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The Impact of the Offshore Wind Farm on Radar Navigation

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ABSTRACT: Offshore wind farms can improve safety at sea because they are clearly visible landmarks at sea. Although they limit the sea area available to sailors and ships, they will increase the scope of observation of the sea traffic from land, constitute additional landmarks and, thanks to the installation of additional devices in their waters, expand the area of communication between ships and land services, and increase the scope of information on sea traffic available to the services. They also practically do not limit the possibility of observation through the farm's reservoir.

1 INTRODUCTION

In the area of Ławica Słupska, several Offshore Wind Farms OWF are planned to be built and they are to cover an area of about 10 nautical miles wide and 50 nautical miles long. The mainstream of ship's traffic through the shoal leads in the W-E direction to the south of the planned investments, but there will also be designated passages in the N-S direction between individual OWF. Activities related to safety at sea are corrected by the Maritime Office, but they are agreed with the Navy and Border Guard, as well as with the sea rescue service. The requirements of these institutions will change as the period considered is 30 years or more.

The issue of the impact of OWF on the safety of navigation should be considered in two aspects. Shipping near OWF and inside the wind farm. Each of these issues should be related to three stages:
– power plant construction,
– operation and exploitation,
– demolition.

During the construction phase, the offshore wind farm area is closed to navigation and the investor is to secure this area. Inside, there are ships servicing investments, and in exceptional cases, the navy, SAR ships. Wind turbines are being built larger and larger and their blades reach a height of over 250 m and observation should be carried out to at least this height.

The construction phase, which will last until approximately 2030. Then the current National Maritime Safety System will be technically obsolete. Until then, broadband Internet will probably be operational in the coastal zone at sea. This will result in a significant increase in the support of the ship by land services in the field of safe ship operation, unmanned ships supervised from the shore will appear, and the traffic of recreational vessels may also increase.

Merchant ship traffic, if it increases, is not much. A rapid development of fisheries should not be expected, if it comes to the example of Norway, i.e., fish farming at sea. The traffic of the ships servicing investments at sea will increase, their cruise routes will cross shipping routes.

One OWF is up to two hundred wind turbines. The distance between them is several hundred meters to over a kilometre. The wind turbine is a foundation slightly protruding above the water, a concrete pillar with a diameter of several meters and a height of over 100 m. On it there is a generator the size of a large single-family house (10 m x 30 m) and propellers with a length of up to 100 m each. One wind turbine covers an area of several dozen hectares. During construction, ships must deliver a huge number of materials, specialized ships will operate on site. Cables should be laid between the wind turbines and the control center (one or more), the main power cable to the shore.

In a few years, after the construction of part of the OWF, the construction will continue at the same time and the transmission of electricity to land will begin. After the construction of the investment is completed, there will be an exploitation phase lasting 20-30 years, if in the meantime we do not withdraw energy production from this source in favour of another technology, e.g., hydrogen energy.

The last stage is the demolition of the OWF and the reclamation of the reservoir. It is difficult to predict anything about this, because by then the farms currently in operation will be decommissioned and the technologies and regulations regulating this process will be developed. It will resemble the construction phase. It will be necessary to use heavy equipment and specialized ships equipped with cranes, as well as ships transporting rubble and other materials to shore.

It is highly probable that the construction and demolition phases will be costly, and much attention will have to be paid to protecting the marine environment. Currently, cables and pipelines are usually left behind after the end of the operation. They will have to be removed, because by then there will be a lot of them, and ecologists are setting their growing demands. Therefore, in the design phase, the length of power cables should be reduced as far as possible, so that there is less to clean up at the end.

When laying the cables, a 12 or 24 core optical fibre should also be laid, because the farm area is to be monitored, the generators are remotely controlled, the power plant is to be marked, illuminated, monitored, the movement of units outside the farm is to be observed and supervised and all these data must be sent to farm control center and onshore to the National Maritime Safety System center in Ustka for other services. During the operation of the OWF, there may be a need to install new devices, so it is better to ensure remote control and data transmission between the power plants and the control center at the initial stage. The fibre optic network is to ensure data exchange, observation, and control of individual generators.

2 CHARACTERISTICS OF THE RESEARCH AREA

OWF must be marked from the beginning, marked on nautical charts, and the ships are to be kept informed about the ongoing works. The National Maritime Safety System monitors the movement of ships in the Polish Economic Zone. One of the centres is located in the port of Ustka.

It can transmit local navigational warnings about the OWF using the AIS or live messages via VHF radiotelephone, if justified.

2.1 *Navigational markings of OWF*

The requirements of the Maritime Administration will be presented for the OFW markings. At the initial stage, the investment area is to be marked with navigation lights placed on buoys to indicate the boundaries and vertices of the investment. The buoys can be easily moved when the work area increases. In addition, the Maritime Office in Gdynia may require the marking of the water area with RACONs to identify navigational marks on the radar. They will be placed on the same buoys. The area is also to be marked with AIS devices.

Information on sea charts is provided by the Hydrographic Office of the Polish Navy. It also transmits navigational information to other countries. The investor is to provide data on constructions constituting obstacles to navigation. During the construction phase, wind turbine structures must be built, generators installed and power cables between the generators and the switchgear, fibre optic cables from the generators to the control center and the main power cable and fibre optic cable from the farm to the shore networks.

2.2 *OWF's monitoring*

Currently, one transmitting device is used for this purpose, which can generate several AtoN characters for, for example, marking the control center as real and the extreme vertices as virtual characters. The real AtoN sign transmits the real-time determined position of the mark on which it has been mounted. The virtual mark data is sent from elsewhere and its current position can be monitored by another system (GPS), or the mark position can be sent regardless of its current position, or the beacon itself can be taken down.

OWF also requires remote monitoring, so CCTV will be installed there. Monitoring around all investments should be carried out comprehensively. If all planned investments are implemented in Ławica Słupska, there is no justification for installing radars, AIS devices, radiotelephones, hydro-meteorological stations separately for the Maritime Office, Border Guard and Navy on each OWF.

