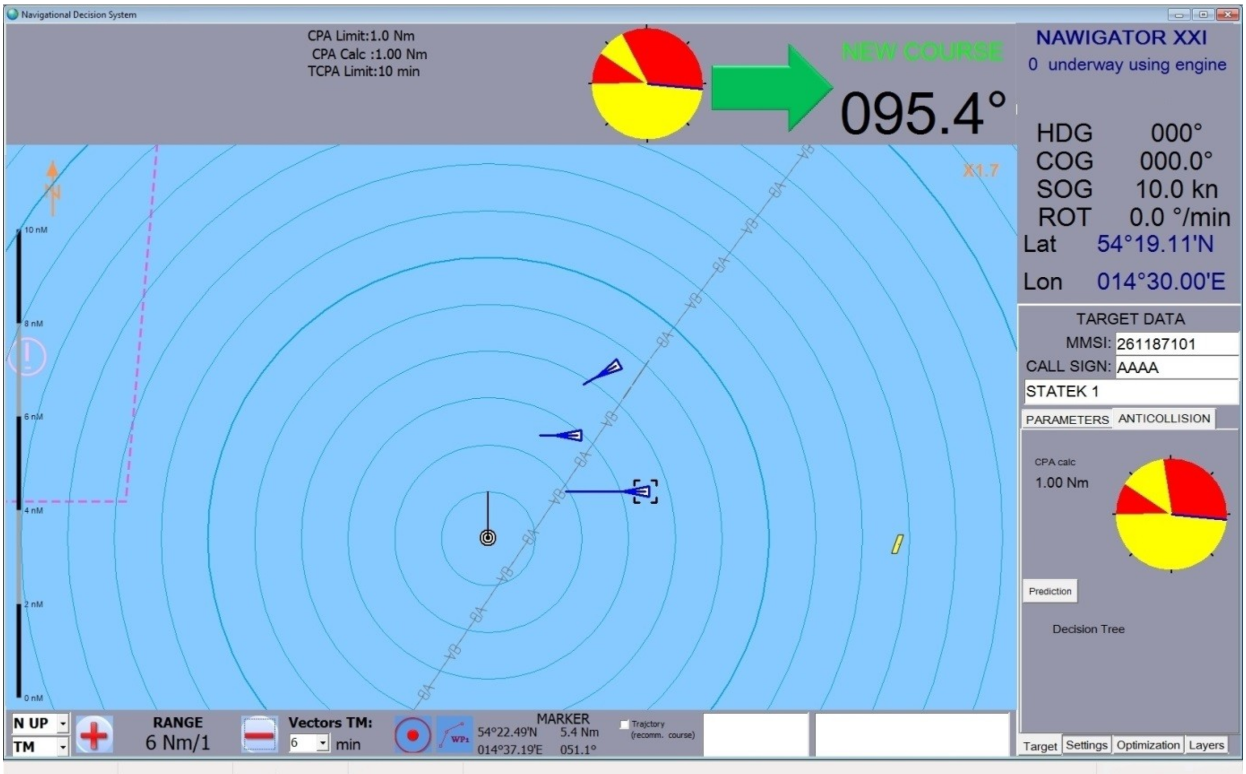

Fig. 6. Presentation of a global solution of an example collision situation and solutions relating to one selected target (ship 1) – screen two

Figures 6, 7 and 8 illustrate the previous collision situation seven minutes later. Because the m/v “Nawigator XXI” did not perform a recommended anti-collision manoeuvre, ranges of allowable course alteration ranges are narrower than in the initial encounter phase.

