



IALA GUIDELINE

GNNNN ON RADAR REFLECTORS ON AIDS-TO- NAVIGATION

Edition 0.1

Date (of approval by Council)

urn:mrn:iala:pub:gnnnn

DOCUMENT REVISION

Revisions to this document are to be noted in the table prior to the issue of a revised document.

Date	Details	Approval
03/2019	initial document	
09/2020 and 10/2020	further development during ENG12	
01/2022	further development during intersessional work	
02/2022	<ul style="list-style-type: none">- migration into the actual IALA guideline template- further development during intersessional work	
03/2022	further development during ENG15	
09/2022	further development, intersessional	

CONTENTS

1. INTRODUCTION	7
2. SCOPE	7
3. NOTES ON THE APPLICATION OF THIS GUIDELINE	8
3.1. Theoretical basics	8
3.2. horizontal and vertical reflection behaviour	8
3.3. pre-selection of potentially usable radar reflectors	9
3.4. Range determination	9
3.5. Final determination of the required radar reflector	9
4. RADAR AS AN ELECTROMAGNETIC WAVE	10
4.1. propagation of radar waves and maximal radar Range	10
4.2. Polarization of electromagnetic waves.....	11
5. THEORY AND PRINCIPLES OF RADAR WAVE REFLECTION.....	11
5.1. Directional reflection	11
5.2. Diffraction	11
5.3. Refraction	12
5.4. Scattering.....	12
5.5. Multipath propagation	12
5.6. Radar cross section (RCS).....	14
6. RADAR WAVE REFLECTION ON OBJECTS	16
6.1. radar wave reflection on simple Objects.....	16
6.1.1. Metal sheet.....	16
6.1.2. Cylinder.....	17
6.1.3. Bent sheet metal 90°	18
6.2. radar reflection on Complex shapes and structures.....	19
7. RADAR REFLECTORS: DEFINED AND REPRODUCIBLE REFLECTION OF RADAR WAVES	19
7.1. Task of a radar reflector.....	19
7.2. Requirements and Regulations.....	20
7.2.1. Radar specific requirements	20
7.2.2. Non-Radar specific requirements	20
7.2.3. Regulations by international bodys	20
7.3. Working principle - Corner reflector as a central component of radar reflectors	21
7.4. radar reflectors tailored to the respective application	21
7.4.1. Radar reflector for one main direction - Corner reflector	21
7.4.2. multidirectional radar reflectors	23
7.4.3. omnidirectional radar reflectors.....	24
8. DETECTION RANGE OF RADAR REFLECTORS	25

CONTENTS

8.1.	Overview	25
8.2.	Key parameters for calculating the maximum detection range	26
8.2.1.	Target parameters	26
8.2.2.	Propagation parameters	27
8.2.3.	Clutter parameters	28
8.2.4.	Radar equipment	28
8.3.	Typical achievable maximum radar ranges	29
9.	SIMULATION.....	34
9.1.	Possibilities and benefits	34
9.2.	Procedure, required data	34
10.	MEASUREMENT OF THE REFLECTION PROPERTIES OF RADAR REFLECTORS	35
10.1.	Concept for the measurement	35
10.2.	measurement example of a radar reflector	35
11.	INFLUENCE OF PLASTIC BY INSTALLING THE RADAR REFLECTOR IN A PLASTIC HOUSING	37
11.1.	considerations.....	37
11.2.	Summary of measurement and test results on the influence of plastic covers on the reflection behaviour of radar reflectors.....	37
11.3.	Priliminary results	37
12.	CONSTRUCTION	38
12.1.	general	38
12.2.	Materials	38
12.3.	Surface protection	39
12.4.	manufacturing quality	39
12.5.	Incoming goods inspection	39
12.6.	Further requirements	40
13.	MAINTENANCE	40
13.1.	Maintenance for outside mounted radar reflectors	40
13.2.	Maintenance for covered radar reflectors	40
14.	PROCUREMENT OF RADAR REFLECTORS	40
14.1.	Market available radar reflectors	40
14.2.	Manufacturing based on given specifications	41
15.	MOUNTING	41
16.	ACRONYMS	41
17.	REFERENCES	41
18.	ABBREVIATIONS	41
19.	SOFTWARE TOOLS	42

CONTENTS

20. LITERATURE.....	42
20.1.1. Measurment results	54

List of Tables

<i>Table 1: radar wave reflection of a metal sheet.....</i>	<i>16</i>
<i>Table 2: radar wave reflection of a metal cylinder.....</i>	<i>17</i>
<i>Table 3: radar wave reflection of a metal sheet bent to 90°.....</i>	<i>18</i>
<i>Table 4 : Minimum detection ranges in clutter-free conditions.....</i>	<i>20</i>
<i>Table 5: radar wave reflection of a corner reflector.....</i>	<i>22</i>
<i>Table 6: bidirectional double corner reflector / 180°.....</i>	<i>23</i>
<i>Table 7: omnidirectional 6 corner reflector “SR6-330”.....</i>	<i>24</i>
<i>Table 8: Typical achievable maximum radar ranges.....</i>	<i>33</i>
<i>Table 9: typical test concept.....</i>	<i>35</i>
<i>Table 10: tolerances.....</i>	<i>39</i>

List of Figures

<i>Figure 1: examples for different horizontal reflection properties.....</i>	<i>8</i>
<i>Figure 2: tilt angle of buoys</i>	<i>9</i>
<i>Figure 3: radar reflector.....</i>	<i>9</i>
<i>Figure 4: Directional reflection</i>	<i>11</i>
<i>Figure 5: Diffraction.....</i>	<i>11</i>
<i>Figure 6: Refraction</i>	<i>12</i>
<i>Figure 7: Scattering.....</i>	<i>12</i>
<i>Figure 8: Multipath propagation</i>	<i>12</i>
<i>Figure 9: Radar cross section.....</i>	<i>14</i>
<i>Figure 10: steel beacon without radar reflector.....</i>	<i>19</i>
<i>Figure 11: dolphin with.....</i>	<i>19</i>
<i>Figure 12: reflection principle of a corner reflector</i>	<i>21</i>
<i>Figure 13: corner reflector</i>	<i>21</i>
<i>Figure 14: Corner reflector on a bridge</i>	<i>21</i>
<i>Figure 15: buoy with fixed orientation to the waterway.....</i>	<i>23</i>
<i>Figure 16: plastic buoy.....</i>	<i>24</i>

