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**TNO report**

**2021 R12270** | **Final report**

# Feasibility study "Radar-B"
# On the applicability of Radar-B systems on main waterways


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# Samenvatting

In Nederland worden strikte regels gesteld aan radars die bedoeld zijn voor gebruik op binnenvaartschepen. Op kleine schepen en jachten worden vaak jachtradars gebruikt die niet aan deze regels voldoen. Diverse belangengroepen hebben zich verenigd in een werkgroep die ervoor moet zorgen dat bepaalde jachtradars toch gebruikt mogen worden. Deze werkgroep heeft eisen voorgesteld voor jachtradars waarmee het kleine schip een vrije doorgang kan zien op een afstand van 625 m. Jachtradars die aan deze eisen voldoen zullen worden aangeduid als Radar-B en de werkgroep heeft zich dienovereenkomstig werkgroep radar-B genoemd.

In opdracht van het Ministerie van Infrastructuur en Waterstaat heeft TNO de door de werkgroep voorgestelde eisen geëvalueerd.

TNO heeft geconstateerd dat aan de eisen voor radar-B alleen kan worden voldaan met 'open array'-antennes van 1 meter of meer. Deze antennes zijn vanwege de afmetingen en het gewicht niet haalbaar voor kleine boten zoals de RHIBs die worden gebruikt bij politie en KNRM.

De werkgroep suggereert dat “beam sharpening” ervoor kan zorgen dat bepaalde radome radars aan de radar-B-eisen kunnen voldoen. TNO heeft echter niet voldoende bewijs gevonden dat “beam sharpening” onder alle omstandigheden voldoende detail zal opleveren. Ook heeft tot op heden geen enkele certificerende instantie “beam sharpening” gecertificeerd. Als gevolg hiervan zal TNO het gebruik van “beam sharpening” niet aanbevelen.

TNO heeft een alternatieve set van eisen afgeleid waarmee het kleine schip een vrije doorgang kan zien op een afstand van 330 m en heeft aangetoond dat dit nog voldoende reactietijd biedt voor het kleine schip. Bovendien is er voor het handelsschip geen verschil voor zijn acties en waarnemingen tijdens het passeren van het kleine schip (vergeleken met het kleine schip uitgerust met een originele radar-B).

De meeste radars, waaronder de radome radars die populair zijn bij de Nederlandse Politie en de Koninklijke Nederlandse Redding Maatschappij (KNRM), zullen voldoen aan de door TNO voorgestelde alternatieve eisen voor radar-B. De voorgestelde alternatieve radar-B-eisen zijn:

- Detectiebereik 1200 m
- Antenne bundelbreedte 5,2° (@-3 dB)
- Range resolutie 30 m

# Summary

In the Netherlands strict rules are imposed on the operation of radars that are intended for use on commercial ships. On small ships and yachts, often yacht radars are used that do not comply with certain of these rules. Various interest groups have united in a working group which aims to ensure that certain yacht radars may nevertheless be used. This working group has proposed requirements for yacht radars that will allow the small ship to check a free pass way at a distance of 625 m. Yacht radars that comply with these requirements will be designated as Radar-B, the working group has baptised itself as working group radar-B.

Commissioned by The Dutch Ministry of Infrastructuur en Waterstaat, TNO has done an evaluation of the requirements proposed by the working group.

TNO found that the radar-B requirements can only be met by “open array” antennas of 1 meter or more. These antennas are not feasible for small boats like the RHIBs in use with police and rescue organizations, due to the antenna’s dimensions and weight.

The working group suggests that beam sharpening could allow certain radome radars to meet the radar-B requirements. TNO however did not found sufficient proof beam sharpening will provide sufficient detail under all conditions. Also, to date, no certifying body has certified the concept of beam sharpening. As a consequence, TNO will not recommend the use of beam sharpening.

TNO has derived an alternative set of requirements will allow the small ship to check a free pass way at a distance of 330 m and has shown that this still offers sufficient reaction time for the small ship. In addition, for the commercial ship there is no difference for his actions and observations while passing the small ship (as opposed to the small ship having an original radar-B).

Most radars, including the radome radars that are popular with the Dutch Police and the Koninklijke Nederlandse Redding Maatschappij (KNRM) will meet the alternative requirements for radar-B as proposed by TNO. The proposed alternative radar-B requirements are:

- Detection range 1200 m
- Antenna beamwidth 5.2° (@-3 dB)
- Range resolution 30 m

# Contents

# 1 Introduction

In the Netherlands (and also internationally, under the International Convention for the Safety of Life at Sea - SOLAS) strict rules are imposed on the operation of radars that are intended for use on commercial ships. On small ships and yachts, often radars are used that do not comply with certain of these rules. This type of radar will be designated as Radar-B (in concordance with the AIS-B for small ships) and is smaller and cheaper than the aforementioned certified radar for commercial ships.

Radar-B does not meet the requirements for navigation under poor visibility conditions. In those cases that the presence of a certified radar is a prerequisite to sailing. Ships equipped with this type of radar are therefore not allowed to sail.

Various interest groups have united in a working group Radar-B which aims to ensure that this type of radar system may nevertheless be used under the above-mentioned conditions.

## 1.1 Radar-B

The Radar-B working group has published a document [1] that addresses the various relevant aspects of Radar-B. This document also provides a proposal for requirements for Radar-B, as derived by the working group. Besides requirements to the radar equipment, the document also refers to requirements regarding AIS, VHF-communication, and operator training.

This TNO-report only focusses on the requirements related to the radar equipment itself and its intended use. The requirements for VHF radio, AIS and operator training are not evaluated. A trained operator is expected to be able to perform all actions described in this document in due time.

The main aspect mentioned in [1] relates to the required azimuth resolution:

*“The radar shall be able to show separately two targets that are at 625 m distance and 30 m apart. This corresponds to an azimuth resolution of 2.75°.”*

The separation of 30 meter is a standard based on a normalized width of a waterway. The distance of 625 meter is composed of 550 meter stopping distance for a large commercial ship and 75 meter for a small Radar-B equipped ship. Those stopping distances both are 5 times the ship length (110 meter for the large ship and 15 meter for the small ship).

The same document requires the small ship to carry a radar reflector for additional visibility by radars on other ships. Requirements for range resolution and minimum detection range are deemed not necessary. The requirements for radar-B are given in Table 1.1.

Table 1.1 Radar-B requirements (from [1]).

| Requirement | Value |
|---|---|
| Azimuth resolution | *2.75°*<br>*30 m at 625 m distance* |
| Radar reflector | Obligatory |

## 1.2 Scope of this report

Commissioned by The Dutch Ministry of Infrastructuur en Waterstaat, TNO has done an evaluation of the requirements as stated in [1]. Specifically the requirements that relate to the technical aspects of radar equipment and its use have been assessed for a defined set of scenarios. Also a few additional requirements have been proposed. Subsequently the specifications of typical radar systems from various manufacturers have been tested based on the aforementioned set of existing and additional requirements.

The outline of the report is as follows:

- In Section 2 the definition of terms is given.
- In Section 3 a set of radar systems that are intended for small ships is introduced as well as an overview of the specific radar systems that are in use by a number of stakeholders.
- In Section 4 a number of scenarios are introduced and the requirements for Radar-B as given in [1] are tested.
- In Section 5 alternative requirements are derived for Radar-B as proposed by TNO.
- Section 5 gives an overview of the compliance of the available radar systems based on the Radar-B requirements and their alternatives.

## 1.3 Terminology

For the sake of easy reading, the following terminology is used:

- Where the term “requirements” is used, it should be read as “proposal for requirements”.
- Where “radar-B” (or sometimes “original radar-B”) is used, reference is made to the radar-B as proposed by the radar-B working group, as described in [1].
- Where “alternative radar-B” is used, reference is made to the radar-B requirements as proposed by TNO in Section 5.
- A merchant ship with certified radar for navigation on Dutch waterways is referred to as “large ship”
- A ship with a Radar-B system is referred to as “small ship”.

## 1.4 Main conclusions

The main outcome of the report is that the available radar systems with open array antennas all meet the original Radar-B requirements specifically for azimuth resolution. Without taking into account beam sharpening techniques, the requirements exclude the use of small and light radome radars, explicitly intended for small ships.

Beam sharpening techniques are potentially beneficial in this case, but TNO has not yet found sufficient proof that, from a safety point of view, beam sharpening will provide sufficient sharpening under all conditions, without any flaws. TNO cannot conclude that beam sharpening will always work under all conditions. As a consequence we cannot recommend it for a safety related issue. For this reason , the performance-increase of beam sharpening is not taken into consideration.

All radar systems comply with the alternative set of Radar-B requirements proposed by TNO, even without beam sharpening techniques. These alternative requirements are based on the reasoning that, when ships are able to early detect each other, the azimuth resolution requirement can be relaxed, while there is still sufficient time to react for both skippers. Moreover this will not make any difference for the skipper of the commercial ship. By this proposed relaxation all radome radars (as well as the open array radars) comply to the alternative radar-B requirements.

