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PRACTICAL ASPECTS OF USING RADAR IN MARITIME NAVIGATION WITH ANALYSIS OF ITS POTENTIAL ERRORS AND LIMITATIONS

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Abstract: In this article, the author will try to explain the basic principles of the practical focus of using radar in maritime navigation, analysing its potential errors and limitations. An attempt will also be made to describe the basic seamanship practice of how to set up the radar, determine the radar blind sectors, calculate the radar position accuracy, generate a basic anti-collision radar report, calculate CPA, TCA, BCR, BCT etc., and verify the effectiveness of a trial anti-collision manoeuvre by using the radar in the different radar modes when navigating in restricted sea areas.

Keywords: radar, ARPA, closest point of approach (CPA), time for closest point of approach (TCPA), bow crossing rage (BCR), bow crossing time (BCT), radar blind sectors, true motion, relative motion, true vectors, relative vectors, sea stabilised mode, ground stabilised mode, parallel indexing (PI).

1. INTRODUCTION

Since radar systems first appeared on the bridges of merchant ships in the 1950s, they have undergone considerable change, both in their technology and in their functionality [Bilden and Norris 2008; Brunicardi 2012]. They have changed from being an occasionally used aid, brought into play in unusual and difficult navigational circumstances, to central and always available tools on watchkeepers' consoles [The American Practical Navigator Bowditch 2002; Wróbel 2019]. The presentation of radar information to the officer of the watch (OOW) has undergone considerable modernisation and computerisation [Brunicardi 2012]. Recent new performance standards produced by the IMO [IMO 2004; IMO SN/Circ.243 2004] have recognised this changing technology [Brunicardi 2012]. In fact, the OOW [STCW 2010] shall know how to set up the radar, how to determine the radar blind sectors, how to calculate the radar position accuracy, how to generate a basic anti-collision radar report, and how to calculate the CPA, TCA, BCR, BCT, etc.

Unfortunately, evidence [Brunicardi 2012] and practice [MCA 2007; Rutkowski 2019; Wróbel 2019] indicates that these activities are not always known or properly understood, resulting in numerous comments on observations and/or nonconformities being made during maritime inspections (Port State Control, vetting, etc. [VIQ Vessel Inspection Questionnaires for the Oil Tankers 2017; Maersk Line Internal Documentation 2018; Teekay Shipping SA 2019]). The author's intention in this paper was to prepare a short guide for OOW about the basic principles of using radar and ARPA, and describing their limitations.

2. THE USE AND LIMITATIONS OF RADAR

Radar (from radio detection and ranging) is a radio system which measures distance and usually direction by comparing reference signals with radio signals reflected or retransmitted from the target whose position is to be determined [Bilden and Norris 2008; Brunicardi 2012]. If the radar is also equipped with a tracking computer, called an **ARPA** (Automatic Radar Plotting Aid) [IMO 2004; Brunicardi 2012], it helps in tracking targets when assessing navigational situation awareness (CPA, TCPA, BCR, BCT). For shipboard navigational applications, pulse-modulated radars are used. In this type of radar, the distance to the target is determined by measuring the time required for an extremely short burst or pulse of radio-frequency energy to travel to the target and return to its source as a reflected echo. Directional antennas allow the direction of the target echo from the source to be determined [IMO 2004; Bilden and Norris 2008; Brunicardi 2012].

Most of the main requirements and legal provisions for radar equipment and ARPAs are included in the SOLAS convention [SOLAS 2019] with amendments, the STCW convention [STCW 2010], and a number of IMO Resolutions [IMO 2004; IMO SN/Circ.243 2004] (i.e. MSC.192(79) Annex 34 "Adoption of The Revised Performance Standards for Radar Equipment", A.422 (XI), A.823(19) etc.).