The radars working at KSBM are Terma 2001i, a very reliable and high-class device, the Border Guard had older Terma 2000 devices in stock, also very good and proven at VTS Zatoka Gdańska, which were replaced with the 2001i model. Their price is proportional to the technical parameters. Currently, it is planned to replace them with an even newer model.

The works inside the OWF take place in a closed area and can be organized efficiently and without collisions, while the laying of cables ashore will at some stage cross the TSS, and then it is especially important to ensure current information for ships navigating there. In addition to the warnings provided by the shore services, the assistance of the supervising vessel is required, which informs the vessels approaching the place of laying the cable on an ongoing basis about the activities carried out and, if necessary, intervenes, forcing the vessel to change course.

Vessels employed for the construction and operation of the OWF should be equipped with AIS devices. This device informs about the presence of other units and facilitates establishing communication with them. The OWF area is marked with traditional navigation marks. Once the constructions of the offshore wind turbines are built, they are properly painted and illuminated (red flashing light), which ensures their very good visibility.

On the radar, OWFs are shown from distances exceeding 20 nautical miles as polygons consisting of many point echoes. Problems with the radar observation occur during heavy precipitation when the detection range decreases drastically.

Surveillance inside the OWF is carried out by the owner and includes supervision of the works carried out there and protection against unauthorized intrusion, and the tracking of vessels passing in its vicinity. For this purpose, remotely controlled optical cameras are used, which will provide much more information than radar. In addition, there may be infrared cameras that enable observations also in limited visibility.

The range of the camera is related, so you need to choose the right compromise. The cameras are remotely controlled from the farm control center. The image from the cameras can be made available to land services. During the SAR operation, the image of the cameras can be very helpful for the rescue services. The procedure to be followed in different scenarios should be agreed with the relevant institutions. The use of radar to observe the situation inside the OWF does not seem advisable. Currently, land services use Danish Terma radars (type 2000i).

The radar allows to track vessels at sea and automatically determine their movement parameters and detect the risk of collision with the OWF elements early. Therefore, they should be used to control traffic near OWF. In relation to small vessels that manoeuvre quickly, this device does not work. But the collision of a yacht or a motorboat with the structure of the offshore wind turbines will not cause damage to the power plant and pollution of the sea. OWF, similarly to the Baltic Beta & Petrobaltic platforms, can be a station for the installation of the devices of the Maritime Office, Border Guard or Navy to extend the traffic monitoring area along the Polish coast and/or in the Polish Economic Zone.

The scope of the activities should be agreed between the institutions concerned. The fibre optic network built by the investor enables the transmission of data and images and connecting it to the fibre optic bus along the coast, which is at the disposal of the maritime administration.

The AIS base station will increase the range of marine traffic monitoring around the OWF. The cost of the AIS base station is low and will significantly increase the range of the system. Installing one or two stations (north and south sides, or tops) for each farm is expedient.

The OWFs are located mainly close to Ławica Słupska, north of the TSS traffic separation zone. Table 1 shows their distances from important points.

Each of the discussed OWFs occupies an area of several dozen square kilometres. One radar installed at a height of 20-30 meters can cover the entire area, but the construction of wind turbine will create radar shadow sectors, which may result in missing small targets. Therefore, the concept of installing two devices should be applied, one on the southern side of the OWF to improve the observation of traffic on the TSS and the other on the northern side of the OWF to increase the radar monitoring area in Polish Economic Zone.

Table 1 – Distances of the selected facilities from OWF (Baltic II & Baltic III)

	Objects	BS II [Nm]	BS III [Nm]
1	Wymiar WE	6,00	9,60
2	Wymiar NS	7,20	5,00
3	Lane NE	13,50	1,10
4	Lane SE	16,00	5,50
5	Lane NW	7,00	11,60
6	Lane SW	11,40	13,00
7	Lth. Czołpino	19,20 – 27,50	13,30 – 19,50
8	Lth.Łeba	25,00 – 33,50	12,500 – 19,5
9	Lth. Ustka	26,00 – 32,60	26,00 – 34,00

2.3 *Presentation of OWF on the navigation devices*

Currently, electronic chart and navigational information systems - ECDIS (Electronic Chart Display and Information System) or integrated systems INS or IBS are commonly installed on ships. They allow the presentation of multiple data on the indicator or different sets of data on different screens. OWF areas are very well marked on navigation charts, but excess data on one screen is a bad idea. Some examples are shown below.

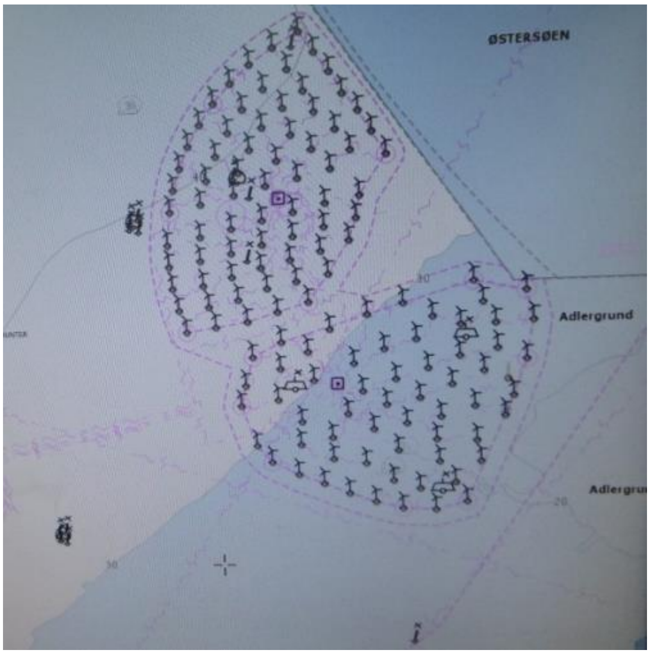

Figure 1. OWF on ECDIS screen

Figures 1 shows an image of an electronic map with two wind farms located in German waters on the Pomeranian Bay. The position of each wind turbine and the routing of the submarine cables are marked.