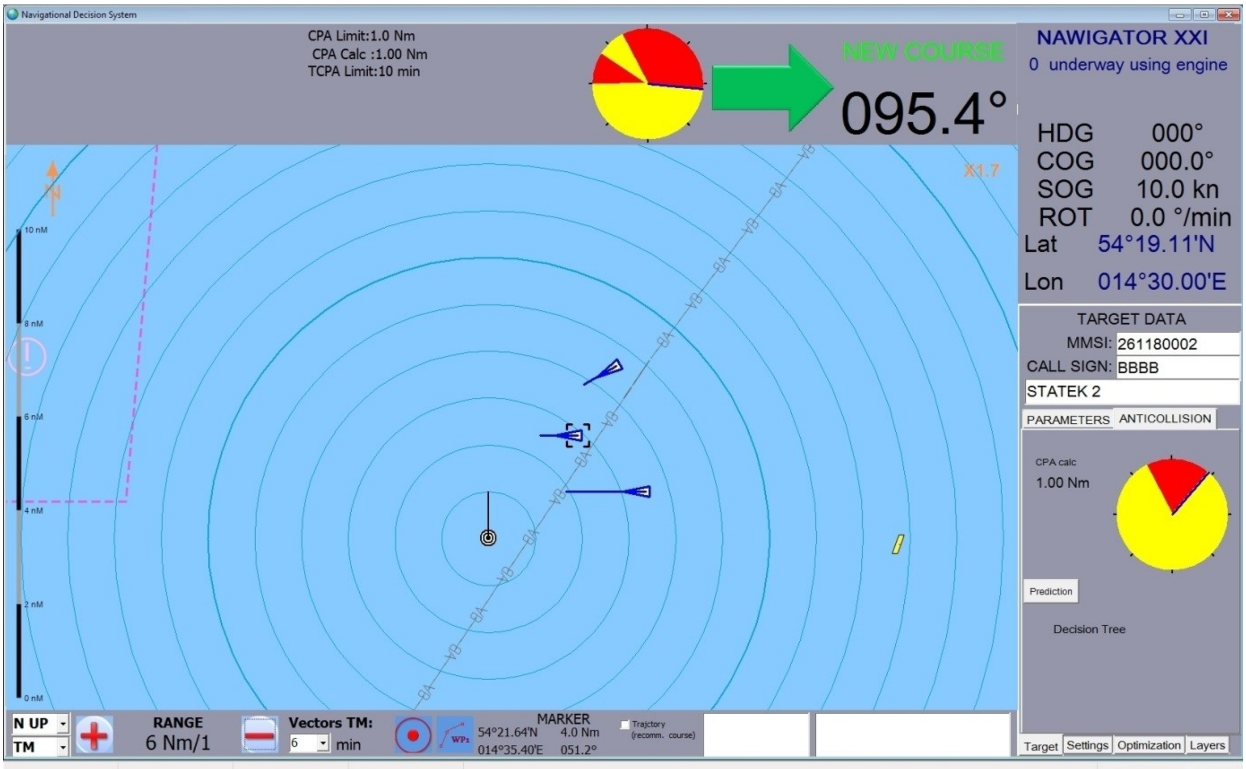

Fig. 7. Presentation of a global solution of an example collision situation and solutions relating to one selected target (ship 2) – screen two

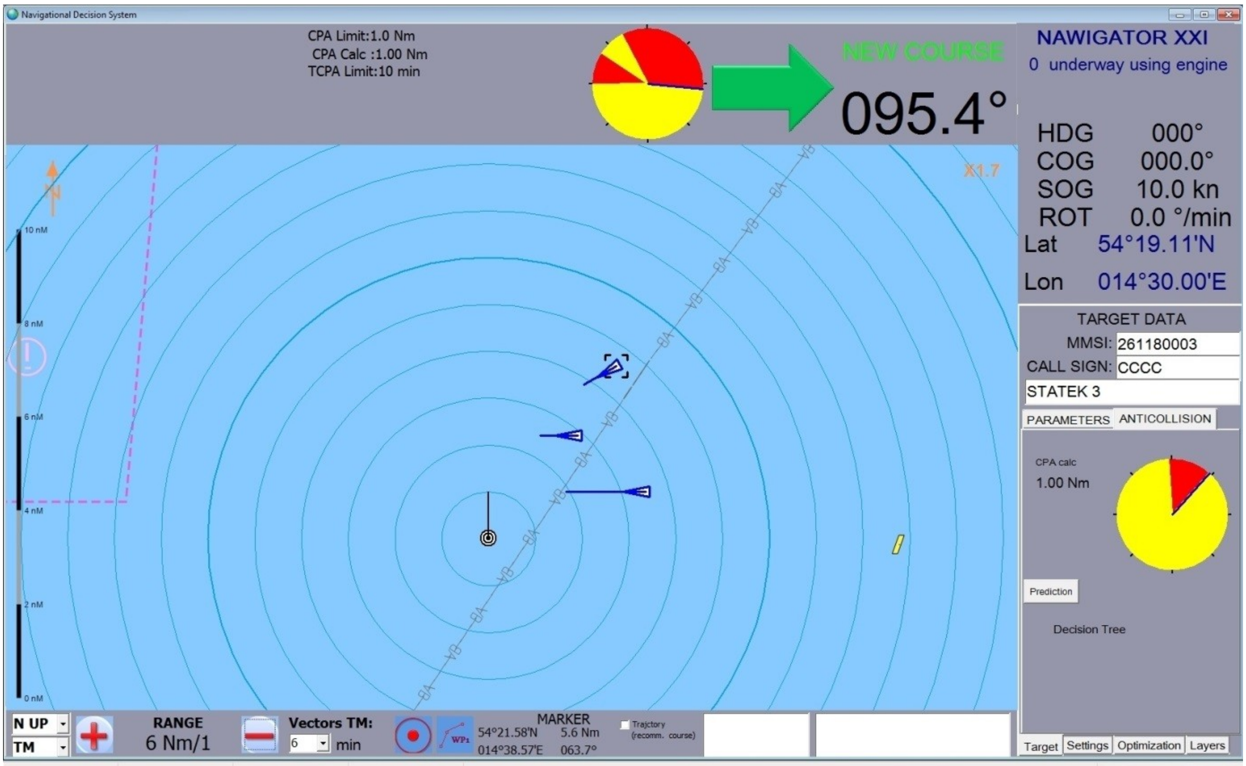

Fig. 8. Presentation of a global solution of an example collision situation and solutions relating to one selected target (ship 3) – screen two

Conclusions

This author describes a presentation algorithm for acceptable solutions to navigational situations, used by sea-going vessels. The algorithm, implemented in the navigational decision support system NAVDEC, is one of the principal components of the system's main innovation. A clear and comprehensible prompt for the navigator is essential in collision situations involving a number of participants. Field research done onboard the m/v "Nawigator XXI" has confirmed that the proposed algorithm is useful and verified its correctness.

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