According to the SOLAS requirements [SOLAS 2019], all ships of 10,000 GT and upwards shall be fitted with 2 radars, each being capable of being operated independently of the other, and one of which must be capable of operating at 9 GHz (3 cm, X band), to determine and display the ranges and bearings of other surface craft, obstructions, buoys, shorelines, and navigational marks to assist in navigation and in collision avoidance. Usually such ships are fitted with one X-band radar and one S-band radar. X-band radar has a short wavelength (3 cm) for better directivity, and small, light-weight antennas, but with increased attenuation in precipitation than S-band radars. S-band radar has a longer wavelength for long-range detection, a larger antenna than X-band radar, and can penetrate precipitation for much better performance than X-band radar in inclement weather.

The officer of the watch (OOW) shall remember that both visual and radar position fixing and monitoring methods should be used whenever possible. This means that frequent checks should be made of the ECDIS by using a different position fixing system (normally DGPS/DGNSS) [Weintrit 2009; Rutkowski 2018] as well as by the use of radar to check the accuracy of the charted position by comparing the location of the radar target against the charted symbol [IMO SN/Circ.243 2004] plus parallel indexing and/or the use of clearing radar bearings and/or distances [The American Practical Navigator Bowditch 2002; Rutkowski 2019; Wróbel 2019].

The officer of the watch (OOW) is also responsible for checking the operating status of each navigational radar [STCW 2010]. He/she shall adjust the brilliance, gain, sea clutter, and rain clutter in order to obtain the optimum picture, be familiar with the radar's limitations, radar horizon (the sensible horizon of a radar antenna), radar blind sectors, and radar effectiveness.

Examples of radar limitations are as follows [Rutkowski 2019]: the minimum range is given by a ½ pulse length (typical error = 15–20 m) over a short range, the range accuracy is given as a percentage of the radar range and the installation calibration (typical error = 5–15 m), antenna location (setup), beam width (typically 1 x 30° (-3db)/approx. 2 x 60°(-6db), geometric dependent measurement at a short range, bearing accuracy is given e.g. by the gyro limitations (reference high latitude problems), shadows and multiple ghost echoes close to the ship, stabilising is dependent on the gyro, log and GPS/GNSS performance.

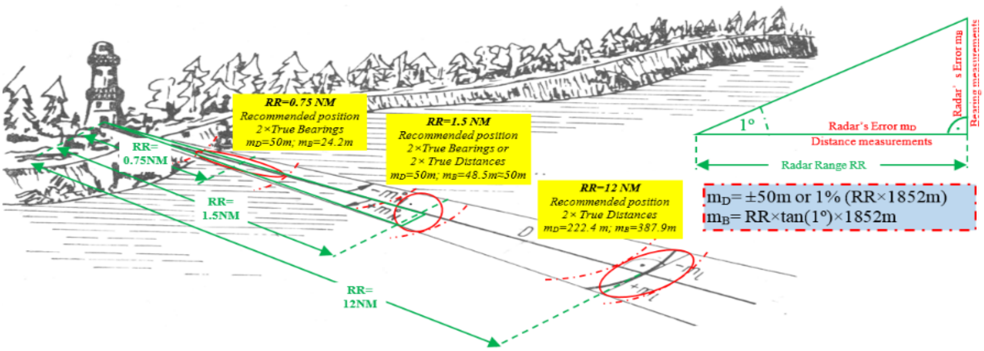


Fig. 1. The graphical method used for the Radar error m_D and m_B with reference to Radar Range (*RR*)

Source: Author's own research based on [Rutkowski 2019].

The accuracy of a fixed position obtained by radar with a probability P = 95% can usually be calculated as $m_D = \pm 50$ m or 1% of the radar range (RR) with reference to the distance measurements, and $m_B = \pm 1°$ with reference to the bearing measurements (e.g. gyro error). In such a case, the error for the distance measurements can be calculated as $m_D = \pm 50$ m for RR≤1.5 NM, and 1% of the RR for RR>1.5 NM. For RR=3 NM, it will be m_D = 55.6 m, and for RR = 12 NM, it will be m_D = 222.4 m. With reference to the measurements of bearing, the total error (m_B = RR×tg(1º)×1852 m) will be calculated accordingly as m_B = 24.2 m for RR = 0.75 NM, m_B = 48.5 m for RR = 1.5 NM, m_B = 97 m for RR = 3.0 NM, m_B = 387.9 m for RR = 12 NM, etc.