Figure 2 shows the image on the screen of the ECDIS.A radar image overlay (the echoes marked by red) and data from the AIS system (the ship is marked with an isosceles triangle) have been applied to the nautical chart background. The distance of the ship on which the photo was taken from the farm exceeds 3 nautical miles. The image of the echoes is clear, and it is easy to identify which echo comes from which object.

Figure 2. OWF on ECDIS screen with AIS

The range of 24 nautical miles of the radar operation corresponds approximately to the chart scale of 1:200,000. Figure 3 shows the image of the same farm as in Figure 2, but the SAM Electronic integrated bridge indicator shows the night image. It is illegible, due to the wrong colour palette, the radar image is lost. The radar echoes are red, but the black background and the excess of white symbols make this image unusable.

Figure 3. OWF on ECDIS screen with night mode, range 24 nautical miles

Figure 4 shows the image after correcting the color palette. The radar echoes of OWF are easy to recognize, but the echoes of small objects such as a fishing boat or a yacht remain invisible in the radar image superimposed on the map background.

Figure 5 shows the same image as before, but with a working range of 12 nautical miles. The number of symbols shown has been reduced, making the image more usable. There is a radar echo to the south of the home ship and an AIS symbol delayed to it. It is likely that the ship is moving at a slow speed and the AIS data is transmitted less frequently. (A small boat with a class B AIS device transmits every 30 seconds). Many soundings are displayed on the screen, which makes the radar image very poorly visible.

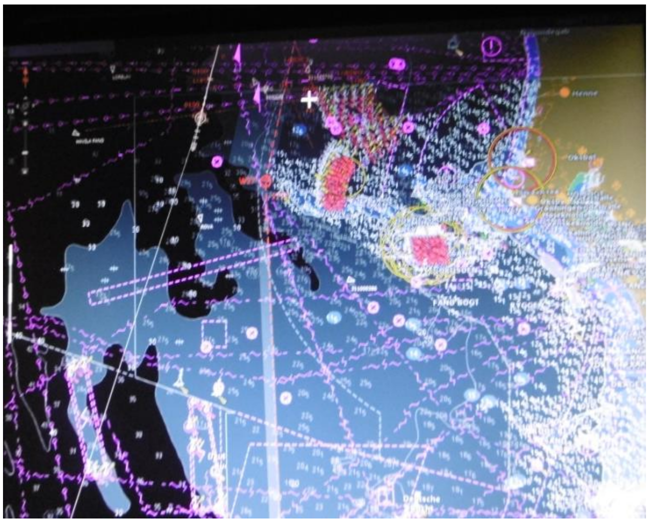

Figure 4. OWF on ECDIS screen with night mode

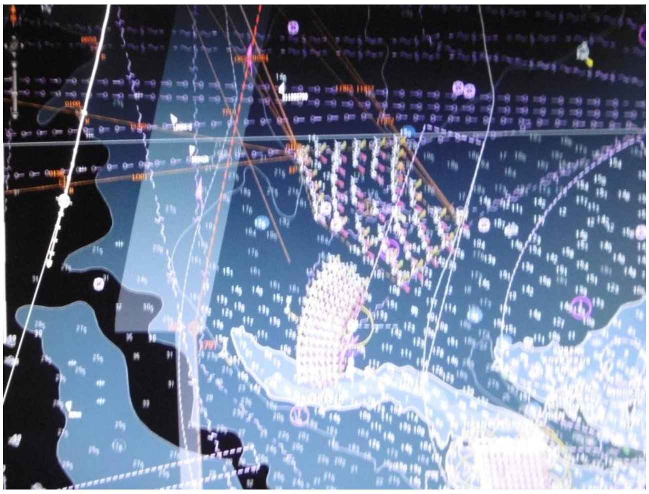

Figure 5. OWF on ECDIS screen with night mode, range 12 nautical miles.

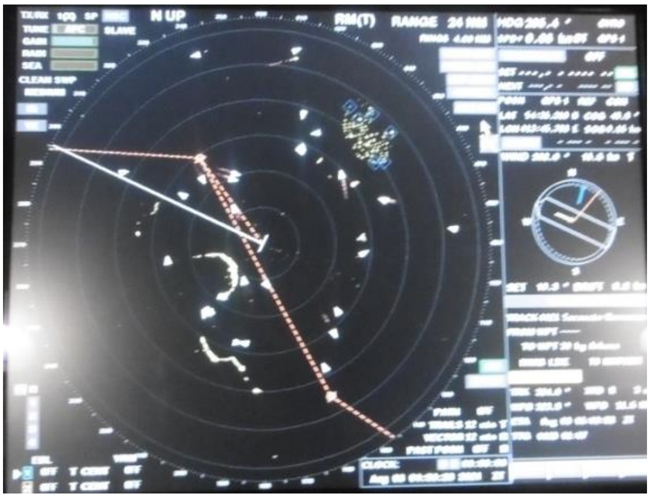

Figure 6. OWF on radar's screen

Figure 6 shows the same situation as in Figure 3 - 5, but only the radar image is presented on the indicator on the integrated bridge and the planned route of the ship has been marked. The presented AIS symbols are also shown. The echoes of two OWFs are shown in the upper right of the screen. The adjustment of the image on the screen and the appropriate selection of the amount of information presented on the screen are very important.

Figure 7 shows an image of OWF along with the routes of the submarine cables. AIS symbols are also shown.