CONTENTS

Figure 17: Range parameters	25
Figure 18: Plastic buoy type “B7”with internal radar reflector	27
Figure 19: Plastic buoy type “LB3000-WSV” with internal radar reflector.....	27
Figure 20: Detection probability of a target with $RCS = 10 \text{ m}^2$,.....	30
Figure 21: Detection probability of a target with $RCS = 10 \text{ m}^2$, seastate 3, <i>with multipath propagation</i>	30
Figure 22: Detection probability of a target with $RCS = 10 \text{ m}^2$, <i>seastate 7</i>	31
Figure 23: Detection probability of a target with $RCS = 10 \text{ m}^2$, with <i>evaporation duct (height 10 m)</i>	31
Figure 24: Detection probability of a target with $RCS = 10 \text{ m}^2$, with <i>rainfall (4 mm/hr)</i>	31
Figure 26: RCS-simulation for a metal sheet	34
Figure 27: radar reflector on measuring tower, elevation angle 0°	35
Figure 28: radar reflector on measuring tower, elevation angle 10°	35
Figure 29: measurement results at 0° elevation.....	36
Figure 30: measurement results at -10° elevation	36
Figure 31: measurement results at -20° elevation	36
Figure 32: measurement results at -30° elevation	36
Figure 33: welded radar reflector	38
Figure 34: radar reflector consisting of single corner reflectors mounted on a structure.....	38
Figure 35 plastic insulation between different metals	38
Figure 36: plastic buoy.....	39
Figure 37: steel buoy.....	39
Figure 38: surface protected with colour.....	40
Figure 39: SR6 radar reflector.....	53
Figure 41: Spherical 3D RCS plot.....	54
Figure 42: RCS at 0° , -10° , -20° and -30°	54
Figure 43: first sample	54
Figure 44: RCS at 0° , -10° , -20° and -30°	54
Figure 45: measurement results, attenuation of plastic samples	55
Figure 46: test setup	55
Figure 47: radar reflector without cover	55
Figure 48: radar reflector with plastic cover.....	55
Figure 49: Result of the comparative measurements at 9.4 GHz and 0° elevation:.....	55
Figure 50: Setup for free field measurements on land	55
Figure 51: RF absorber.....	55
Figure 52: measurement setup.....	55
Figure 53: "SZM Bussard"(small buoy tender).....	55
Figure 54: simulated maximum radar range	55
Figure 55: radar picture	55

1. INTRODUCTION

Navigational radar equipment plays an important role in the navigation of vessels by providing reliable, safety related traffic information to the captain. Radar enables the surveillance of the traffic situation around the own vessel, including landmarks, other vessels and aids to navigation (AtoN). Radar has the capability to detect objects even in poor visibility conditions such as darkness, fog and, with some restrictions, even in heavy precipitation, snow or hail. Radar is non-cooperative, i.e. other objects can be detected without been equipped with a radar themselves. The probability of detection of an object by radar highly depends on the intensity an object reflects the radar wave back to the radar.

However, not all objects reflect the radar wave with the same intensity, depending on the geometry, dimension, material properties and roughness of the surface. Large structures, such as big vessels, typically made of steel, are well suited for detection by radar since metal is a good conductor of electric currents and therefore reflects almost all of the energy of an incident electromagnetic wave. Other objects, especially when made of non-metal material such as plastic, do not reflect the electromagnetic radar wave as well.

To increase the probability of radar detection of an object while making the reflection properties reproducible and measurable, it can be equipped with a radar reflector.

Radar reflectors are optimized to reflect the incident radar wave back to the radar with the highest possible intensity.

When selecting an appropriate radar reflector for an application, also mechanical and construction aspects have to be considered.

Especially for AtoN it is recommended to equip them with radar reflectors to make them most visible for vessels, sailing under radar.

2. SCOPE

This guideline deals exclusively with passive radar reflectors. In comparison, active radar reflectors, such as radar markers and radar target enhancers, have better radar reflectivity properties, but for large-scale deployment on AtoN in adverse maritime environments, passive radar reflectors are more suitable. The main reasons for this are that passive radar reflectors have

- a high robustness;
- a long service life (usually as long as the AtoN itself);
- a low or no technical maintenance efforts;
- a high reliability and
- a low total costs of ownership.

The guideline is intended to help maritime administrations and manufacturers to select and dimension a suitable radar reflector for an AtoN. Among other things, it describes

- applicable international requirements and standards;
- theoretical principles of radar waves and their reflection;
- examples for radar reflectors in use and
- possibilities for range calculations.

Racon and Radar Search and Rescue Transponder (SART) are not covered by this guideline.

- For Racons see: IALA Recommendation R-101 On Marine Radar Beacons (Racons), Edition 2 December 2004 [IALA1] and IALA Guideline No. 1010 On Racon Range Performance [IALA2].
- Radar SART are subject to Rec. ITU-R M.628-3 [ITU].

Luneberg reflectors are also not covered by this guideline.

Luneberg reflectors are applications of the so-called Luneberg lens. Luneberg - lenses are radiolucent, inhomogeneous dielectric spheres [LUN 1]. They offer over the complete azimuth and up to an elevation of about 20 ° an almost constant reflection value. As a result, they are ideal to be used as a reference radar reflector in a measurement environment. However, they have not yet become significant for usage on AtoNs. The reason for this is the unavoidable absorption and reflection losses in the dielectric material. In addition, they do not have any mechanical strength; even slight damage to the protective layer poses the risk of water penetrating into the interior of the lens and rendering it ineffective. Luneberg reflectors are considerably more expensive and can be produced economically only up to a certain RCS size (order of magnitude 10 m²).

3. NOTES ON THE APPLICATION OF THIS GUIDELINE

As described in the scope, this guideline is intended to help finding an appropriate radar reflector for a particular application. Using the guideline, this can be done via the following steps:

3.1. THEORETICAL BASICS

Understand the theoretical principles of radar waves and their reflection based on chapters 4, 5 and 6.

3.2. HORIZONTAL AND VERTICAL REFLECTION BEHAVIOUR

The desired horizontal reflection behaviour results from the required direction(s) of reflection according to Figure 1:

- Only one reflection direction may be required e. g. for marking the pylons of a bridge (1).
- Two or more reflection directions could be necessary for buoys with a fixed orientation to the waterway (2).
- Often an omnidirectional reflection behaviour is needed for buoys at the open sea. (3).