# 2 Definitions

| | |
|---|---|
| Azimuth resolution | The minimum azimuth difference the radar can discern. Azimuth is expressed as angle. At a given distance, the angle can be translated to a value in meters, see Figure 2-1. |
| Detection range | The range over which the radar can detect objects. The range is expressed in meters. |
| KNRM | Koninklijke Nederlandse Redding Maatschappij (KNRM) Royal Netherlands Sea Rescue Institution. |
| Minimum detection range | The shortest distance at which the radar can detect objects. |
| Open array antenna | The antenna structure is in the open air, one can see the antenna rotating when the radar is in operation. Usually open array antennas have a length of 1 meter or more. |
| Radome radar | Radar and rotating antenna are covered by a radome. In operation, one cannot see the antenna rotating. Typical dimensions are 50 or 62 cm diameter. |
| Range cell | Distances within a range cell are treated by the radar as one distance. The radar is unable to see or detect range differences that are less than the range cell. Example, if the range cell is 10 meter, then all distances between 995 and 1005 m are considered to be 1000 m. See also Figure 2-1. |
| Range resolution | Size of the range cell. It is the minimum range difference the radar can discern. |
| RHIB | Rigid Hull Inflatable Boat |

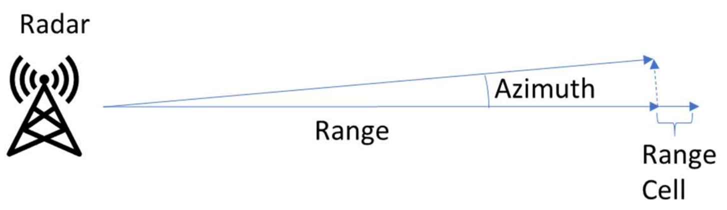


Figure 2-1 Definitions of azimuth and range

# 3 Available radar systems for small ships

## 3.1 Available radar systems on the market

Various radar systems are on the market that are intended for use on small ships. The smallest systems have antennas that fit in a cylindrical radome with 50 cm diameter, followed by 62 cm radome systems. Also systems with 3 and 4 ft (1 and 1.3 m) open array antennas are primarily intended for use on small ships. These radar types are of main interest for Radar-B. The various radar systems that are intended for use on small ships are produced by a number of manufacturers. An extensive list of these systems from major manufacturers is given in Table 3.1.

Radars with antennas of 6 feet (1.8 m) and larger, meet the requirements for certified radar as stated in [3] (beamwidth =< 1.2°) and are therefore not taken into account in this report.

Table 3.1 List of available radar systems with their relevant technical parameters. Beamwidth refers to the horizontal/azimuth beamwidth.

| Brand | Type | Antenna beamwidth (°) | Antenna (O = Open, R = Radome | Antenna size (mm) | Transmit power (W) | Pulse compression | Beam sharpening |
|---|---|---|---|---|---|---|---|
| Furuno | DRS2D NXT | 5.2 | R | ~500 | 25 | Yes | Yes, max 2.6° |
| Furuno | DRS4D NXT | 3.9 | R | ~620 | 25 | Yes | Yes, max 2° |
| Furuno | DRS6A NXT 3.5 ft | 2.3 | O | 1036 | 25 | Yes | No |
| Furuno | DRS6A NXT 4.0 ft | 1.9 | O | 1255 | 25 | Yes | No |
| Furuno | DRS6A NXT 6.0 ft | 1.35 | O | 1795 | 25 | Yes | Yes, max 0.7° |
| Furuno | DRS12A NXT 3.5 ft | 2.3 | O | 1036 | 100 | Yes | No |
| Furuno | DRS12A NXT 4.0 ft | 1.9 | O | 1255 | 100 | Yes | No |
| Furuno | DRS12A NXT 6.0 ft | 1.35 | O | 1795 | 100 | Yes | Yes, max 0.7° |
| Furuno | DRS25A NXT 3.5 ft | 2.3 | O | 1036 | 200 | Yes | No |
| Furuno | DRS25A NXT 4.0 ft | 1.9 | O | 1255 | 200 | Yes | No |
| Furuno | DRS25A NXT 6.0 ft | 1.35 | O | 1795 | 200 | Yes | Yes, max 0.7° |
| Garmin | GMR Fantom™ 18 | 5.2 | R | ~500 | 40 | Yes | No |
| Garmin | GMR 24 | 3.7 | R | ~620 | 40 | Yes | No |
| Garmin | GMR 54 | 1.8 | O | 1219 | 50 | Yes | No |
| Garmin | GMR 56 | 1.25 | O | 1829 | 50 | Yes | No |
| Garmin | GMR 124 | 1.8 | O | 1219 | 120 | Yes | No |
| Garmin | GMR 126 | 1.25 | O | 1829 | 120 | Yes | No |
| Garmin | GMR 254 | 1.8 | O | 1219 | 250 | Yes | No |
| Garmin | GMR 256 | 1.25 | O | 1829 | 250 | Yes | No |
| JRC | JMA-3314 | 4 | R | ~620 | 4000 | No | No |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| JRC | JMA-5104 | 4 | R | ~620 | 4000 | No | No |
| JRC | JMA-610 | 1 | O | 2270 | 4900 | No | No |
| Simrad | HALO 20 | 4.9 | R | ~500 | 10 | Yes | No |
| Simrad | HALO 24 | 3.9 | R | ~620 | 25 | Yes | Yes, max 2.0° |
| Simrad | 3G | 5.2 | R | ~500 | 0.165 | FMCW | No |
| Simrad | 4G | 5.2 | R | ~500 | 0.165 | FMCW | Yes, max 2.6° |
| Simrad | HALO 3 | 2.4 | O | 1141 | 25 | Yes | Yes, max. 1.7° |
| Simrad | HALO 4 | 1.8 | O | 1431 | 25 | Yes | Yes, max 1.3° |
| Simrad | HALO 6 | 1.2 | O | 2045 | 25 | Yes | Yes, max 0.8° |
| Raymarine | Quantum 2 | 4.9 | R | ~500 | 20 | Yes | No |
| Raymarine | Cyclone | 1.99 | O | 1336 | 55 | Yes | No |
| Raymarine | Cyclone | 1.32 | O | 1945 | 55 | Yes | No |

## 3.2 Systems currently in use by stakeholders

A selection of the tabulated radar systems is in use by the Dutch Police, the Koninklijke Nederlandse Redding Maatschappij (KNRM) and the Koninklijke Roeiers Vereeniging Eendracht (KRVE). From the Ministry of Defence no information could be obtained.

Dutch Police
The police employs the Garmin GMR Fantom™ 18 radar on their RHIBs[1]. This radar is a radome radar (Figure 3-1), has an antenna beamwidth of 5.2° and employs pulse compression. The diameter of the radome is approximately 500 mm. The radar has no beam sharpening.


Figure 3-1 Garmin GMR Fantom™ 18 radar antenna dome

### 3.2.1 *KNRM*

The KNRM uses three types of radome radars from Simrad; see Figure 3-2:

- **Simrad HALO 20**
  This radar has an antenna beamwidth of 3.9° and employs pulse compression. The diameter of the radome is approx. 620 mm. The radar has beam sharpening down to 2°.

- **Simrad 3G**
  This radar has an antenna beamwidth of 5.2°. This radar does not transmit

[1] Rigid hull Inflatable boat

pulses, but is based on the frequency modulated continuous wave (FMCW) principle. The diameter of the radome is approx. 500 mm. The radar has no beam sharpening.

- **Simrad 4G**
  This radar has an antenna beamwidth of 5.2° and employs pulse compression. The diameter of the radome is approx. 500 mm. The radar has beam sharpening down to 2.6°.


Figure 3-2 Radar systems in use with KNRM

The KNRM will replace their remaining Furuno radars in the near future.

### 3.2.2 *Royal Boatmen's Association Eendracht (KRVE)*

The KRVE uses four types of radars:

- **JRC JMA 3314**
  This radar has an antenna beamwidth of 4°, uses a magnetron and employs no pulse compression. The diameter of the radome is approx. 620 mm. The radar has no beam sharpening.

- **JRC JMA 5104**
  This radar has an antenna beamwidth of 4°, uses a magnetron and employs no pulse compression. The diameter of the radome is approx. 620 mm. The radar has no beam sharpening.

- **JRC JMA 610**
  This radar has an antenna beamwidth of 1°, uses a magnetron and employs no pulse compression. The antenna is an open array type with a length of 2270 mm, see Figure 3-3. The radar has no beam sharpening.

- **Simrad HALO 20**
  This radar has an antenna beamwidth of 4.9° and employs pulse compression. The diameter of the radome is approx. 500 mm. The radar has no beam sharpening.


Figure 3-3 JRC JMA-610 radar, note the size as compared to the wheel house (Picture Alphatron Marine)

### 3.3 Radar principles and techniques

As reference, Appendix A contains information about radar principles and properties of various radar techniques such as pulse (compression) radar and FMCW.