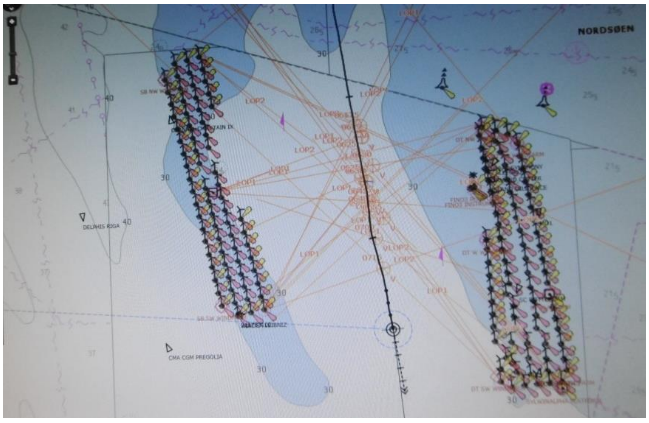

Figure 7. OWFs with power cables connections on ECDIS screen

On Figure 8, in the upper right corner, other wind farms operating in this area are shown along with the ranges of the lights working on the farms. On the same Figure 8 several ships equipped with AIS devices operate inside the construction site. Trade ships can pass between two buildings. Probably in the future, the entire area may be occupied by one large OWF. The OWF is marked with buoys and AIS signs.

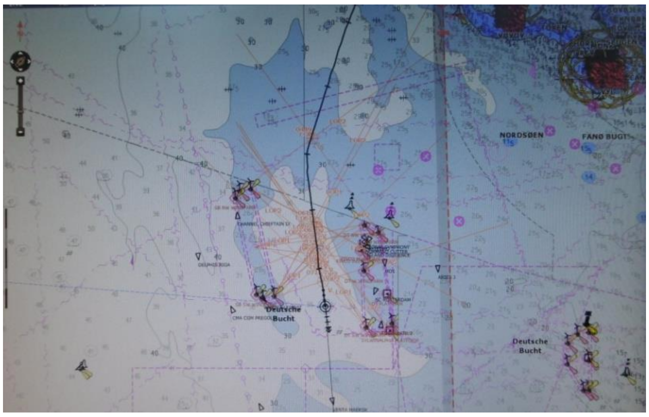

Figure 8. OWF under construction

Figure 9 shows the information about the OWF that we will get on the screen of the electronic chart of the ECDIS system. The name of the OWF, position and designation of the offshore wind turbine, its type and light characteristics are given.

In Figure 10, available information on the ECDIS screen, concerning the marked OWF using the real sign of the Automatic Identification System. Typically, the real AIS sign is installed at the farm headquarters (it broadcasts its position determined by means of a GPS receiver). The same device can send data about virtual characters pointing to farm vertices.

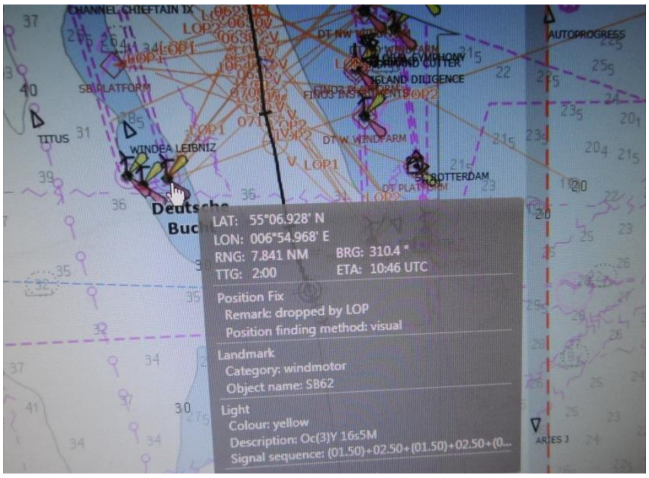

Figure 9. Offshore wind turbine information

Figure 10. Real AIS AtoN information

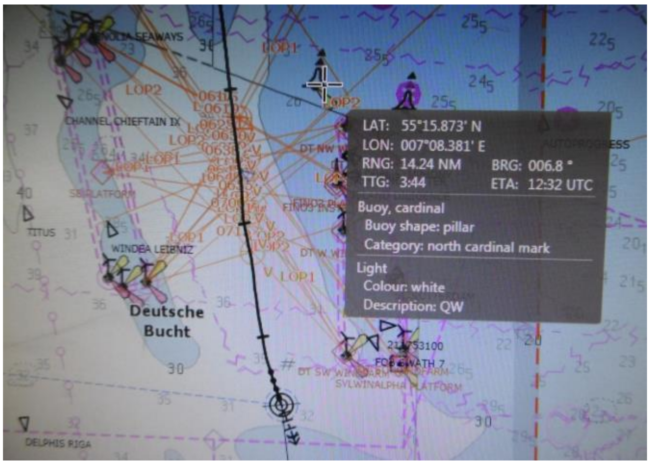

Figure 11. OWF with N cardinal buoy

Figure 11 shows the marking of the northern edge of the OWF with a cardinal buoy.

Figure 12. OWF on the German Bight

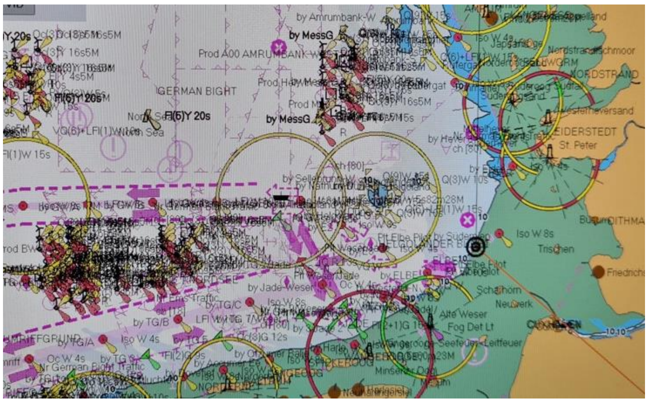

Figure 13. OWF on the German Bight

Figures 12 and 13 show the OWF located on the German Bight, all pictures were made by the authors on board ship Dar Młodzieży in 2021 during onboard training.