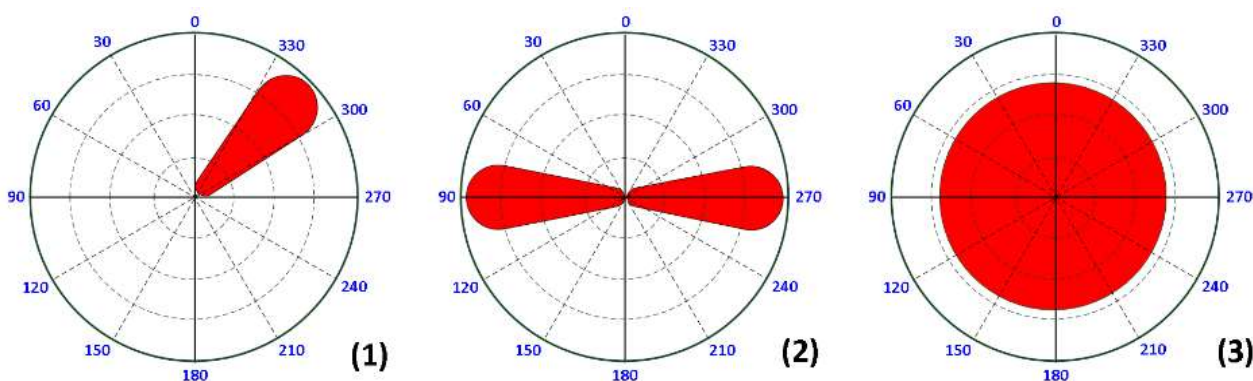


Figure 1: examples for different horizontal reflection properties

Also the vertical reflection angle(s) have to be considered. Is the radar reflector for the use on buoys, their maximum tilt angle has to be taken into account, see Figure 2. This could be from -20° to 0° to $+20^{\circ}$ for example.

For the use on fixed structures the vertical reflection angle may be smaller.

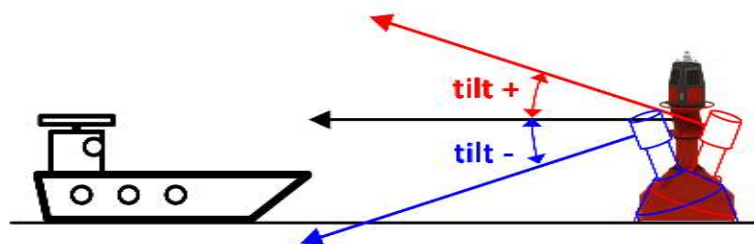


Figure 2: tilt angle of buoys

3.3. PRE-SELECTION OF POTENTIALLY USABLE RADAR REFLECTORS

Chapter 7 and ANNEX A give a rough overview of potentially usable radar reflectors. Environmental conditions, installation possibilities and maintenance requirements should also be taken into account in accordance with chapters 12, 13, 14 and 15.

3.4. RANGE DETERMINATION

Chapter 8 explains the theory for the (not quite trivial) calculation of the reflector range. The maximum reflector range can be derived from the radar cross section (RCS), see chapter 5.6. The table at the end of chapter 8 helps to determine it.

3.5. FINAL DETERMINATION OF THE REQUIRED RADAR REFLECTOR

Based on the pre-selection and the required RCS value, the final design of the radar reflector results. It is important to note here:

- The RCS value is directly related to the reflector size.
- For simple corner reflectors, this value can be easily calculated according to chapter 7.4.1.
- For more complex reflectors, the characteristic of the radar reflector should be measured or simulated. See ANNEX A for examples of simulated radar reflectors.
- ANNEX C shows examples for the dimensioning of radar reflectors for buoys.



Figure 3: radar reflector type "SR6" on a steel buoy

4. RADAR AS AN ELECTROMAGNETIC WAVE

4.1. PROPAGATION OF RADAR WAVES AND MAXIMAL RADAR RANGE

A radar wave is an electromagnetic wave with an electric and a magnetic field component. In free space, these two field vectors are perpendicular to each other. The propagation of the radar wave is orthogonal to both field components with the velocity v . This can be expressed by Equation (1):

$$v = \frac{1}{\sqrt{\mu_0 \mu_r \epsilon_0 \epsilon_r}} = \frac{c}{\sqrt{\epsilon_r \mu_r}} \quad (1)$$

where:

- v = speed of propagation;
- μ_0 = $4\pi \times 10^{-7}$ H/m, vacuum permeability;
- μ_r = relative permeability;
- ϵ_0 $\approx 8,8542 \times 10^{-12}$ F/m permittivity of free space / electric constant;
- ϵ_r = relative permittivity;
- c \approx speed of light, 299 792 458 m/s.

For propagation in free space, the following special case applies:

$$\epsilon_r = 1 \quad \mu_r = 1$$

This means that the radar wave propagates in air, in very good approximation, with the speed of light, i.e. approximately 299 792 km/s.

The maximum range can be calculated according to Equation (2):

$$R_{max} = \sqrt[4]{\frac{P_t G_t G_r \sigma \lambda^2 F_t^2 F_r^2}{(4\pi)^3 P_r}} \quad (2)$$

where:

- R = radar-to-target distance (range);
- P_t = transmitted-signal power;
- G_t = transmitting-antenna gain;
- G_r = receiving-antenna gain;
- σ = radar target cross section;
- λ = wavelength;
- F_t = pattern propagation factor for transmitting-antenna-to-target path;
- F_r = pattern propagation factor for target-to-receiving-antenna path;
- π $\approx 3,14159$; mathematical constant;
- P_r = received-signal power.

Note: Under ideal conditions, for a target in free space and in the maxima of both the transmit and receive antenna patterns, $F_t = F_r = 1$.

The propagation of electromagnetic waves follows quasi-optical laws, presuming normal conditions, i.e. a uniform and constant medium. However, effects such as absorption, scattering, total reflection, dispersion and super- and sub-refraction due to ducting etc. have an impact on the propagation of radar waves and the maximal range of detection of an object.

4.2. POLARIZATION OF ELECTROMAGNETIC WAVES

The polarization plane of an electromagnetic wave is the spatial plane in which the electric field component oscillates. There are linear and circular polarized electromagnetic waves. The representatives of linear polarization are horizontal and vertical polarization.

While coastal surveillance radars (VTS radar) sometimes utilize vertical or circular polarized radar waves, the most VTS radars and nearly all shipborne radars have horizontal polarized antennas to generate horizontal polarized radar waves.