# 4 Evaluation of the Radar-B requirements

## 4.1 Proposed Requirements

In this section, an evaluation of the requirements proposed by the working group radar-B is given.

An antenna beamwidth of 2.75° (see Section 1.1) is feasible for (almost) all radars equipped with an open array scanner of 3 ft (~ 110 cm) or more, as indicated in Table 3.1. All radars with a cylindrical radome do not meet the beamwidth requirement, unless beam sharpening is applied, which will be addressed in Section 4.4.

Open array scanners do have however some major drawbacks for (very) small ships and might therefore be unsuitable for these ships:

- The antenna is large (as compared to the ship)
- The antenna + pedestal are relatively heavy (more than 20 kg). The construction needs to be sturdy to withstand high wind forces. The ship's construction, especially for sailing boats, might be too weak to install this type of radar at an elevated height (to enable free view on the surroundings, to look over personnel and ship structure)
- To keep the antenna rotating at constant speed under high wind load a substantial amount of power is needed (more than 150 W).

The detection range is, according to Section 1.1, no issue. The procedure in [1] however requires large ships to be seen at 625 m, so the implicit requirement for the detection range is 625 m. It is advisable to make the detection range requirement explicit. TNO suggests to use a detection range requirement of 1200 m, to be in line with [3].

Note that, if both ships sail at 20 km/h, they will meet 56 s after they see each other at 625 m. If the small boat sails 40 km/h, this reduces to 37.5 s.

The range resolution is, according to Section 1.1, no issue. Nevertheless, it is advisable to use the same requirement as for the azimuth resolution: 30 m.

The resulting list of parameters is given in Table 4.1.

Table 4.1 Radar-B requirements.

| Requirement | Value |
|---|---|
| Azimuth resolution | *2.75°*<br>*30 m at 625 m distance* |
| Radar reflector | Obligatory |
| Detection range | 625 m<br>1200 m (advice TNO) |
| Range resolution | 30 m (advice TNO) |

### 4.2 Scenarios

The effects of the Radar-B requirements can be assessed by means of a number of scenarios that have been identified.

These scenarios are:

1. Encounter of a ship equipped with Radar-B with a ship equipped with commercially certified radar in open water.

2. A ship equipped with Radar-B attempts to find a port entrance.

3. Encounter of a ship equipped with Radar-B with a ship equipped with commercially certified radar in an inland waterway.
   Case 3B: With an additional ship that performs an overtaking manoeuvre.

4. A ship equipped with Radar-B navigates through a waterway with obstacles such as choke points and bridges.

Figure 4-1 shows these scenarios schematically. Scenario 3 is the most stringent, in involves interaction with another ship in combination with limited room to manoeuvre.

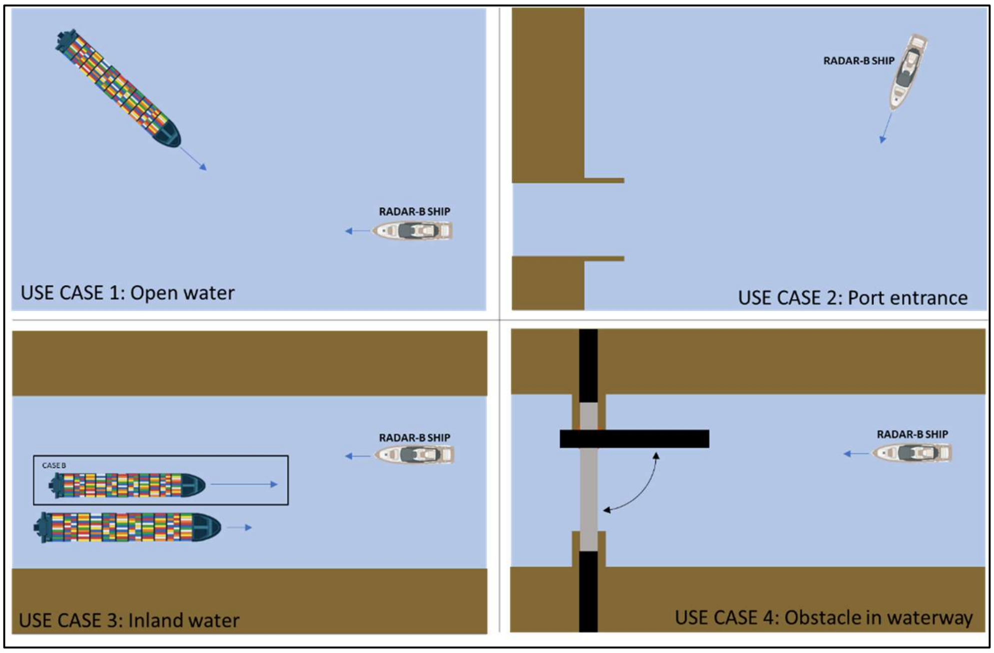


Figure 4-1 Schematic overview of the identified scenarios.

Scenario 3 is deemed the most critical for the Radar-B requirements, with two (or more) ships approaching each other in a relatively narrow waterway with little room for manoeuvring. The other scenarios involve more manoeuvring space and/or only deal with non-moving objects, for which all of the potential Radar-B radar systems have sufficient detection and resolution capability.

## 4.3 Implications of use

Implications of the requirements for Radar-B are described in this section, specifically for scenario 3. In the remainder of this section, a merchant ship with certified radar for navigation on Dutch waterways is referred to as "**large ship**", whereas a ship with a Radar-B system is referred to as "**small ship**".

The large ship can see the small ship, which is clearly visible since it has a mounted radar reflector, at a distance of 1200 meter. The certified radar has an azimuth resolution of 1.4° or better, which corresponds to a resolution of 30 m (perpendicular to the range) at 1200 m distance. In other words, the radar is able to show separately two targets that are at 1200 m distance and 30 m apart.

1200 meter is assumed to be a standard required observation distance:

- Testing the observation quality of the radar up to 1200 meters is part of the inspection procedure [3] . It is therefore stated that undisturbed and undistorted radar observation should be possible at least up to 1200 meters.
- In the training, skippers learn to make a decision on ships at a distance of 1200 meters how to act, such as on which side to pass, swerve, contact the other ship, etc. The acceptance of the 1200 meter value is found in case law (jurisprudence), see as an example [2].

The large ship detects the small ship at 1200 meter and makes a decision to either continue its course and speed or to perform an evasive manoeuvre. Given the combined safety distances of the two ships, this evasive manoeuvre is to be initiated at latest at 625 m distance from the small ship.

The situation for the small ship is comparable. He will see the large ship at 1200 m. When the ships are 625 m apart, he can see whether there is enough space to pass and if not, he can decide whether evasive manoeuvres are required. He can stop within 75 m distance and reverse before the large ship has sailed 550 m, which offers an escape.

Note 1: One might argue that this is a too strict interpretation. Ships might slow down to decrease stopping distance, which is not being considered. The large ship however can only count on the fact that the small ship will see him at 625 m and will need no more than 75 m to stop. Same for the small ship: the large ship might need the full 550 m to stop.

Note 2: One might argue that both ships also have AIS and are aware of each other's presence. However radar is a primary safety feature. Even if (the other ship's) AIS fails or is misaligned one has to be able to navigate safely.

## 4.4 Improving azimuth resolution: beam sharpening

One of the features that are advertised to enhance azimuth resolution, is called beam sharpening. This concept is described here more in detail.

### 4.4.1 *Azimuth resolution*

A target is detected by the radar if it is in the radar beam, i.e. in the main lobe of the azimuth antenna pattern. The antenna beamwidth determines how "wide" a target is presented on the radar screen. If the beamwidth is large, the echo (blob) on the screen will also be large, as is shown in Figure 4-2.

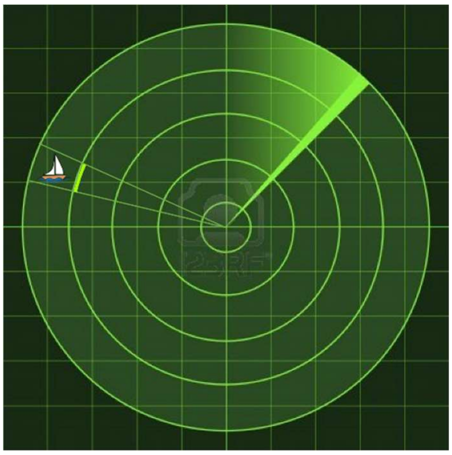

Figure 4-2 Target echo on radar screen, size is beamwidth dependent.

Targets at the same distance can be seen separately if they are at least one antenna beamwidth apart, see Figure 4-3. In this case there is sufficient empty space between the two targets for them to be detected as two individual objects.

Please note that this is a simplification of actual situations in which two ships will probably have unequal radar cross sections (RCS). In a situation with, in terms of RCS, a strong and a weak target, the mutual distance in azimuth between the ships needs to be larger than the aforementioned empty space to resolve them individually.