Considering **radar accuracy** [IMO 2004] for larger radar ranges (usually RR>1.5 NM), it is always recommended to use the radar distances techniques for position fixing and monitoring [Rutkowski 2019]. By using this method, the position fixing error can be reduced. It is also recommended to use simultaneous bearings techniques for radar ranges smaller than 1.5 NM [Rutkowski 2019]. Both methods can be used, i.e. two bearings and/or two distances techniques, at a radar range of RR = 1.5 NM for position fixing and monitoring [Rutkowski 2019]. The error for position fixing at a radar range of RR = 1.5 NM will be more or less the same, that is to say, about 50 m.

The effectiveness of the radar measured using a **Radar Performance Monitor** should be recorded by the OOW at the end of each watch whenever the radar is operational to ensure that optimal efficiency is being maintained. Radar minimum performance standards are set by the IMO Resolution MSC 192(79) Annex 34 “Adoption of the Revised Performance Standards for Radar Equipment” [IMO 2004].

A numerical, percentage, graphical, or other measurement value should be recorded. Records should be maintained whether the vessel is on an international voyage or not. This is not only a question of good practice [Maersk Line Internal Documentation 2018; Teekay Shipping SA 2019]. There are also the Oil Companies International Marine Forum (OCIMF) requirements (for reference, see i.e. VIQ Vessel Inspection Questionnaires for the Oil Tankers, Combination Carriers, Shuttle Tankers, Chemical Tankers and Gas Carriers [VIQ Vessel Inspection Questionnaires for the Oil Tankers 2017]).

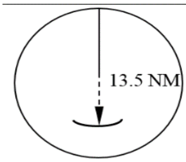
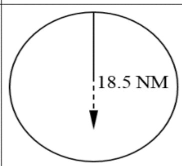
Display	Radar State	Display	Radar State
	Transmitter: Normal Receiver: Normal		Transmitter and receiver: 10 dB loss, Echo is not visible

Fig. 2. Radar performance test result [Rutkowski 2019]

The OOW needs to turn on the performance monitor referred to in the appropriate paragraph in the radar’s manual, and after observing the results, should turn the performance monitor back off [IMO 2004; Rutkowski 2019]. As an example in Figure 2, the radar range scale is automatically set to 24 NM. The radar screen will show one or two arcs. If the radar transmitter and receiver are in good working condition, the innermost arcs should appear between 13.5 and 18.5 NM. The performance monitor can observe a total of 10 dB of loss in the transmitter and receiver. The lengths of the arcs may vary according to the installation environment. The OOW needs to judge the strength of the echo which appears within 90° behind their own ship to confirm if the radar is working properly or not.

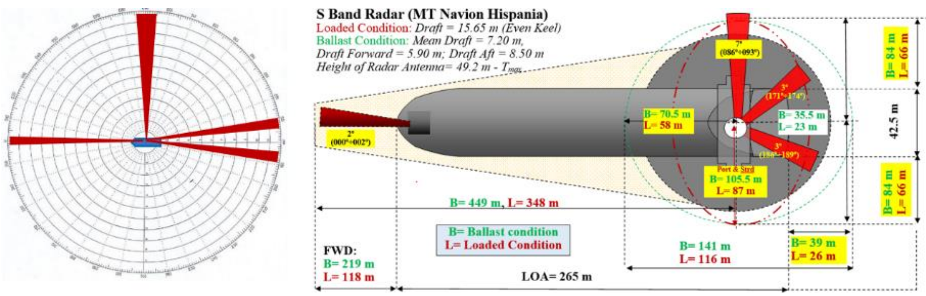


Fig. 3. The Radar blind sectors form commonly used in the shipping industry (on the left) and the Radar blind sectors recommended by the author prepared for mt Navion Hispania in May 2018