5. THEORY AND PRINCIPLES OF RADAR WAVE REFLECTION

When the radar wave hits a metallic conductive object, the entire electromagnetic wave is reflected with a phase shift of 180° in the electric field component. The angle of incidence is equal to the angle of reflection. When the object is electrically non-conductive and non-magnetic, parts of the energy penetrate into the medium while the rest is reflected.

There are several types of effects that affect the propagation path of an electromagnetic wave, such as directional reflection, diffraction, refraction, and diffuse reflection.

5.1. DIRECTIONAL REFLECTION

The radar principle is based on the retro reflection of the electromagnetic wave from objects. The strongest form of retro reflection is the "directional reflection", also known as "mirror reflection", see Figure 4.

The angle of incidence θ_i is equal to the angle of reflection θ_r .

When an electromagnetic wave hits a flat metallic object at an incident angle of 0° , the energy of the incident wave is reflected back to the transmitter.

5.2. DIFFRACTION

Sharp edges, peaks or even spherical surfaces ("circulating wave") as shown in Figure 5 can affect the propagation of the radar waves. This effect is called diffraction. Therefore, under certain conditions, it is possible for the radar to detect objects outside the line-of-sight behind a large obstacle.

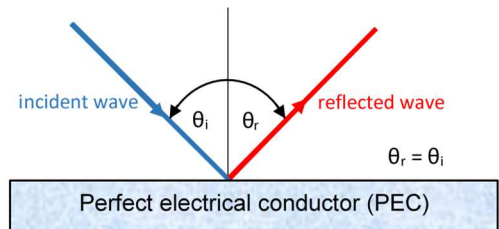


Figure 4: Directional reflection

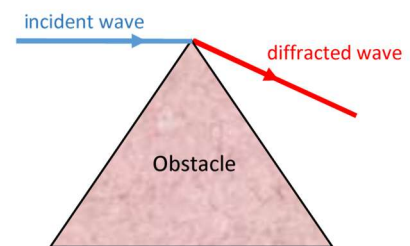


Figure 5: Diffraction

5.3. REFRACTION

When an electromagnetic wave passes from one non-conductive, non-magnetic medium into another non-conductive, non-magnetic medium, a part of the energy is reflected. The angle of incidence θ_i is equal to the angle of reflection θ_r as shown in Figure 6.

The other part penetrates into the second medium under a certain angle θ_t , which does not equal the angle of incidence θ_i . The wavelength and propagation velocity of the wave is different in both materials.

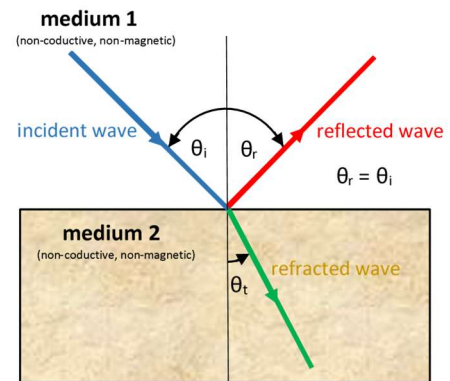


Figure 6: Refraction

5.4. SCATTERING

Vegetation on the large scale and the roughness of the surface of a material on the small scale causes an incident radar wave to scatter in any direction, see Figure 7. This is known as scattering. The rougher the surface, the larger the spatial angle into which the energy is reflected.

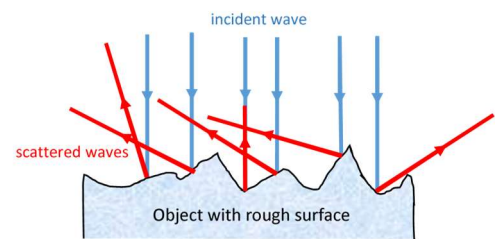


Figure 7: Scattering

5.5. MULTIPATH PROPAGATION

The electromagnetic radar wave reflected from an object does not only return to the radar antenna by a direct path. A part of the energy returns along different paths. A typical return path is the reflection from the water surface as shown in Figure 8.

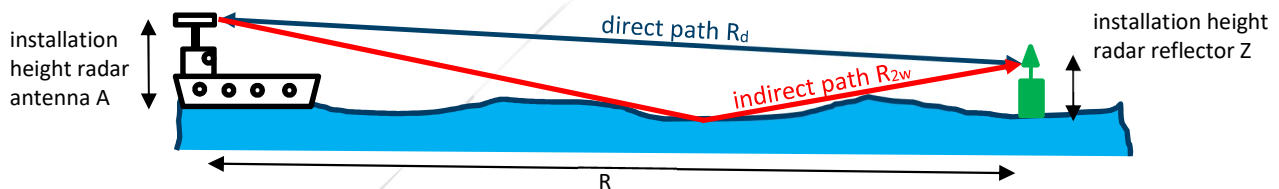


Figure 8: Multipath propagation

At the radar antenna, the returning radar waves from the different spatial directions overlap. In extreme case, this can lead to addition (if the two waves have the same phase) or to complete cancellation of both signals (if the two waves have opposite phases). This effect is most prominent in calm seas and decreases with increasing sea state ("clutter").

The maximal degradation occurs when the difference $\Delta R = R_{2w} - R_d$ equals odd multiples of half the wavelength λ . This is expressed in Equation (3):

$$\Delta R_{max.degradation} = n \cdot \frac{\lambda}{2} \text{ with } n = 1, 3, 5 \text{ etc.} \quad (3)$$

where:

- ΔR = difference in distance between R_{2w} and R_d ;
- n = sequential number;
- λ = wavelength;
- R_{2w} = length of indirect path;
- R_d = length of indirect path.

For navigational radars, operating in the x-band, the free space wavelength is about 3,19 cm.

In good approximation, the difference length ΔR can be calculated as shown with Equation (4):

$$\Delta R = R_{2w} - R_d \sim 2 \cdot \frac{A \cdot Z}{R_d} = 2 \frac{A \cdot Z}{\sqrt{R^2 + (A - Z)^2}} \quad (4)$$

where:

- ΔR = difference in distance between R_{2w} and R_d ;
- R_{2w} = length of indirect path;
- R_d = length of indirect path;
- R = distance between radar antenna and target;
- A = installation height of radar antenna;
- Z = installation height of radar reflector on target.

5.6. RADAR CROSS SECTION (RCS)

The intensity of the echo, scattered back to the source of the wave (i.e. the radar), is expressed by the radar cross section RCS.

Among other parameters, size, shape and especially orientation of an object have a deep impact on its RCS. Hence, an object has not only one RCS. It has a RCS for any spatial direction.