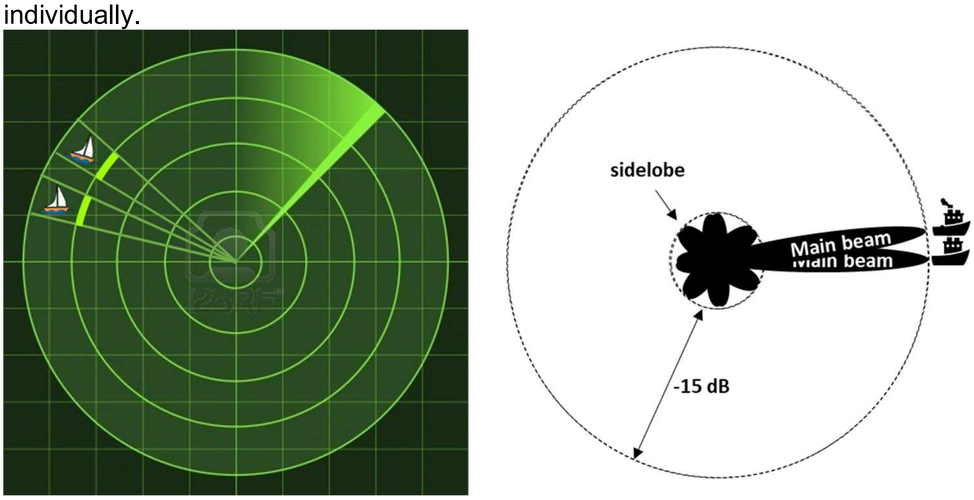


Figure 4-3 Azimuth resolution. Left radar screen, right targets and antenna beams. Please note that this is a simplification of real situations in which two ships will have unequal radar cross sections.

### 4.4.2 *Beam sharpening*

It is obvious that the real target on the screen of Figure 4-2 is (somewhere) in the middle of the blob on the radar screen, or in other words, is in the middle of the antenna beam. The antenna diagram of Figure 4-4 gives an impression of the shape of the azimuth antenna pattern. Depending on whether the target is exactly in the middle of the beam, or a few degrees to the left or right, the returned target signal strength will vary.

Computer software can use this variation in target strength to determine where the target actually is. The use of this principle is called beam sharpening.

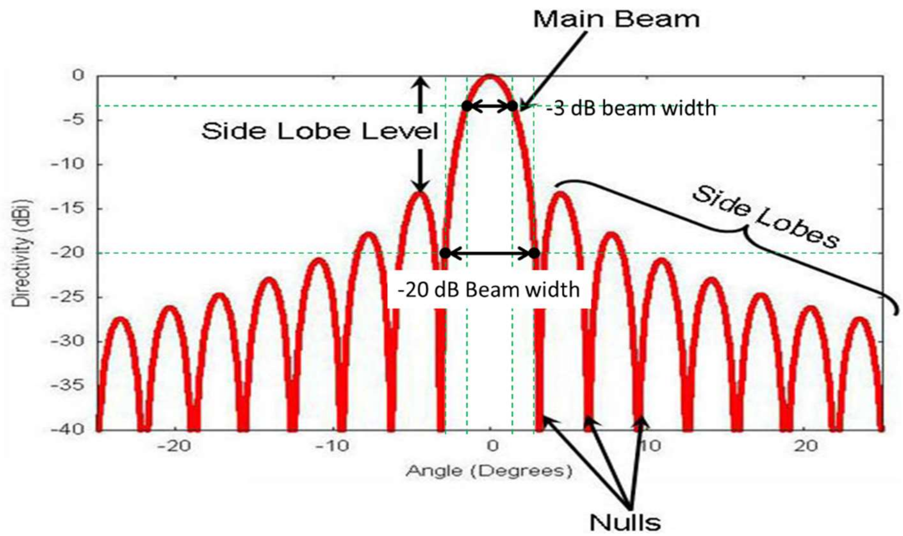


Figure 4-4 Antenna diagram in azimuth.

The amount of improvement that can be achieved depends on a number of aspects. These are:

- The shape of the antenna diagram
- The number of radar pulses that hit the target during one pass, this is determined by:
  - Antenna beamwidth
  - Rotation speed of the antenna
  - Pulse repetition frequency

  Usually between 7 and 10 pulses will hit the target in one pass.
- The target: a target is not a single reflection point but a large set of reflectors
- The target strength: the smaller the reflective properties of the target, the more the received signal is distorted by noise and clutter

Beam sharpening utilizes the known shape of the beam, *i.e*. its antenna gain as function of angle.

Radar manufactures claim a beam sharpening factor of 2. However, the achieved sharpening is dependent on how well the antenna diagram can be recognized in the received echo signals. If the signal strength is high (e.g. due to reflection of a large ship or a large land mass), a large part of the diagram is revealed, even the side lobes might result in a useful echo signal. If the signal strength is low (e.g. due to reflection of a small ship) only the top part of the diagram is revealed (the remainder is distorted by noise).

Land masses and large ships are not just large reflectors, they consist of numerous smaller reflectors, so the received radar echo consists of many overlapping “antenna beam shaped” signals, which might confuse the sharpening algorithm.

Navico (related to Lowrance and B&G that in turn relate to Simrad) has a patent [4] that describes their beam sharpening concept. They state that they reduce the amount of sharpening depending on the distance (less sharpening nearby) and also that they reduce sharpening for land masses (for reflectors that the radar identifies as land mass).

Both radar manufacturers (Furuno, Simrad) and the little available literature [5] show pictures as proof of the achieved amount of sharpening. However, this shows the increase of detail that is achieved, but not the details that are still concealed, despite of the sharpening. For that, one had to provide a picture of a radar that had a native sharp beam. In other words, Simrad could have compared the sharpened image of the HALO 20 (3.9° antenna beamwidth, 2.0° with sharpening on) with the image of the HALO 4 (1.8° unsharpened). However such information is not available.

Note that Furuno has its DRS*A NXT radars (* = 6, 12, 25) in portfolio. These radars meet the 1.2° requirement when they use beam sharpening. Furuno however does not offer these radars for commercial shipping, the radar does not have the applicable certificate.

To TNO’s knowledge, radars that meet the 1.2° beamwidth requirement by using beam sharpening are not certified for commercial shipping.

In summary, TNO does not recommend beam sharpening in a safety related context for the following reasons:

- It is unclear to what extent sharpening is dependent on target size and other target characteristics
- A used patent indicates reduction of the amount of applied sharpening, based on range and presence of land mass. So the actual amount of sharpening does not always meet the requirement.
- No proof is provided that beam sharpening is effective for each and every detail.

# 5 Alternative requirements for Radar-B

This section describes the derivation of an alternative set of radar-B requirements, proposed by TNO. It will be shown that with this set of requirements, there is still sufficient time to react for both skippers. Moreover, this will not make any difference for the skipper of the large ship.
In addition, virtually all radome radars (as well as the open array radars) comply to the alternative radar-B requirements.

Given the assessment of requirements of the Radar-B concept as described in Section 4, an alternative formulation of the azimuth requirement has been drawn up which is outlined below. Again, scenario 3 will be considered throughout this Section.

## 5.1 Requirements

The large ship will start to make decisions at a distance of 1200 m. If the small ship would also follow the same procedure, both ships would take appropriate actions to pass in time, and, being aware of these corrections, neither the large ship nor the small ship will need to perform evasive actions. As a consequence, a minimum detection range of 1200 m is required.

In terms of azimuth resolution, the small ship (with a required azimuth resolution better than 2.75°) will not be able to see details in the order of 30 m at this distance of 1200 m, and therefore cannot detect whether the opposing ship has taken appropriate action (e.g. if the large ship indeed keeps right). This however is not necessarily an issue, as the small ship will reveal these details at a closer distance of 625 m.

The popular radome radars have an antenna beamwidth of 5.2° or less. This implies an azimuth resolution capability of 30 m at a distance of 330 m. So ships having a radome radar will reveal the 30 m detail (and hence the possibility to pass) at a distance of 330 m. With a stopping distance of 75 m, the small ship can easily stop and reverse in case anything would go wrong with the large ship (e.g. it cannot keep right).

Note that, if both ships sail at 20 km/h, they will pass each other 29.7 s after the small ship sees passing is possible. If the small boat sails 40 km/h, this reduces to 19.8 s. If this timing is believed too short, one could consider introducing a maximum speed.

A 30 m resolution at 1200 m implies a beamwidth of 1.4° which requires an antenna of 2 m length, which is not practical for many small ships.

TNO proposes an alternative for Radar-B requirements:
- Maximum antenna beamwidth (-3 dB points) 5.2°
- Detection range 1200 m

The alternative radar-B requirements are summarized in Table 5.1.