3 RESEARCH STUDIES

The computer program CARPET 2.0 (Computer Aided Radar Performance Evaluation Tool), developed by TNO Physics and Electronics Laboratory, was used to carry out the simulations. CARPET 2.0 is an extensive computer program that allows to simulate the propagation conditions in which marine radar, and land devices are used, as well as those installed on e.g., airplanes or helicopters, and define the objects they detect.

The purpose of the simulations is to assess the possibility of detecting an offshore wind farm by ship radar depending on the parameters of the radar antenna, weather conditions as well as the dimensions of the wind turbines. Table 2 presents typical parameters of the ship radar used for simulations.

Table 2. Raytheon NSC34 pulse radar parameters

Parameter	Value	Units
Radar band	X	[-]
The horizontal width of the characteristic	1,2	[°]
The vertical width of the characteristic	23	[°]
Gain	29	[db]
Polarization	horizontal	[-]
Frequency	9410	[MHz]
Pulse length	1,00	[μs]
Pulse frequency	3000	[Hz]
Bandwidth	20	[MHz]
Peak power	25	[kW]

The radar installed to monitor traffic around offshore wind farms is to be remotely controlled and provide relevant data compatible with the system. They are standard because the ship's radar image is transmitted to the electronic charting and navigational information system ECDIS from various manufacturers. However, some manufacturers make exceptions. A composite signal can be used (trigger pulses, analogy, digital, trigger video signals in one package) and an interface that will separate them must be attached. Signals are transmitted between navigation devices using the NMEA standard. The signals are to comply with the IEC 61162-1 standard. It was also issued by the Polish Committee for Standardization - Table 2. The signals are sent via the RS-232c serial link.

This standard allows for free presentation of the data from various devices on any indicators. However, it should be remembered that new versions of this standard are created, but each subsequent version removes all older ones, but older versions may not work with newer ones. That is, the new radar will receive data from the older GPS receiver, but the older radar will not receive the position from the new GPS receiver.

Table 3. Detailed list of the formatters using in navigational equipment [1]

Formater	Explanation
ALM	Data from the GPS almanac
DPT	Depth
GLL	Geographical position, lat/long geographical
HDG	Ship heading, deviation, and magnetic variation
HDT	True Course
HTD	Direction/route control data
MWD	Direction & speed of the wind
MWV	Speed & angle of the wind
OSD	Own Ship Data
ROT	Course Change Speed
RSD	Radar System Data
RTE	Routes
TLL	The latitude and longitude of the object
TTM	Message about the tracked object
VBW	speed through the water & over ground
VDR	Direction & speed of the current
VHW	Speed & course of ship through the water
VLW	Distance made good through the water
VTG	Course & speed over the ground
WCV	Waypoint approach speed
WNC	Distance from waypoint to waypoint
WPL	Waypoint location
XTE	Cross track error
XTR	Cross track error, navigation reckoning
ZDA	Hour and date
ZDL	Time and distance to the moving point
ZFO	UTC and time from the starting waypoint
ZTG	UTC and time to destination waypoint

Table 4. Detailed list of the RSD Radar System Data – example [1]

$ - - RSD - Radar System Data	
x.x	the distance of the starting point
x.x	Bearing of the starting point
x.x	VRM 2, distance
x.x	EBL 2 degree
x.x	Cursor distance from own ship
x.x	Cursor bearing degrees clockwise from 0°
x.x	Distance scale used
a	Distance units K= kilometre, N = nautical miles, S = land miles
a*hh	Image rotation:
<CR> <LF>	C- oriented relative to true course, course relative to the ground, degrees N - oriented to the north, north is true 0° H - oriented relative to the bow, the direction (Centre line) of the vessel 0°

4 SIMULATION DATA PROCESSING

The results of the simulation are presented in the form of graphs of the signals received from objects and disturbances, the probability of the detection as a function of the distance from the object. The probability shows how many times the echo is on the screen, e.g., 80% means that the echo is shown in 4 times by 5 turns of the antenna.

The graph showing the signals received by the radar antenna shows:

- thermal noise in blue,
- useful signal in green,
- signal scattered by the surface of the sea in red,
- purple signal reflected by precipitation.

The computer program used for the simulations defines the effective reflecting surface RCS (Radar Cross Section) as the amplification of the radar signal corresponding to the real value of the reflecting object placed in the center of gravity of the tested object. The useful detection range of an object is defined as the probability of the detecting an object and for marine radars, the probability of correct detection is assumed to be 0,995 and the probability of a false alarm of 10-6, which corresponds to a signal to noise ratio of 20.

In the simulations carried out, an exemplary offshore wind farm was used, the effective reflection surface of which is 350,0 m2. The assumed reflection surface of the power wind turbine is quite small, so the given values of the detection distance may be larger. In all simulations, there is rainfall over 5 - 15,00 km (approx. 2,70 to 8,00 nautical miles).

Because the watch officer most often conducts observations in the range of 12,00 nautical miles, it was assumed in the simulations that the radar transmitter works on a long pulse.

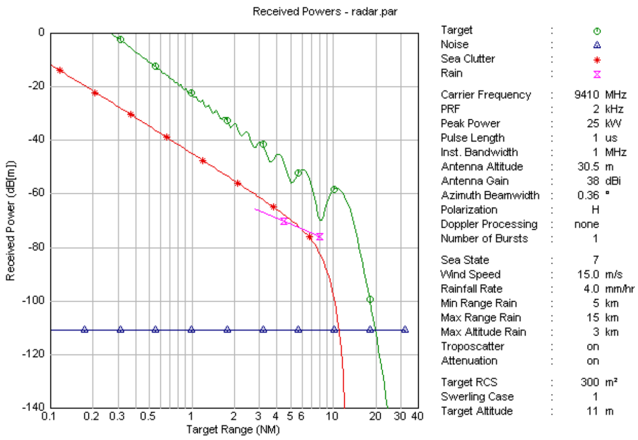

Figure 14. The detection signals of the ship by shore radar in Darłowo

Figure 14 shows a signal for a ship whose effective reflection area is estimated at 300,0 m² and its height is 11,00 m. The level of the signal reflected from the ship exceeds the level of the signal reflected from the sea surface by more than 20 dB. The simulation was carried out for sea state 7, i.e., high disturbance. A similar level of disruption is also caused by rainfall.