According [2], the „RCS is the projected area of a metal sphere which is large compared with the wavelength and which, if substituted for the object, would scatter identically the same power back to the radar (...). The symbol σ has been widely accepted as the designation for the RCS of an object”. Figure 9 illustrates this definition.

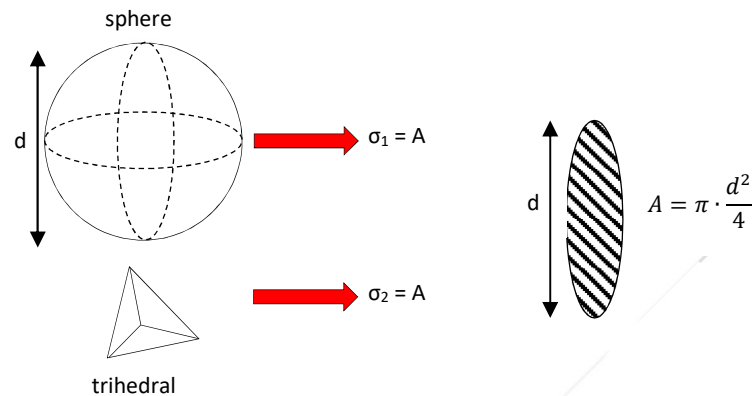


Figure 9: Radar cross section

It is important to understand that the RCS is not directly related to physical dimensions of an object. A metal plate with a geometric dimension of 1 m² has for example a much higher maximal RCS (in the range of several thousand m²).

According [2], the formal definition of radar cross section is:

$$\sigma = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{|E_s|^2}{|E_0|^2} \quad (5)$$

where:

- σ = radar cross section RCS;
- π \approx 3,14159; mathematical constant;
- R = range from radar to target;
- E_s = electric-field strength of the scattered wave at the radar;
- E_0 = electric-field strength of the incident wave impinging on the target;

As this electric field depends on the electric dimensions of the object, the RCS for a given spatial direction of an object also depends on the wavelength of the incident radar wave. As a result, an object has different RCS values for X-band and S-band radar. In case of free propagation, the radar cross section area σ can be measured by the following equation:

$$\sigma = \frac{(4\pi)^3 P_r R^4}{P_t G_t G_r \lambda^2 F_t^2 F_r^2} \quad (6)$$

where:

- σ = radar target cross section RCS;
- π $\approx 3,14159$; mathematical constant;
- P_r = received-signal power;
- R = radar-to-target distance (range);
- P_t = transmitted-signal power;
- G_t = transmitting-antenna gain;
- G_r = receiving-antenna gain;
- λ = wavelength;
- F_t = pattern propagation factor for transmitting-antenna-to-target path;
- F_r = pattern propagation factor for target-to-receiving-antenna path.

Note: Under ideal conditions, for a target in free space and in the maxima of both the transmit and receive antenna patterns, $F_t = F_r = 1$.

The RCS of an object is an important parameter to calculate the maximum distance in which it can be detected by a radar.

6. RADAR WAVE REFLECTION ON OBJECTS

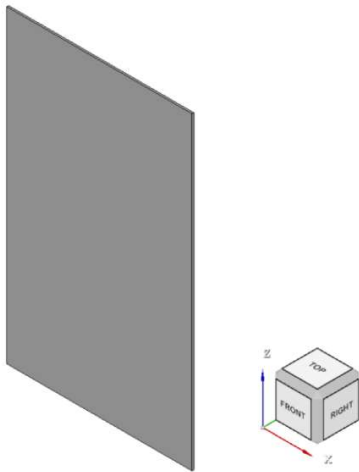
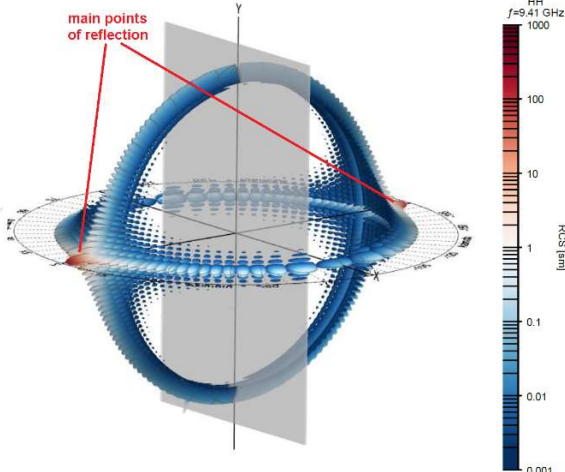
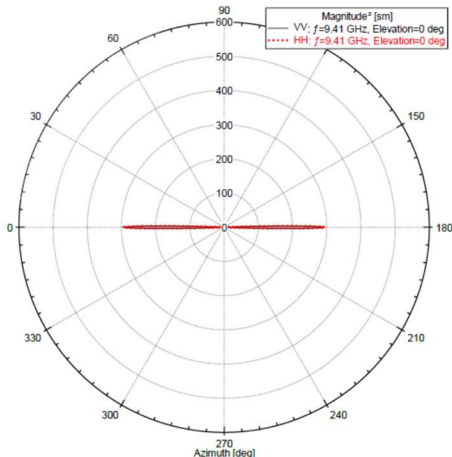
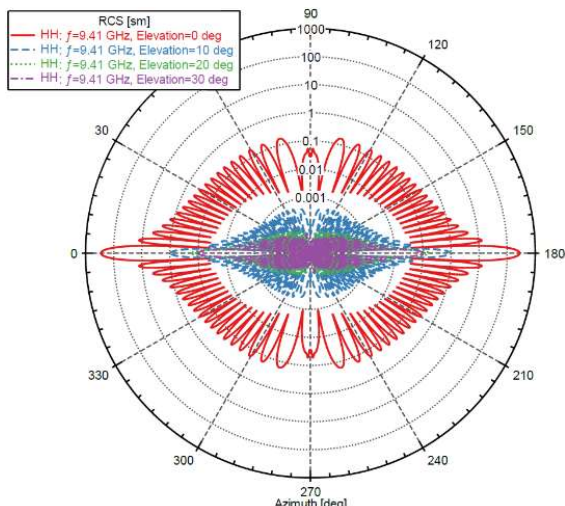
6.1. RADAR WAVE REFLECTION ON SIMPLE OBJECTS

Objects made of metal are generally capable of reflecting incident radar waves. Depending on their shape, the respective reflection behavior results. Simple shapes such as sheets, cylinders etc. produce a radar echo that is relatively easy to describe, see the following sections (6.1.1 - 6.1.3). Note: The results shown in the graphs were simulated based on 3D models, the procedure is described in chapter 9.