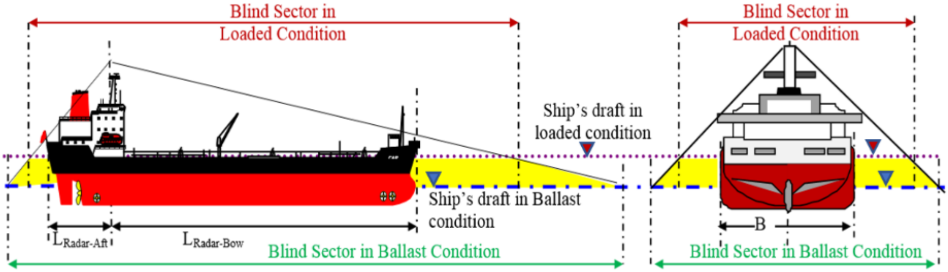


Fig. 4. A practical method recommended by the author to determine the Radar blind sector and shadow areas around the ship by means of the ships drawings, General Ship Arrangement Plan, and/or Thales' theorem

Source: Author's own research.

Another point, and quite an important matter to discuss, is the **Radar Blind Sectors**. In some operational sectors (relative bearings) and/or distances of the ship's radar especially at low radar ranges (RR), the loss of targets/echos may occur. Unfortunately, the evidence [Maersk Line Internal Documentation 2018; Teekay Shipping SA 2019] as well as experience [VIQ Vessel Inspection Questionnaires for the Oil Tankers 2017; Rutkowski 2019] have also shown that on most of the ships in the shipping industry, the radar blind sectors and/or "shadow distances" are not available and/or not prepared properly (see Fig. 3 and 4).

If the radar blind sector on your ship is described as can be seen in the form on the left of Figure 3, this means that your form is not completed and you still need to specify the additional areas around your ship where the radar is not able to detect a target, due to the ship's hull construction, the radar antenna position etc. In such a case, the radar blind sectors and shadow areas all around the vessel shall be obtained (calculated and/or described) for each direction (forward, aft, port, and starboard) and calculated at least for a normal ballast (minimum draft) and the normal loaded (maximum draft) conditions. The final result can be presented or described as seen on the right of Figure 3.

To specify those blind sectors and shadow areas all around the vessel, you can use a simple mathematical formulae (i.e. the intercept theorem, also known as Thales' theorem) and/or determine the blind sectors and shadow areas by means of a graphical method i.e. by using ship's drawings and/or the General Ship Arrangement Plan (see Fig. 4).

3. THE USE OF RADAR FOR COLLISION AVOIDANCE

It must be noted that the use of radar and an ARPA as aids to collision avoidance [COLREG 1972; MCA 2007; STCW 2010], particularly in poor visibility, must not detract from the requirement that a good visual lookout is kept. If the task is going to preoccupy your time, post a lookout [COLREG 1972; STCW 2010; Rutkowski 2019].

Table 1. Advantages and limitations of radar and direct sight when maintaining a proper lookout at all times