Figure 15 shows the probability of the detecting a fishing boat using the radar of the KSBM system in Darłowo for sea state 2. Detection with a probability of 80% is achieved at 13,40 nautical miles, but for smaller distances the object disappears from the screen.

The signal disappears at 5,00 to 7,00 miles from the radar and about 3,00 nautical miles, and short duration dips occur above 1,00 nautical miles. Despite the large detection range of a small object, it is difficult to track it, while the weather conditions are not bad.

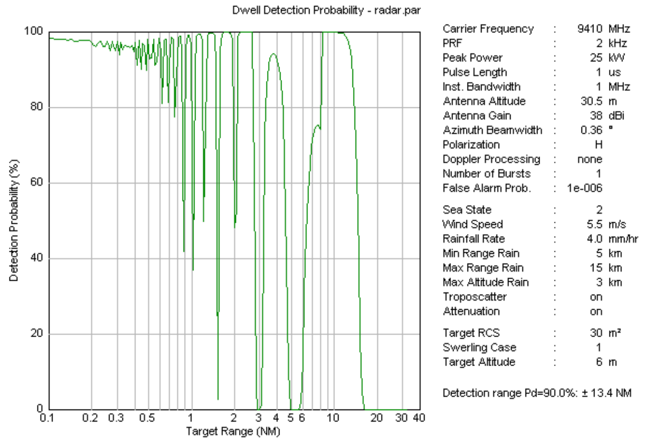

Figure 15. The probability of detecting a fishing boat by shore radar

The diagrams below (Figures 16 – 23) show the possibility of observing offshore wind farms with the use of a ship's radar. Its detection capabilities are lower than those of the shore radars. The study was conducted for three different situations, which are as follows:

- height of the center of the surface 50,00 m, height of the radar antenna 12,00 m, precipitation 4 mm/h,
- height of the center of the surface 75,00 m, height of the radar antenna 20,00 m, precipitation 4 mm/h,
- height of the center of the surface 50,00 m, height of the radar antenna 12,00 m, precipitation 20 mm/h.

A radar antenna height of 12,00 m corresponds to the conditions on a small vessel and 20,00 m on a medium-sized vessel. The higher-mounted antenna allows you to increase the detection range. A rainfall of 4 mm/h is a light rain, and 20 mm/h is a heavy rain.

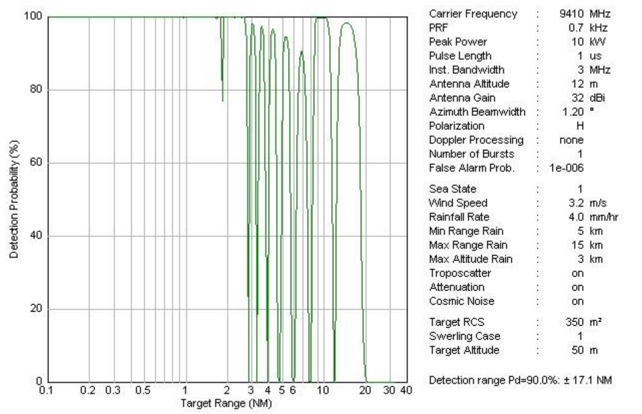

Figure 16. The probability of detecting an offshore wind turbine for the center of the reflection surface at a height of 50,00 m and the height of the radar antenna 12,00 m above sea level, sea state 1

Figure 16 above shows the distribution of the probability of the detecting an offshore wind turbine recorded on a small vessel (e.g., a fishing boat) when the radar antenna is 12,00 m above sea level. For the calculations of the signal reflected from the offshore wind power plant, shown in Figure 16, the precipitation zone occurring at 5 to 15 km from the ship was assumed.

In this zone, the offshore wind farm's reflected radar signal is weakened. In the presented example, it is not important for observing the offshore wind turbine echo on the radar screen. Up to 3,00 nautical miles from the radar antenna, the power plant gives a very good signal, then fluctuations occur causing signal decay caused by interference of the direct signal with the reflected one from the sea surface. The signal disappears at about 18,00 nautical miles, which is over 33,0 km.

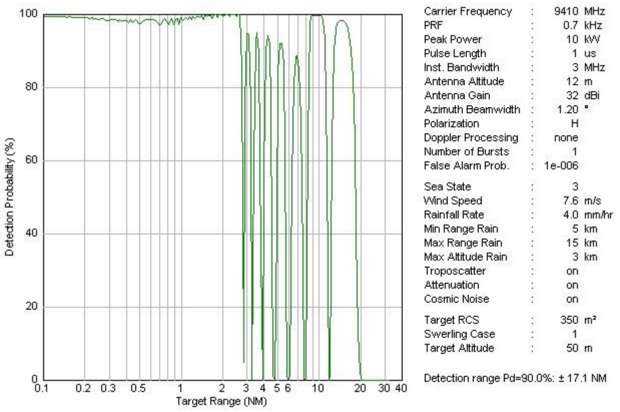

Figure 17. The probability of the detecting an offshore wind turbine, state of the sea 3

A deterioration in detectability can be seen in an area where there is rainfall. It can be assumed that the probability of detecting a wind farm during precipitation, but the maximum detection range is large and amounts to about 18,00 nautical miles. If the ship is closer than 800,00 m from the offshore wind turbine, the antenna illuminates only part of the structure.