6.1.1. METAL SHEET

When a radar wave hits a flat metal sheet, the energy is reflected back to the radar only in the case of a perpendicular incident radar wave. Under different angles, only a very small portion is back scattered due to diffraction, see Table 1. A single metal sheet is therefore not suitable as a radar reflector in practice.

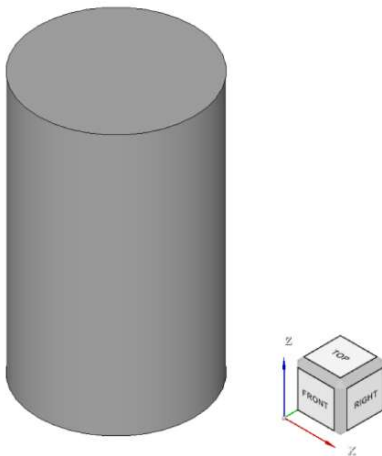
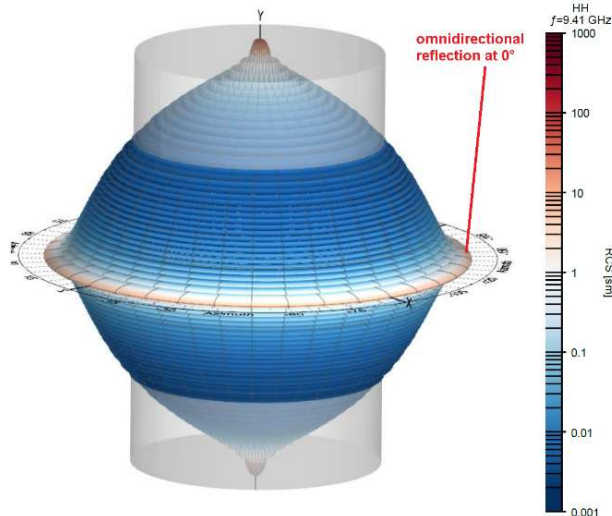
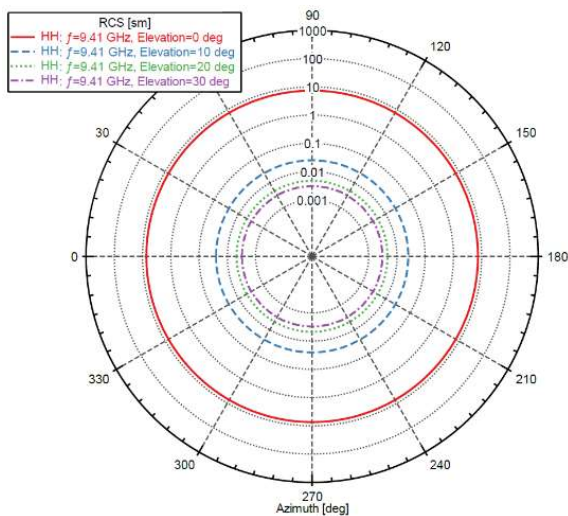
Table 1: radar wave reflection of a metal sheet

Dimensions of simulated sheet (mm)	Max. RCS (m ²)	Short description
width: 300 / height: 500 / thickness: 3	300	two main reflection directions in case of perpendicular incident wave
<div>3D-view</div> <div></div>	<div>3D-reflection diagram (rectangular)</div> <div></div>	
<div>2D reflection diagram, different tilt angles, linear</div> <div></div>	<div>2D reflection diagram, different tilt angles, logarithmic</div> <div></div>	

6.1.2. CYLINDER

A metal cylinder gives a nearly perfect omni-azimuthal reflection characteristic, but only for an elevation of 0°. Any tilting of the cylinder reduces the reflectivity significantly (Table 2). A cylinder is therefore not suitable as a radar reflector in practice.

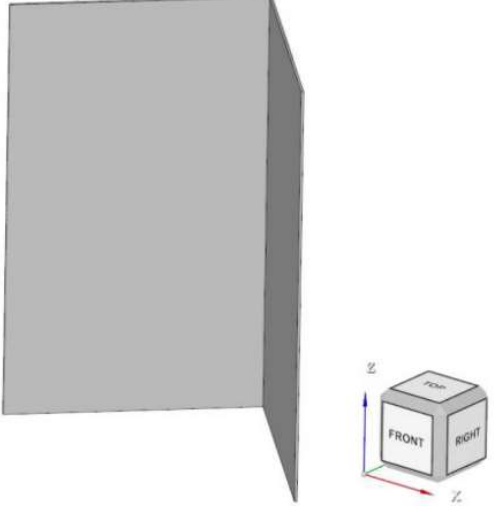
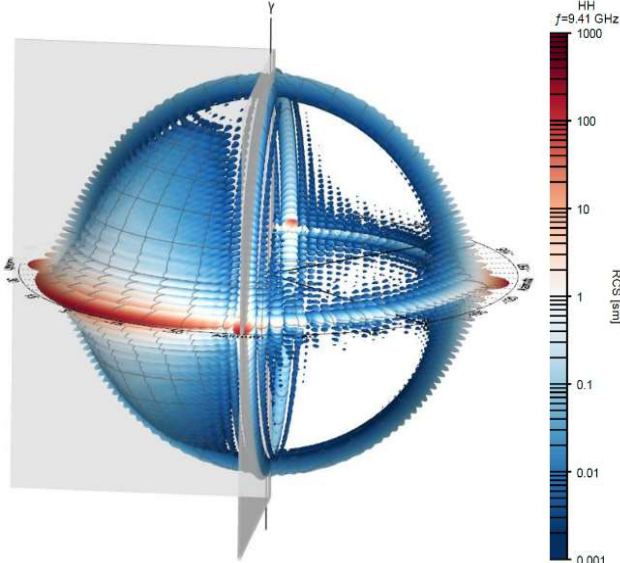
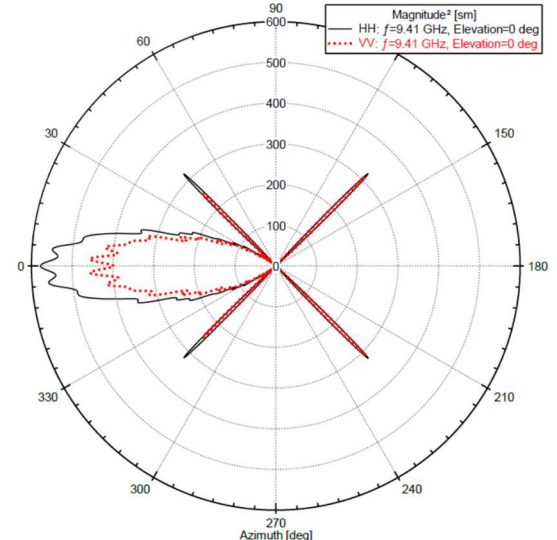
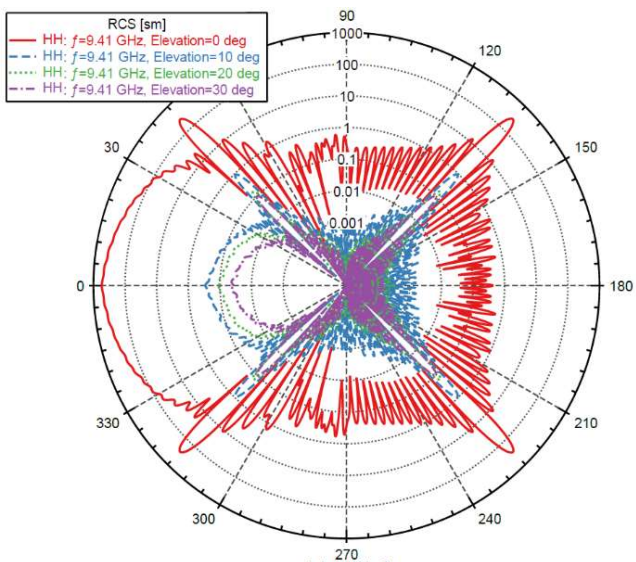
Table 2: radar wave reflection of a metal cylinder