Advantages of Direct Sight	Advantages of Radar
Reliable, sensitive to colour, can assess aspects, can identify small targets, can see light configuration, can assess ship types, can identify some conspicuous marks, can identify the flashing lights, has better discrimination, can see the changing weather patterns, can see the effects of the sea on vessels, not affected by blind arcs (if the observer moves)	Generally reliable, does not get tired, produces accurate range information and a stable bearing platform, simplifies overview, can penetrate fog, has better penetration in rain and snow, is useful for predictive collision avoidance, predictive navigation (parallel index), can have a longer range (height of the aerial), an excellent tool when cooperating with AIS and ECDIS
Limitations of Direct Sight	**Limitation of Radar**
Poor at assessing distance (worse at night), subject to night adaptation, degradation through glare, gets tired while searching, binoculars needed for early identification, other environmental phenomena influencing eye accuracy, such as fog, rain, darkness (a dark unlit object cannot be seen with the eyes), the influence of environmental conditions on human health and perception, limited field of view etc	Radar blind sector, misses some small targets, can miss substantial targets in a clutter, can de-tune, prone to inherent and input errors, targets need transponders for positive identification, is prone to interference, cannot discriminate as well as direct sight, cannot identify ship types as well sight, cannot assess the aspects immediately, bearing less accurate than a compass

Source: Author's own research.

Table 1 shows the advantages and limitations of radar and direct sight when maintaining a proper lookout at all times.

Another issue with which the OOW should be familiar is the correct settings of the radar (to adjust the brilliance, gain, sea clutter, and rain clutter to obtain an optimum picture), and how to use the radar for trial maneuvers. History shows us that a lack of knowledge regarding the proper set-up of the radar and/or even a misunderstanding of the navigational situation presented on the radar screen may be a direct cause of some navigational incidents leading to ship collisions at sea [Bilden and Norris 2008; Brunicardi 2012; Rutkowski 2019].

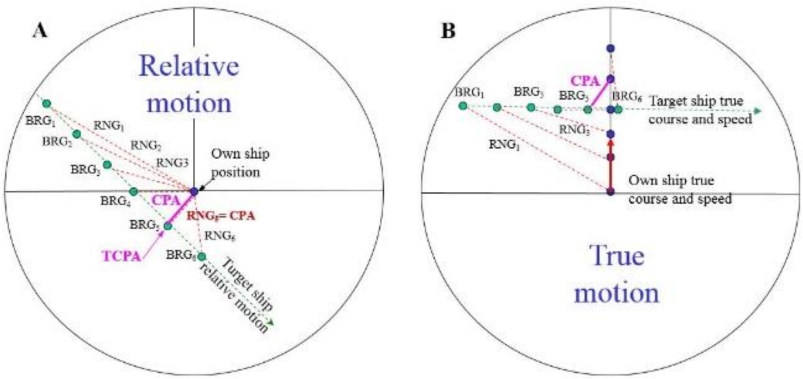


Fig. 5. Practical method used determine the "risk of collision" by means of CPA & TCPA on radar set on relative motion (A) and true motion (B)

Source: Author's own research.

According to Rule No. 7 of COLREG [COLREG 1972], the risk of a collision shall be deemed to exist if the compass bearing of an approaching vessel does not appreciably change. Such a risk may sometimes exist even when an appreciable bearing change is evident, particularly when approaching a very large vessel or a tow or when approaching a vessel at a close range.

Figures 5 presents a practical method used to determine the risk of collision by means of CPA and TCPA on a radar set on relative motion and true motion. Figure 6 depicts a typical radar (ARPA) risk of collision report, which includes bearing to a target (BRG), range to a target (RNG), target closest point of approach (CPA), time to closest point of approach (TCPA), target aspect (A), target bow crossing range (BCR), target bow crossing time (BCT), target heading (HDG), and target speed (SPD). In addition, when the radar is integrated with an Automatic Identification System (AIS), it can also recognise a target course through water (CTW), a target speed through water (STW), a target course over ground (COG), and a target speed over ground (SOG).

The ship's radar display can be set on true motion or relative motion. In **relative motion**, we can choose the following modes of display: north up stabilised, head up unstabilised and course up stabilised. Your own ship can be displayed at a fixed position on the display either centred or off-centred.