Table 5.1 Alternative Radar-B requirements, as proposed by TNO.

| Requirement | Value |
|---|---|
| Azimuth resolution | *5.2°*<br>*30 m at 330 m distance* |
| Radar reflector | Obligatory |
| Detection range | 1200 m |
| Range resolution | 30 m |

In the remainder of this section, the consequences for this alternative are described.

## 5.2 Comparison Radar-B versus alternative Radar-B

The original Radar-B requirements (proposed by the working group radar-B) and the alternative Radar-B requirements (proposed by TNO in the previous section) are compared for scenario 3, the most stringent one. We consider three situations:

- Both ships act normally and a standard pass is executed. The actions are listed in Table 5.2.
- The large ship does not follow standard procedure for any reason. There is no space for the small ship to pass. The actions are listed in Table 5.3.
- The small ship does not follow standard procedure for any reason. There is no space for the large ship to pass. The actions are listed in Table 5.4.

Just for reasons of simplicity, we will use the phrase "**keep starboard**" for the standard situation, and "**cannot keep starboard**" for the abnormal situation.

For ease of comparison, text in the tables will be shown in green if the texts are equal and happen at the same distance, and in red if they are different.

Table 5.2 Standard pass

| Distance | Radar-B | Alternative Radar-B |
|---|---|---|
| **1200 m** | Large ship detects small ship and keeps starboard<br><br>Small ship detects large ship and keeps starboard | Large ship detects small ship and keeps starboard<br><br>Small ship detects large ship and keeps starboard |
| **Less than 1200 m** | Large ship detects that the small ship keeps starboard and there is enough space to pass (radar can see this at 1200 m) | Large ship detects that the small ship keeps starboard and there is enough space to pass (radar can see this at 1200 m) |
| **625 m** | Small ship detects that the large ship keeps starboard and there is enough space to pass | |
| **330 m** | | Small ship detects that the large ship keeps starboard and there is enough space to pass |

Table 5.3 Non-standard situation large ship

| Distance | Radar-B | Alternative Radar-B |
|---|---|---|
| **1200 m** | Large ship detects small ship but cannot keep starboard<br><br>Small ship detects large ship and keeps starboard | Large ship detects small ship but cannot keep starboard<br><br>Small ship detects large ship and keeps starboard |
| **Less than 1200 m (more than 625 m)** | Large ship detects that the small ship keeps starboard | Large ship detects that the small ship keeps starboard |
| **625 m** | Small ship detects that the large ship does not keep starboard and will stop (and turn around if needed) He only needs 75 m to do this.<br><br>Large ship detects the action of the small ship | |
| **330 m** | | Small ship detects that the large ship does not keep starboard and will stop (and turn around if needed) He only needs 75 m to do this.<br><br>Large ship detects the action of the small ship |

Table 5.4 Non-standard situation small ship

| Distance | Radar-B | Alternative Radar-B |
|---|---|---|
| **1200 m** | Large ship detects small ship and keeps starboard<br><br>Small ship detects large ship but cannot keep starboard | Large ship detects small ship and keeps starboard<br><br>Small ship detects large ship but cannot keep starboard |
| **Less than 1200 m (more than 550 m)** | Large ship detects that the small ship cannot keep starboard and will stop. He needs 550 m to do so. | Large ship detects that the small ship cannot keep starboard and will stop. He needs 550 m to do so. |
| **At a given distance***<br><br>Note this distance is equal for radar B and the alternative Radar-B | Small ship notices large ship is slowing down | Small ship notices large ship is slowing down |

* Note that for seeing the large ship slowing down, the small ship radar will evaluate the range. The azimuth resolution (this is where Radar-B and the alternative Radar-B differ) is not involved.

By comparing the tables, we see:

- For the large ship, there is no difference for his actions and observations at a normal pass, or at an emergency with the small ship. Only if the large ship has an emergency, he will notice the reaction of the small ship is at 330 m instead of at 625 m.
- For the small ship, there is only a difference when the large ship has an emergency. He will notice this with the original Radar-B at 625 m and with the alternative Radar-B at 330 m. Note that he only needs 75 m to stop.

## 5.3 Implications of use

Implications of the use of the alternative Radar-B solution are described in this section.

The large ship is equipped with a radar that is allowed on the Dutch waterways. As a consequence, he can detect the small ship at a distance of 1200 meter (it has a radar reflector). The certified radar has an azimuth resolution of 1.4° or better, which corresponds to a resolution of 30 m (perpendicular to the range) at 1200 m distance. In other words, the radar is able to show separately two targets that are at 1200 m distance and 30 m apart.

The large ship detects the small ship at 1200 meter and makes a decision to either continue or to perform an evasive manoeuvre. This evasive manoeuvre needs to be initiated at 625 m distance from the small ship. The same is valid for the small ship, he detects the large ship at 1200 meter and will act accordingly.

The large ship detects the actions of the small ship at a distance of 1200 m. The small ship detects the actions of the large ship only at 330 m, however this leaves enough time for evasive actions, should they be necessary. And at 330 m the skipper of the small ship can also see that he can safely pass the large ship (e.g. that the large ship keeps starboard and there is plenty of space to pass).

Note: One might argue that this also counts for the original radar-B, which is true. Relaxing the beamwidth requirement to 5.2° extends the concept to the popular radome radars, which are frequently used on small ships, not only for leisure but also by police forces and the KNRM.

### 5.4 Implications for Radar-B

By relaxing the requirement for the beamwidth from 2.75° to 5.2°, a greater number of radars becomes available as Radar-B. Also the popular radome radars meet this requirement. Relevant data is given in Section 6.

# 6 Compliance of Radar-B systems

## 6.1 Compliance to original Radar-B requirements

In this section, the compliance of radars to the original radar-B requirements is given.

The systems are divided in two categories, those that are fully compliant and those that would only be compliant while employing beam sharpening. The compliance of the radar systems that were introduced in Section 3, is tabulated in Table 6.1.

Fully compliant Radar-B systems (green marked systems in Table 6.1) have an antenna beamwidth of (-3 dB points) 2.75° or less which is achieved without beam sharpening. Note that some of those radars do employ beam sharpening, however they meet the requirements also without this feature.

A set of other radars will comply to the requirements for Radar-B under the condition that beam sharpening would be accepted (yellow marked systems in Table 6.1). Note that these radars are all radome radars which are considerable smaller and lighter than their open array counterparts.

The remaining radars (marked white) are non-compliant to the original Radar-B requirements.

Table 6.1 Compliance to requirements of available radar-B systems

| **Brand** | **Type** | **Antenna beamwidth (°)** | **Antenna (O = Open, R = Radome** | **Antenna size (mm)** | **Transmit power (W)** | **Pulse compression** | **Beam sharperning** |
|---|---|---|---|---|---|---|---|
| **Furuno** | DRS2D NXT | 5.2 | R | ~500 | 25 | Yes | Yes, max 2.6° |
| **Furuno** | DRS4D NXT | 3.9 | R | ~620 | 25 | Yes | Yes, max 2° |
| **Furuno** | DRS6A NXT 3.5 ft | 2.3 | O | 1036 | 25 | Yes | No |
| **Furuno** | DRS6A NXT 4.0 ft | 1.9 | O | 1255 | 25 | Yes | No |
| **Furuno** | DRS6A NXT 6.0 ft | 1.35 | O | 1795 | 25 | Yes | Yes, max 0.7° |
| **Furuno** | DRS12A NXT 3.5 ft | 2.3 | O | 1036 | 100 | Yes | No |
| **Furuno** | DRS12A NXT 4.0 ft | 1.9 | O | 1255 | 100 | Yes | No |
| **Furuno** | DRS12A NXT 6.0 ft | 1.35 | O | 1795 | 100 | Yes | Yes, max 0.7° |
| **Furuno** | DRS25A NXT 3.5 ft | 2.3 | O | 1036 | 200 | Yes | No |
| **Furuno** | DRS25A NXT 4.0 ft | 1.9 | O | 1255 | 200 | Yes | No |
| **Furuno** | DRS25A NXT 6.0 ft | 1.35 | O | 1795 | 200 | Yes | Yes, max 0.7° |
| **Garmin** | GMR Fantom™ 18 | 5.2 | R | ~500 | 40 | Yes | No |
| **Garmin** | GMR 24 | 3.7 | R | ~620 | 40 | Yes | No |
| **Garmin** | GMR 54 | 1.8 | O | 1219 | 50 | Yes | No |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Garmin** | GMR 56 | 1.25 | O | 1829 | 50 | Yes | No |
| **Garmin** | GMR 124 | 1.8 | O | 1219 | 120 | Yes | No |
| **Garmin** | GMR 126 | 1.25 | O | 1829 | 120 | Yes | No |
| **Garmin** | GMR 254 | 1.8 | O | 1219 | 250 | Yes | No |
| **Garmin** | GMR 256 | 1.25 | O | 1829 | 250 | Yes | No |
| **JRC** | JMA-3314 | 4 | R | ~620 | 4000 | No | No |
| **JRC** | JMA-5104 | 4 | R | ~620 | 4000 | No | No |
| **JRC** | JMA-610 | 1 | O | 2270 | 4900 | No | No |
| **Simrad** | HALO 20 | 4.9 | R | ~500 | 10 | Yes | No |
| **Simrad** | HALO 24 | 3.9 | R | ~620 | 25 | Yes | Yes, max 2.0° |
| **Simrad** | 3G | 5.2 | R | ~500 | 0.165 | FMCW | No |
| **Simrad** | 4G | 5.2 | R | ~500 | 0.165 | FMCW | Yes, max 2.6° |
| **Simrad** | HALO 3 | 2.4 | O | 1141 | 25 | Yes | Yes, max. 1.7° |
| **Simrad** | HALO 4 | 1.8 | O | 1431 | 25 | Yes | Yes, max 1.3° |
| **Simrad** | HALO 6 | 1.2 | O | 2045 | 25 | Yes | Yes, max 0.8° |
| **Raymarine** | Quantum 2 | 4.9 | R | ~500 | 20 | Yes | No |
| **Raymarine** | Cyclone | 1.99 | O | 1336 | 55 | Yes | No |
| **Raymarine** | Cyclone | 1.32 | O | 1945 | 55 | Yes | No |