Dimensions of simulated cylinder (mm)	Max. RCS (m ²)	Short description
diameter: 300 / height: 500	10	nearly perfect omnidirectional reflection, but only for an elevation of 0°
3D-view	3D-reflection diagram (rectangular)	
		
2D reflection diagram, different tilt angles, linear	2D reflection diagram, different tilt angles, logarithmic	
Missing in MARCH report		

6.1.3. BENT SHEET METAL 90°

A bent sheet metal 90° gives a good sectional reflection characteristic, but only for an elevation of 0°. Any tilting of the bent metal 90° reduces the reflectivity significantly, see Table 3. Therefore, even a metal bent by 90° cannot be used as a radar reflector in practice.

Table 3: radar wave reflection of a metal sheet bent to 90°

Dimensions of simulated bent sheet (mm)	Max. RCS (m2)	Short description
width: 425 / height: 500 / depth: 215	600	good sectional reflection characteristic, but only for an elevation of 0
3D-view 		3D-reflection diagram (rectangular) 
2D reflection diagram, different tilt angles, linear 		2D reflection diagram, different tilt angles, logarithmic 

6.2. RADAR REFLECTION ON COMPLEX SHAPES AND STRUCTURES

On more complex shapes and constructions, such as beacons made of steel (Figure 10), the radar reflection occurs on the various components of the object, e.g. on surfaces, cylindrical shapes, edges, corners, etc.

The reflected radar waves are superimposed, resulting in a more or less undefined and strongly direction-dependent reflection behaviour. Therefore, objects that are not specifically designed for the reflection of radar waves are only suitable as radar reflectors to a limited extent in practice. As a rule, the installation of a radar reflector with defined reflection properties is recommended here.



Figure 10: steel beacon without radar reflector

7. RADAR REFLECTORS: DEFINED AND REPRODUCIBLE REFLECTION OF RADAR WAVES

7.1. TASK OF A RADAR REFLECTOR

A radar reflector improves the probability of detection by radar significantly by increasing the intensity of the back scattered radar wave. Especially when a radar reflector is mounted on an AtoN, which is made of non-conductive material such as plastic, this can substantially improve visibility by radar.

In addition, a radar reflector can increase the availability of an object in the radar image. As described in section 6.2, an object without a radar reflector does not reflect the radar wave uniformly over all solid angles, depending on the shape of the object. Fluctuation must also be taken into account. A radar reflector should have a defined reflection behaviour over a certain range of spatial angles. In accordance with these limits, the availability of a radar reflector is very good predictable.

As an example, Figure 11 shows a dolphin made of steel, which by itself has a reflection behaviour according to section 6.1.2. In order to obtain a defined and reproducible reflection behaviour, the dolphin was additionally equipped with a radar reflector.



Figure 11: dolphin with radar reflector

7.2. REQUIREMENTS AND REGULATIONS

7.2.1. RADAR SPECIFIC REQUIREMENTS

A radar reflector should meet the following radar specific requirements:

- high, uniform reflectivity over the entire azimuth (omni-azimuthal reflective radar reflector) or sector (sectoral reflective radar reflector);
- reasonable reflection up to an elevation of about 30°;
- optimized radar reflection behaviour for the relevant radar frequency.

7.2.2. NON-RADAR SPECIFIC REQUIREMENTS

Design related and assembly related requirements are discussed in the chapter 12 and following.

7.2.3. REGULATIONS BY INTERNATIONAL BODYS

The International Maritime Organization, IMO, defines regulations for shipborne equipment. IMO does not define requirements for radar reflectors used on AtoN. However, it assumes a certain specification (in terms of a RCS value) for AtoN, to be able to define minimum performance requirements for shipborne radar installations, mandated by the 1974 SOLAS Convention, resulting in minimum detection ranges.

According to IMO Resolution MSC.192(79)[2], in clutter-free conditions, a shipborne radar with an antenna height of 15 m above sea level shall detect a typical navigation buoy with a height of 3,5 m above sea level, equipped with a radar reflector, in the range given in Table 4.

Table 4: Minimum detection ranges in clutter-free conditions		
	RCS of navigation buoy with corner reflector ¹	Minimum Detection Range ¹
X-band radar	10 m ²	4,9 NM
S-band radar	1 m ²	3,6 NM

Note 1: clutter-free conditions is understood as normal propagation conditions, in the absence of sea clutter, precipitation and evaporation duct

Note 2: A typical navigation buoy is taken as 5,0 m² for X-band and 0,5 m² for S-band.

Note 3: The detection of the target is based on an indication of the target in at least 8 out of 10 scans or equivalent and a probability of a radar detection false alarm of 10⁻⁴.