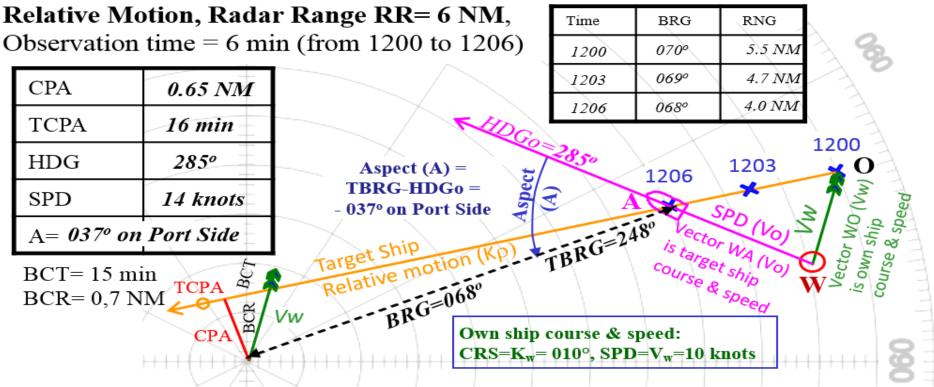


Fig. 6. A practical method used to formulate a typical radar (ARPA) risk of collision report by means of a radar set in relative motion

Source: Author's own research.

In **true motion**, we can choose the display mode with a true motion moving origin or a true motion fixed origin. Both modes can be sea or ground stabilised. Both can be north up or course up.

In a moving origin display, the ship moves across the display until it reaches a pre-defined distance from the edge of the screen, at which point it then jumps to an initial starting position. Before the advent of ARPAs, these display modes were reasonably named; now they should only be considered to be a name for whether the ship remains in a fixed position on the radar display, or whether it moves across the screen.

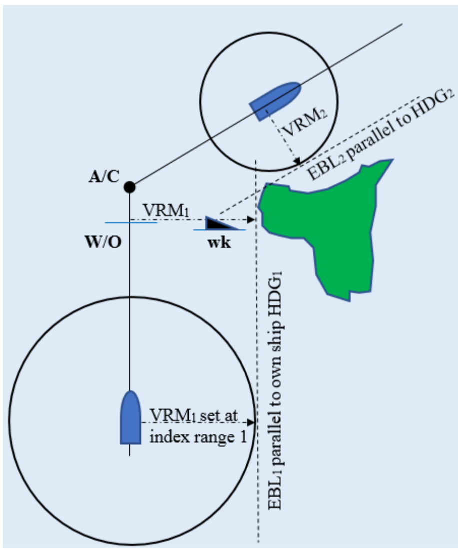


Fig. 7. The use of radar for Parallel Indexing

Source: Author's own research.

Parallel Indexing (PI): On a relative motion display, the PI line will remain static. On a true motion display, the PI line moves across the display with the same motion as the ship. Although normally used in a north up configuration, PI can be used in any orientation mode (Fig. 7).

Target vectors in true motion or relative motion mode can be either true or relative, and therefore the displayed vectors do not change their reference when changing between display modes. On a radar screen, we can also select a sea-stabilised display or a ground-stabilised display.

Sea stabilisation shows the ship's course and speed through the water, and no allowance is made for water flow (tide stream & current).

Ground stabilisation shows the ship's course and speed over the ground, where allowance is made for the tide stream and current.

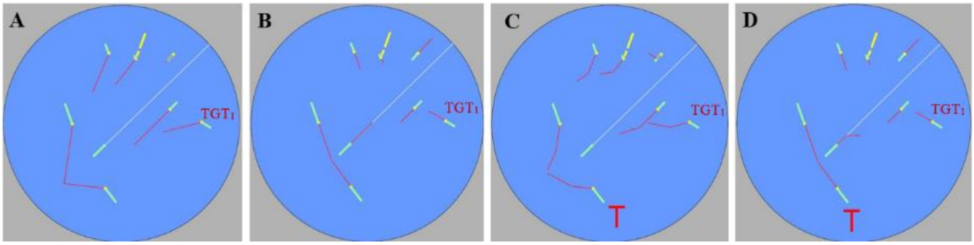


Fig. 8. The same navigational situation presented on radar screens set north-up, with a ship heading of HDG=045°, where target TGT_1 generated a potential risk of collision (small CPA) and a Trial Manoeuvre of a 45° alteration to starboard is presented on radar screens set on True Motion with Relative Vectors (A, C), and True Motion with True Vectors (B, D)

Source: Author's own research.