Green indicates a fully compliant radar system
Yellow indicates a compliant radar system if beam sharpening would be accepted
White indicates a non-compliant radar system

## 6.2 Compliance to alternative radar-B requirements

The alternatively compliant Radar-B systems, as proposed by TNO, do have a detection range of at least 1200 m and have an antenna beamwidth of (-3 dB points) 5.2° which is achieved without beam sharpening.

All of the radars that were identified as potential Radar-B systems are compliant with the proposed alternative requirements.

Please note that:
- some radars do employ beam sharpening, however they meet the requirements without this feature.
- this list also comprises the radars of section 6.1.
- this list encompasses many small and light radome radars

## 6.3 Compliance of systems in use with stakeholders

### 6.3.1 *Police*

The Garmin GMR Fantom™ 18
This radar is only compliant with the alternative Radar-B requirements.

### 6.3.2 *Royal Dutch Rescue Company (KNRM)*

- **HALO 20**
  This radar is compliant with the alternative Radar-B requirements.
  This radar is compliant with the Radar-B requirements only if beam sharpening

is considered.

- **3G**
  This radar is only compliant with the alternative Radar-B requirements.

- **4G**
  This radar is compliant with the alternative Radar-B requirements.
  This radar is compliant with the Radar-B requirements only if beam sharpening is considered.

#### *6.3.3 Royal Boatmen's Association Eendracht (KRVE)*

The KRVE uses four types of radars:

- **JRC JMA 3314**
  This radar is only compliant with the alternative Radar-B requirements.

- **JRC JMA 5104**
  This radar is only compliant with the alternative Radar-B requirements.

- **JRC JMA 610**
  This radar is compliant with both the Radar-B and alternative Radar-B requirements.

- **Simrad HALO 20**
  This radar is only compliant with the alternative Radar-B requirements.

### 6.4 Summary of compliance for Radar-B systems

For many major (yacht) radar manufacturers a number of models is listed here, radome radars as well as open array antenna's. Many more examples can be given, however they all follow the same pattern:

- Antennas inside radomes of about 500 mm diameter have beamwidths of around 5°.
- Antennas inside radomes of about 620 mm diameter have beamwidths of around 4°.
- Open array antennas haves sizes of 1 meter and larger, and have beamwidths of around 2.5°.
- Open array radars meet the requirements for Radar-B.
- Radome radars meet the requirements for the alternative Radar-B.

Some radars (Furuno, Simrad) employ beam sharpening.

The companies mentioned using small boats, all have also non-compliant Radar-B.

Note that Simrad, B&G and Lowrance share some radar models (3g and 4 G for example).

# 7 Conclusions and recommendations

## 7.1 Conclusions

The major conclusions from this study are:

The original radar-B requirements proposed by the radar-B working group do exclude the small and light radome radars, explicitly intended for small ships.

The description of Radar-B by the working group accepts the use of beam sharpening to achieve a beamwidth of 2.75°. TNO has not found sufficient proof yet that, from a safety point of view, beam sharpening will provide sharpening under all conditions, without any critical flaws.

The larger open array antennas meet the Radar-B requirements.

## 7.2 Recommendations

The major recommendations from this study are:

TNO has proposed alternative Radar-B requirements that allows also the popular radome radars to be used:

- Detection range 1200 m
- Antenna beamwidth 5.2° (@-3 dB)
- Range resolution 30 m

TNO has provided an alternative scenario for use of alternative Radar-B, which takes into account sufficient reaction time.

# 8 References

[1] RADARGEBRUIK voor KLEINE SCHEPEN, Wenselijkheid en technische samenstelling; version 3.17; 20 February 2019

[2] Uitspraak van de Raad voor de Scheepvaart inzake de aanvaring van het Nederlandse betonningsvaartuig "Schuitengat" met het Nederlandse vissersvaartuig "Grietje" UK 164, in de Blauwe Slenk, nabij boei BS 36., Staatscourant, 6 december 1995 (https://zoek.officielebekendmakingen.nl/stcrt-1995-237-URS61.html?zoekcriteria=%3Fzkt%3DEenvoudig%26vrt%3Dstcrt%2B1995%2B237&resultIndex=9&sorttype=1&sortorder=4)

[3] RICHTLIJN VAN HET EUROPEES PARLEMENT EN DE RAAD van 12 december 2006 tot vaststelling van de technische voorschriften voor binnenschepen; (2006/87/EG); 12 december 2006

[4] US patent 9,182,482 B2, Radar beam sharpening system and method, Nov. 10, 2015.

[5] Analysis of Beam Sharpening Effectiveness in Broadband Radar on Inland Waters; Witold Kazimierski, Andrzej Stateczny; Conference Paper 16th International Radar Symposium (IRS), 24-26· June 2015.

# A Radar basics

Radars can be divided into three categories:
- Pulse radar,
- Pulse compression radar,
- FMCW radar.

In this section the basics of each type are explained as well as the radar signals they use.

A radar transmits a signal that travels from the radar to a target. At the target the signal partially reflects back to the radar. The radar receives this signal and determines the time it took from transmission to reception.

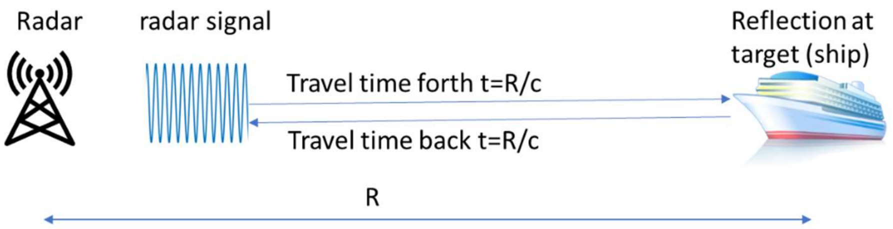


Figure 8-1 Radar basic operation.

The radar signal travels at the speed of light, *c*, which is about 300,000 km/s. The distance *R* will result in a travel time of:

$$t = 2R/c$$

The factor 2 takes into account the signal has to travel back and forth.

The amount of energy received by the radar receiver is given by the radar equation for free space and no loss conditions:

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

where:
$P_r$ is received power [W]
$P_t$ is transmitted power [W]
$G$ is antenna gain
$\lambda$ is wavelength of the radar signal [m]
$\sigma$ is radar cross section (RCS) [$m^2$]
$R$ is range (or distance) [m].

The wavelength relates to the transmitter frequency as:

$$\lambda = {}^{c}/_{F_t}$$

where $F_t$ is transmit frequency [Hz].

## A.1 Pulse radar

The common way of measuring *t* in the early days of radar was the use of a short radar pulse, see Figure 8-2. The radar measures the time it takes the pulse to travel forth and back:

$$R = \frac{t * c}{2}$$

The radar repeats the pulse transmission every PRI (pulse repetition interval) seconds, or the pulse is repeated PRF (pulse repetition frequency) times per second, PRI=1/PRF. The pulse itself has a duration of $t_p$ seconds.