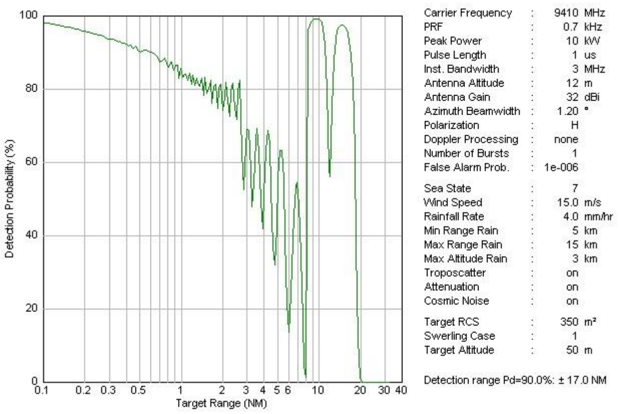

Figure 18. The probability of detecting an offshore wind turbine, state of the sea 7

The probability shown in Figure 18 is for the same offshore wind turbine seen in the previous two cases, but this time at a high sea level of 7. During such a high sea level and rainfall, the radar detects the power plant much weaker. Already at less than 3,00 nautical miles from the radar antenna, interference caused by sea waves reduces the probability of the detecting an offshore wind turbine to less than 80%. Outside the fallout zone, the object is clearly visible up to about 17,00 nautical miles, although at about 12,00 nautical miles, the echo signal weakens.

Figure 19 shows the probability of the detecting an offshore wind turbine 50% taller and observed from a larger ship whose radar antenna is placed at a height of 20,00 m. At 1,60 nautical miles, a slight decrease in the probability of the detection to about 90% can be observed. Fluctuations caused by rainfall are small at the beginning and up to about 3,50 nautical miles the probability of detection remains above 80%. Further in the fallout zone, frequent power plant echo signal disappearances occur. A several-fold decrease in detection at distances from the radar of approx. 12 - 19 nautical miles can be seen outside the precipitation area.

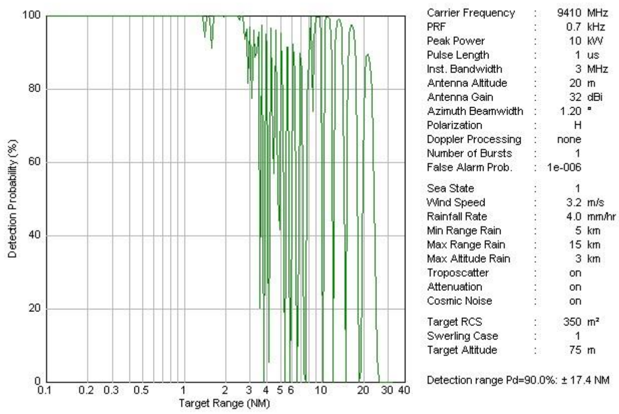

Figure 19. The probability of the detecting an offshore wind turbine for the center of the reflection surface at a height of 75,00 m and the height of the radar antenna 20,00 m above sea level, sea state 1

Increasing the height of the offshore wind turbine by 50% slightly increased the maximum observation range estimated at 90% probability of detection. (increase by about 0,40 nautical miles), while in the precipitation zone the probability is lower by about 10% than in the previous scenario. For the same simulations during a higher sea state 3, the same practical results as shown in Figure 6 are achieved.

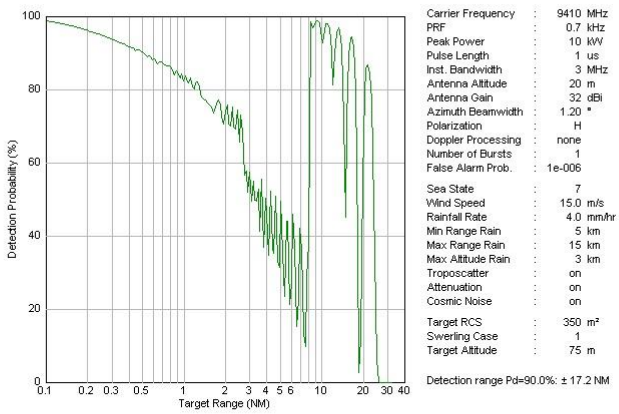

Figure 20. The probability of detecting an offshore wind turbine, state of the sea 7

Figure 20 shows the distribution of the probability of the detecting the offshore wind turbine during precipitation and high sea level. Compared to Figure 5, the turbine observation conditions deteriorated. The reason is mainly the increase in the height of the radar antenna on the ship, which resulted in a greater level of signal reflected from sea waves.

From the smallest distance from the antenna, we observe a rapid decrease in the probability of detecting a wind farm and already at 1,00 nautical miles, the probability of the detection drops to 80%. Due to precipitation, the chance of detecting a windmill drops from 55% at approx. 2,70 nautical miles to nearly 25% at the final border of the area where it is raining (8,00 nautical miles). Further, the probability of the detection remains above 80%, except for two deep drops at 16,00 and 19,00 nautical miles. The signal disappears again around 25,00 nautical miles, which means that with a long pulse, both the state of the sea and atmospheric precipitation do not have a significant impact on the maximum detection range, but the occurrence of both phenomena at the same time complicates the radar observation.

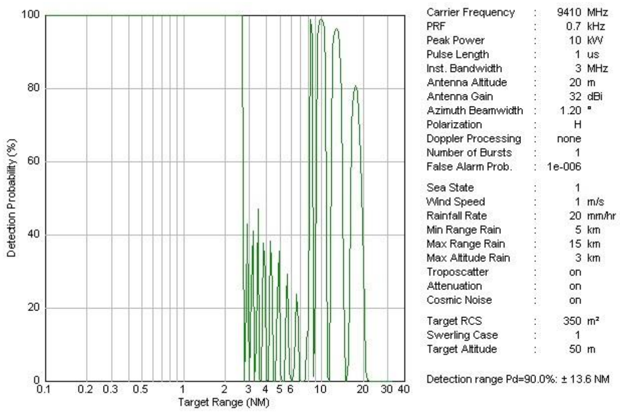

Figure 21. The probability of the detecting an offshore wind turbine during heavy rainfall, sea state 1

Figure 21 shows the probability of the detecting a offshore wind farm during heavy rainfall, which occurs at a distance from the radar antenna of 5,00 to 15,00 km. Heavy rainfall makes it virtually impossible to observe the offshore wind farm in the rainfall zone. The detectability up to 2,70 nautical miles is at 100%, after which it drops drastically below 20%. Outside the rainfall zone, the offshore wind farm is quite well detected, up to 20,00 nautical miles, although due to the large drop above 15,00 nautical miles, the probability of the detecting it is at the level of 50%. The level of the detection outside the heavy precipitation zone is lower than when the precipitation was lighter.