In Figure 8, we can compare the same navigational situation presented on radar screens set north-up, with a ship heading of HDG = 045°, where target TGT_1, generated a potential risk of collision (small CPA). The radar mode has been set on true motion with relative vectors (Fig. 8A), and true motion with the true vectors (Fig. 8B). In addition, Figure 8 presents the trial manoeuvre effect of a 45° alteration to starboard on radar screens set on true motion the relative vectors (Fig. 8C), and true motion with true vectors (Fig. 8D).

Figure 9 shows a comparison between a ship water track, a ground track, the sea-stabilised true vector, and a ground-stabilised true vector. In Figure 10, one can observe how to use the radar to plan a maneuver with the ship course and speed when considering the declared safe distance of passing, and the time necessary to carry out the anti-collision maneuver. When we use radar for the CPA and TCPA calculations, it is recommended that all target ranges and bearings are plotted at equal time intervals, i.e. every 6 minutes. There is also a recommendation to use a radar with ARPA, AIS and ECDIS integrated together [Weintrit 2009; Rutkowski 2019]. If the input into the ARPA is our own vessel course and speed through the water, the target outputs, both alphanumerical and vectors, are the course and speed through the water.

If the input into the ARPA is our own vessel's course and the speed over the ground, the targets outputs are the course and speed over the ground. Input errors in ARPA can be the heading, speed, or both. A speed input error and/or course input error changes the output of the target true course and speed. An error in speed input produces a large error in the course output and a small error in the speed output. An error in the course input produces a large error in the speed output and a small error in the course output. However, the relative motion and CPA will always be correct.

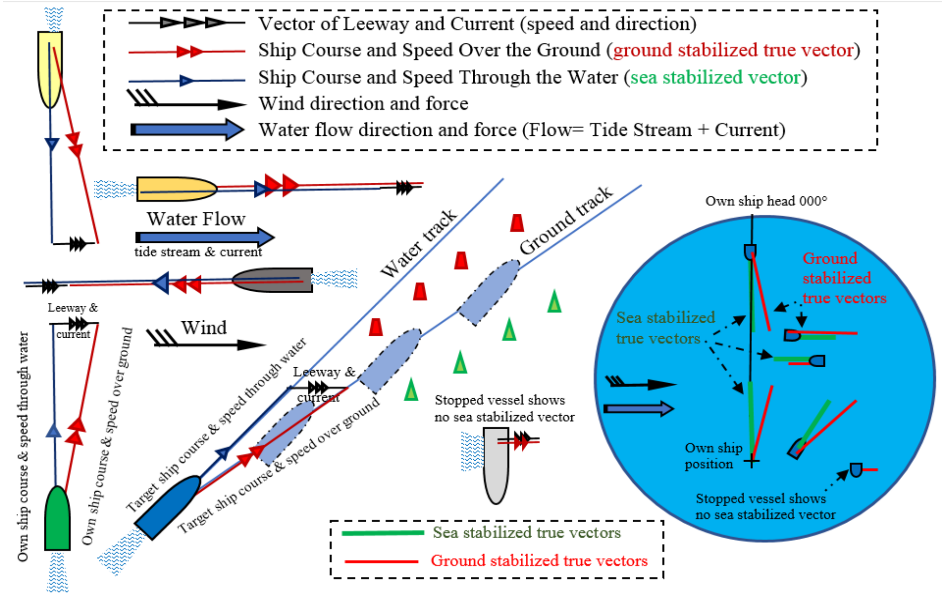


Fig. 9. Comparison of the water track (sea stabilised true vector) and ground track (ground stabilised true vector)

Source: Author's own research.