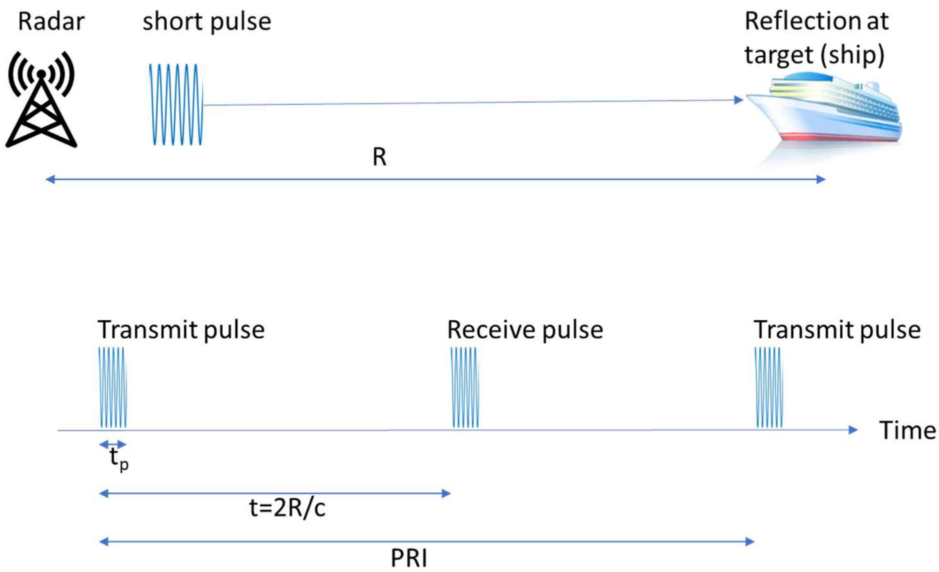


Figure 8-2 (short) pulse radar.

The maximum range of the radar $R_{max}$ = PRI * c / 2. The resolution of the radar is $t_p$ sec, which equals a length of $l_p = t_p * c$. Typical values are:

- PRF between 250 Hz and 5 kHz, this equals to a PRI between 4 ms and 200 μs. The resulting maximum ranges are 600 km and 30 km.
- Pulse duration $t_p$ between 100 ns and 10 μs, equalling pulse lengths and hence a resolution of 15 and 1500 meter.

A generic lay-out of a pulse radar is given in Figure 8-3. The transmitter commonly is a magnetron. The pulses are not modulated, due to the finite length the pulse has a given bandwidth, notwithstanding the fact a "single frequency" is transmitted.

$$B = {}^{1}/_{t_p}$$

where $t_p$ is the pulse length [s] and *B* the resulting bandwidth [Hz].

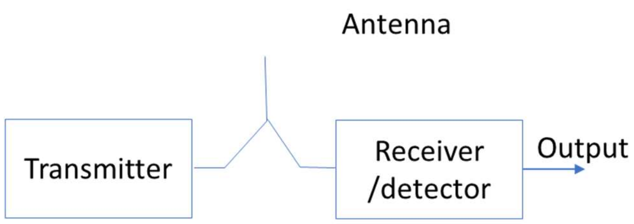


Figure 8-3 Generic layout of pulse radar.

To receive the pulse, the receiver needs to have at least the same bandwidth *B*.

## A.2 Pulse compression radar

Magnetron transmitters are capable of transmitting short pulses at high peak powers. Modern Solid State transmitter are capable to transmit less peak power but at higher duty cycles, thus longer radar pulses. The reason for longer radar pulses is the fact that they contain more energy and thereby increase the sensitivity of the radar, at the expense of a lower resolution. Pulse compression allows the use of longer pulses without sacrificing resolution.

In a radar with pulse compression, a modulated pulse is used, as is shown in Figure 8-4. The radar compares the transmitted pulse with the received pulse, and determines the moment they are aligned, see Figure 8-5. The pulse compression even works with overlapping long pulses, as is shown in Figure 8-6, where the radar receives reflections of three targets, at 40, 70 and 75 km. The pulse length is 66 μs or 10 km.

The ratio between the long pulse and the compressed short pulse is called the pulse compression ratio (PCR).

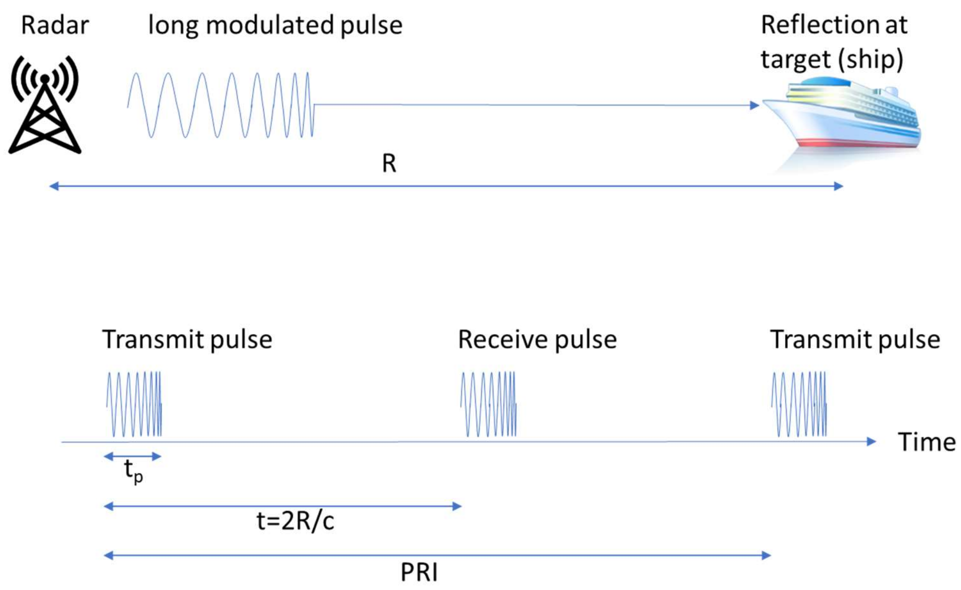


Figure 8-4 Pulse compressor radar.

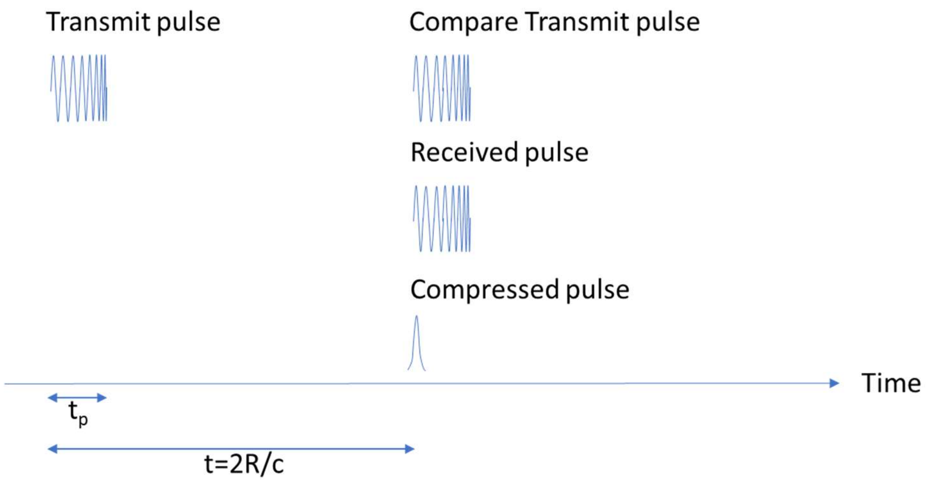


Figure 8-5 Pulse compression operation.

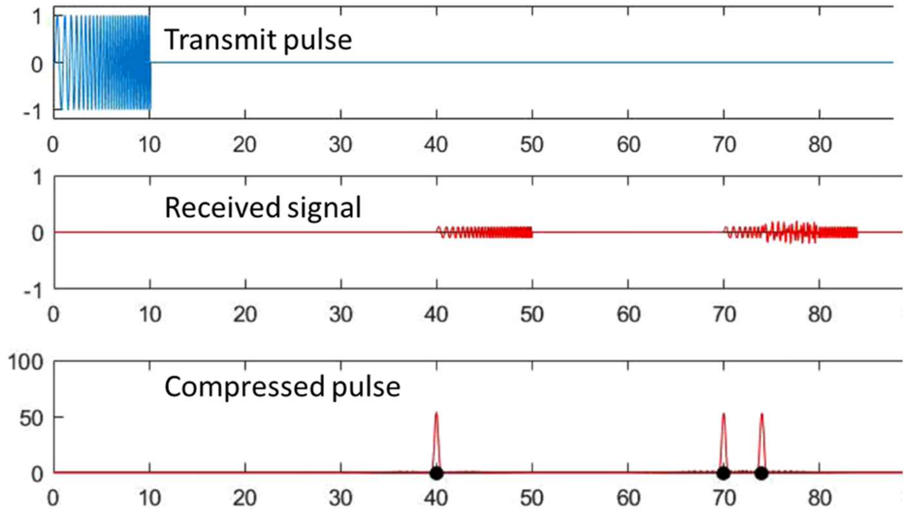


Figure 8-6 Pulse compression with overlapping receive signals.

Pulse compression radars use long and modulated radar pulses. As indicated earlier, pulse compression is most commonly used by modern solid state radars. By transmitting relatively long pulses, they can reduce the transmitter power while maintaining the same average power (e.g. a short pulse of 10 kW in 100 ns emits the same energy as a 100 W pulse of 10 μs).