If the state of the sea increases slightly, the distribution of the probability of the detection will practically change very little.

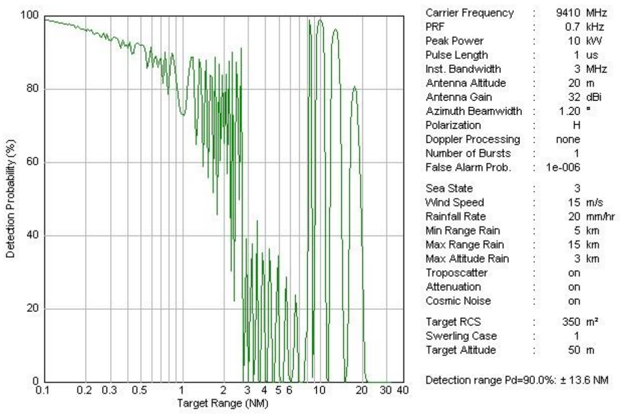

Figure 22. The probability of the detecting an offshore wind turbine, state of the sea 7

In the graph above, Figure 22, the probability of the detecting the offshore wind turbine during a storm and heavy rainfall is practically impossible. It will be even worse on a large ship. If there is no heavy rainfall, the offshore wind farm is visible on the radar screen very well. because more and more wind turbines are being built, they are better visible from a slightly greater distance. The new radars are equipped with software that analyses radar signals and can reduce the impact of hydro-meteorological disturbances, thanks to which ships and marine structures can be tracked in any or almost any conditions.

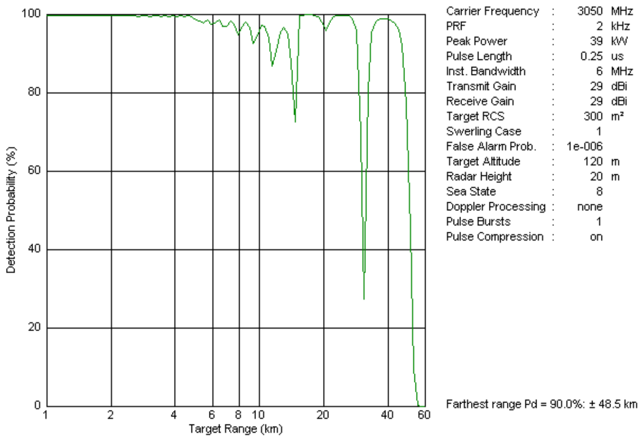

Figure 23. The probability of detecting an offshore wind turbine by the S band radar

Two radars are to be installed on the ships of more than 3 000 gross tonnage. If one of them works in the S-band, the detection range of the offshore wind farm will be greater (26,00 nautical miles) and the signal will be less disturbed by the precipitation and waves. This is shown in Figure 23.

5 SUMMARY

An offshore wind farm is an investment of very large dimensions, which is clearly visible visually and detected by ships' radar even from very long distances, thanks to which it can be treated as a navigational aid. Note, however, that it may also generate false echoes or mask other objects, obstacles, or navigational markings. Restrictions on the visibility of the navigation marks, including RACON, around wind farms should be considered.

The OWF has a significant impact on the ship's radar systems. It creates new problems related to the regulation and interpretation of the radar image. Similar problems occur on the radar regardless of the band in which it works. This is due to the high construction height of the wind generator turbines and the metal structure, which makes the effective reflection area large. It causes multiple and sidelobe indirect echoes, but also generates shadow sectors. As a result, it is difficult to detect other units operating around the farm, but also behind it. Navigating around the farm requires a different adjustment of the radar image, which may result in other units not being detected. Detection of the signals from units operating in the farm area is not always possible. Tracking units by ARPA also poses problems if they are in the vicinity of the wind turbine structure. Also, reducing the gain of the radar signal may result in the loss of navigationally important echoes by ARPA.

Due to the many echoes present on the radar screen, there may be interference with the tracking of ship echoes, the same as in other areas where there are many echoes. In this case, if two echoes pass close, ARPA may swap the echoes or get lost from tracking. Auto-acquisition should not be used in this area as indirect echoes will be introduced into the trace, which will then be lost and a lot of operators distracting alarms will be generated.

The farm is detected by ship radar from more than 12,00 miles away. At short distances from the farm (less than 1,00 nautical miles), ship's X-band radar is more useful than S-band radar due to higher antenna parameters. Large ships passing near the offshore wind farm are observed on the radar without problems with detecting their signals. Due to the large dimensions and good reflecting properties, the echo coming from the offshore wind turbine has larger dimensions than it results from its dimensions and radar properties. At distances below 6 nautical miles from the farm, the possibility of the false reflections from the farm objects should be expected.

If the radar antenna is much higher on a larger vessel, the detection range is slightly greater than on a smaller vessel. On the other hand, heavy precipitation reduces the detection range significantly even by 20%. Intense precipitation can completely prevent radar observation, but also optical. The AIS (Automatic Identification System) is less sensitive in these conditions because it uses ultra-short waves.

In conclusion, offshore wind farms, like all other constructions in the open sea, are a danger to navigation. Due to the fact that they are usually placed in the coastal areas, they can additionally obscure other objects important for the sea navigation, such as lighthouses. Their presence affects the availability of the space when approaching ports, although shipping routes are usually marked out in their vicinity. These structures are very well marked, visible from a distance both during the day and at night. Unfortunately, visual observation and attempts to determine the position using optical bearing may be unsuccessful due to problems with identifying individual offshore wind turbine in the farm.

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