We must also remember that according to the Maritime and Coastguard Agency (MCA) recommendation MGN63, **sea-stabilised displays** should be used on radar **for anti-collision**, as the operator is able to get an accurate focus on the target, i.e. they know the target's heading. **Ground stabilised displays** should *NOT* be used for any anti-collision work, only **for pilotage and navigation** [MCA 2007; Rutkowski 2019]. Nowadays, modern radars give us unparalleled choice of configurations [Bilden and Norris 2008; Brunicardi 2012]. Automatic clutter suppression mode, even when close to land, totally eliminates the need to adjust the radar gain as the operator changes the range or pulse length [The American Practical Navigator Bowditch 2002].

The operator is left free to concentrate on the important navigation activities without the distraction of optimising the marine radar settings [Brunicardi 2012]. As you gain experience, you will become comfortable with your own radar set-up with regard to the display modes, etc. When selecting an operating range, one shall bear in mind the visibility and closure speed with other vessels. If off-centred too far, there is a risk of missing fast targets approaching from astern [Rutkowski 2019].

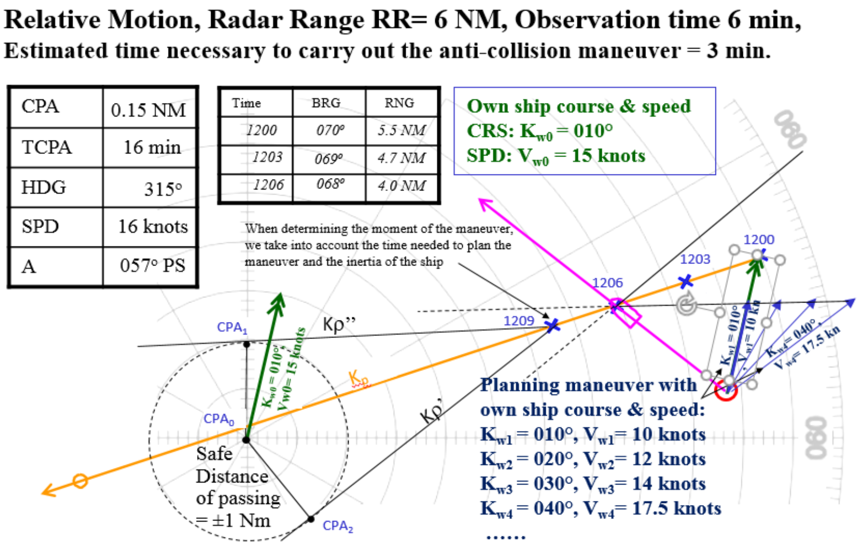


Fig. 10. The use of Radar for planning a maneuver with our own ship course and speed when considering the declared safe distance of passing and the time necessary to carry out the anti-collision maneuver

Source: Author's own research.

4. CONCLUSION

The officer of the watch (OOW) is responsible for checking the operating status of each navigational radar. They shall also know how to set up the radar, how to determine the radar blind sectors, how to calculate the radar position accuracy, how to generate a basic anti-collision radar report, calculate CPA, TCA, BCR, BCT, etc. In the case of errors and/or disturbances in the operation of the radar or other navigation devices, the captain of the ship should be immediately informed and an appropriate record should be made in the ship's log.

According to good seamanship principles, it is also recommended that every navigational officer is requested to check frequently on each watch radar's performance (performance monitor), the radar working mode, radar configuration, heading marker, heading marker alignment, VRM against fixed range rings, EBL against visual bearings, etc. In fact, these activities are not always known or properly understood, resulting in numerous observations made during maritime inspections. This paper has been prepared as a short guide for OOWs about the basic principles of practical focus of mariner's radar usage in real waterways.

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