To achieve the same resolution as with a short pulse, long radar pulses are modulated, most commonly a frequency sweep is used. Due to the modulation, the bandwidth of the transmitted signal increases. As an example, to achieve the same resolution as with the short pulse of 100 ns, the bandwidth of the long pulse also has to be 10 MHz. Also the receiver needs to have a bandwidth of 10 MHz.

During the pulse transmission the receiver cannot receive any signals. In case of transmitting large pulse (e.g. 100 μs), the radar will not be able to receive any echo's from nearby objects (15 km for 100 μs). This is known as the blind distance. To overcome this effect, radar manufacturers often apply multiple interlaced pulse trains with short pulses for short range detection and long pulses for long ranges detection. Sometimes even an intermediate pulse width is applied for distances in between. To separate the various pulse trains, they each have different frequencies This implies that these radars utilise more instantaneous bandwidth, For example, if the bandwidth of the pulse is 10 MHz, then a radar using a short and a long pulse will occupy at least 20 MHz. With an intermediate pulse added, this will raise to 30 MHz. Note however that a typical magnetron navigation radar uses up to 60 MHz due to magnetron frequency variations.

A generic lay-out for a radar using long pulses is given in Figure 8-7. The received pulse is undergoing a process called pulse compression. The pulse compressor uses the modulation of the pulse to calculate the corresponding short output pulse.

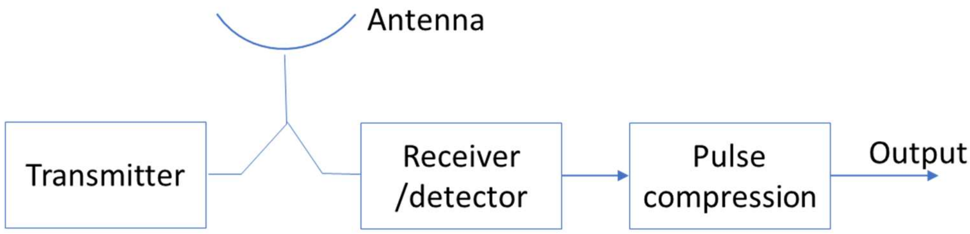


Figure 8-7 Generic lay-out of pulse compression radar.

## A.3 Continuous wave radar

Continuous Wave (CW) radars use frequency modulation (FM), hence the name FMCW radar. They measure the travel time of the transmitted signal by comparing where the received signal is in the modulation sequence, as opposed to the transmit signal.

The concept is explained in Figure 8-8. FMCW radars almost exclusively use a linear frequency sweep as modulation, as is shown in the figure. Also here, *t=2R/c*. Note the fact that FMCW radars do transmit while they receive.

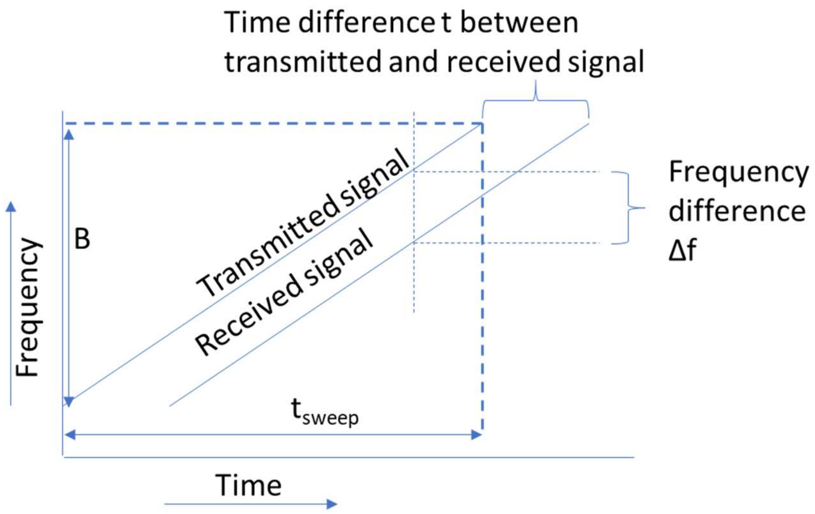


Figure 8-8 Linear frequency sweep in FMCW radar.

As for pulse radar, there is a time difference between the transmitted signal and the received signal, this time difference corresponds to the distance of the target. As can be seen in Figure 8-9, the time difference results in a frequency difference. The frequency difference is measured by the detector. The range is calculated as:

$$R = \frac{\Delta f * t_{sweep} * c}{2B}$$

where:
*R* is the distance to the target [m]
*Δf* is the frequency difference between transmitted and received signal [Hz]

$B$ is the sweep bandwidth [Hz]
$t_{sweep}$ is the time to sweep the full sweep bandwidth B [s]
$c$ is the speed of light [m/s].

The maximum range $R_{max}$ of the FMCW radar corresponds to a maximum frequency difference:

$$f_{max} = \frac{R_{max} * 2 * B}{t_{sweep} * c}$$

FMCW radars usually have a filter suppressing frequency differences above $f_{max}$.

For virtually all FMCW radars, $f_{max} << B$. The theoretical maximum range would be for $f_{max} = B$, or:

$$R_{th,max} = \frac{t_{sweep} * c}{2}$$

where $R_{th.max}$ is the theoretical maximum range [m].

The maximum range $R_{max}$ is hence determined by the processing having a filter cut-off at $f_{max}$. The filter largely contributes to the FMCW radar suppression of signals from interfering radars.

The generic lay-out for a radar is given in Figure 8-9, and shows the detector (frequency difference output), the filter and the frequency analyser (converting frequency to distance).

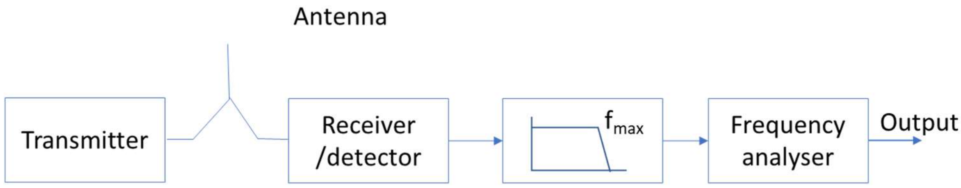


Figure 8-9 Generic lay-out FMCW radar.

As an example:
The FMCW radar uses 10 MHz bandwidth and has a sweep time of 5 ms. The maximum range is 1 km. If we measure a frequency difference of 10 kHz, this implies the distance is 750 m. The maximum frequency difference is 13.3 kHz.

Note that FMCW radars usually have short detection ranges, in the order of kilometres. As a consequence, FMCW frequency differences usually are in the audio range, for which processing is easy. Many components (AD converters, processing) are easily available. Range measurement merely requires a frequency analyser for audio frequencies.

Raymarine, Lowrance, Simrad, B&G[2] all have similar FMCW radar systems. For one of them the relevant specifications are given in Table 8.1, showing typical characteristics.

Table 8.1 Typical FMCW characteristics.

| | |
|---|---|
| Antenna Beamwidth Horizontal | 5.2°+/-10% (-3dB width) |
| Antenna Beamwidth Vertical | 25°+/-20% (-3dB width) ° |
| Transmitter Frequency | X-band - 9.3 to 9.4Ghz |
| Transmitter Power Output | (at antenna port) 100mW nominal |
| Sweep bandwidth B | 75 MHz max. |
| Sweep repetition frequency ($f_{sweep}$) | 200 Hz |
| Side lobe level | -25 dB (outside 10°) |

Given the antenna dimensions and frequency, the antenna gain can be estimated at 24 dBi.

## A.4 Radar range

The range at which a radar can detect depends on many factors: transmit power, antenna gain, noise figure, weather and target size. All these factors are radar system related, except for the weather and the target size. The actual maximum range hence depends on the target size. In addition, there must be “line of sight” between radar and target.

When the distance is too large, the target goes below the horizon, due to the earth’s curvature, as is shown in Figure 8-10. The radar horizon is a little “farther away” than the optical horizon, given the tendency of radar and radio waves to follow the earth’s curvature (assuming an earth radius of 4/3 the real radius gives the correct distance to the radar horizon). Of course, the radar horizon is also determined by the height of both target and radar antenna.
Typical values for the radar horizon are less than 10 km for low antennas as found on small ships. As with the optical horizon, it is possible to see large (high) objects beyond the horizon. Assuming the target is also a small ship, maximum ranges will be less than 15 km.

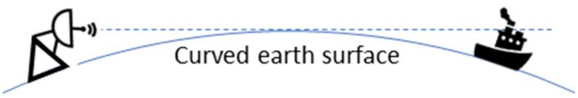


Figure 8-10 Radar horizon.

The range given in specifications often is the instrumented range, this is the maximum distance at which the returning radar signal would be properly processed, under the condition the signal strength is sufficient. These ranges can easily be 24 nm (44.5 km), but do not relate to the maximum distance a radar actually can see the (small) target).

[2] Lowrance, Simrad, B&G co-operate on their models.