SOLAS Chapter V (Safety of Navigation), issued by IMO, requires, that all “ships irrespective of size shall have (...) if less than 150 gross tonnage and if practicable, a radar reflector or other means, to enable detection by ships navigating by radar at both 9 and 3 GHz” [3].

ISO 8729-2010 [4], issued by International Organization for Standardization ISO, specifies the minimum requirements for a radar reflector intended to be used on small vessels. It lays down the specification for construction, installation, testing and inspection of such radar reflectors.

ISO 8729-2010 requires for x-band a maximum radar cross section of at least 10 m². In addition, the “azimuthal polar diagrams shall be such that its response over a total angle of 240 ° is not less than – 6 dB with respect to the maximum echoing area. The response shall not remain below this level over any single angle of more than 10°”.

For the vertical plane, [4] requires that “the performance of the reflector, up to at least ± 15° from the horizontal shall be such that its response at any inclination remains above – 12 dB with respect to its maximum echoing area over the total angle of at least 240°”.

7.3. WORKING PRINCIPLE - CORNER REFLECTOR AS A CENTRAL COMPONENT OF RADAR REFLECTORS

Usually a radar reflector has several metal surfaces arranged at a certain angle to each other, at which a "directed reflection" of the radar waves takes place. The reflection principle can be demonstrated best using the example of a corner reflector. The basic principle of a corner reflector is based on the triple mirror. This consists of three reflecting surfaces at an angle of 90 degrees to each other. This arrangement ensures that the incident radiation is returned almost exactly to the sender of the radiation, see Figure 12.

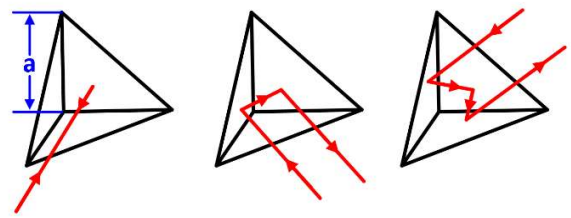


Figure 12: reflection principle of a corner reflector

The reflection effect of these reflectors is physically determined by two factors: The wavelength of the radiation to be reflected and the length of the inner edges of the mirror arrangement. The reflection increases with increasing frequency and increasing edge length.

7.4. RADAR REFLECTORS TAILORED TO THE RESPECTIVE APPLICATION

7.4.1. RADAR REFLECTOR FOR ONE MAIN DIRECTION - CORNER REFLECTOR

Some applications require a radar reflection in only one main direction (see Figure 1 (1)). This can be realized with a single corner reflector, designed to scatter back the radar wave into one spatial sector. Technically, the corner reflector is a trihedral.

Under the assumption of some simplifications, which are not described here in detail, the calculation of the reflecting area RCS is based on the following Equation (7) considering Figure 13.

$$\sigma_{\text{Corner reflector}} \approx \frac{4\pi \cdot a^4}{3 \cdot \lambda^2} \quad (7)$$

where:

- σ = radar cross section of a corner reflector;
- π \approx 3,14159; mathematical constant;
- a = inner length of edge as shown in Figure 13;
- λ = wavelength.

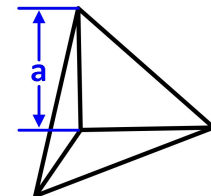


Figure 13: corner reflector

Example:

A radar reflector with an inner edge length of 42 cm achieves a reflection area of approx. 128 m² at a radar frequency of 9,4 GHz (λ = 3,19 cm).

The maximum RCS of the corner reflector is proportional to the fourth power of its side length. To achieve a high RCS value, the side length should therefore be chosen as large as possible.

Corner reflectors are for example used on bridges to indicate the position of the pylon to the captain, see Figure 14.

Table 5 shows the relevant parameters of a corner reflector.

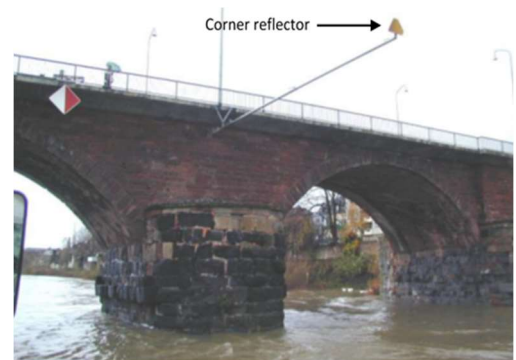
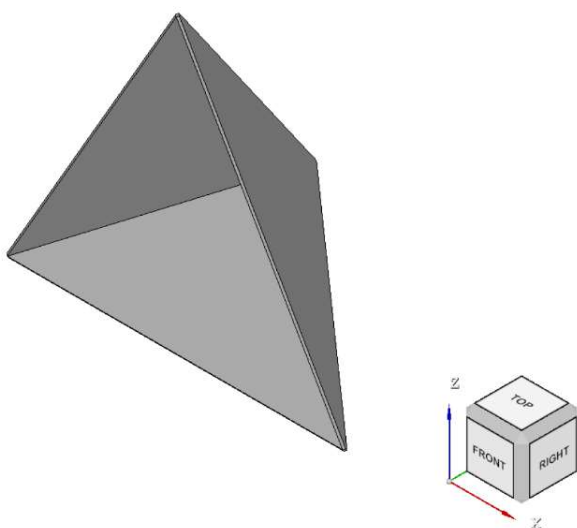
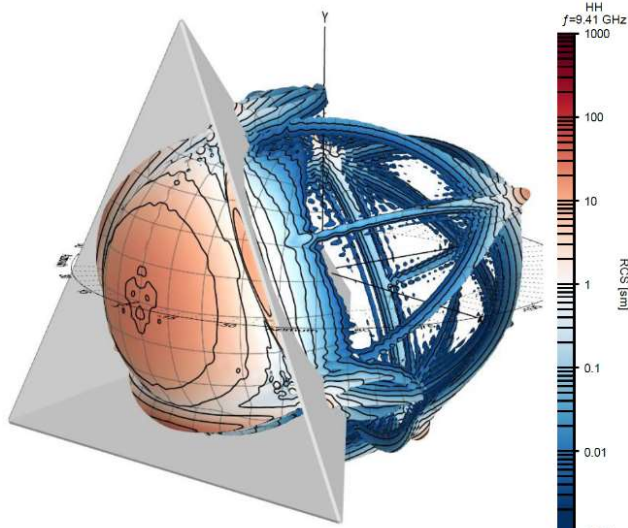
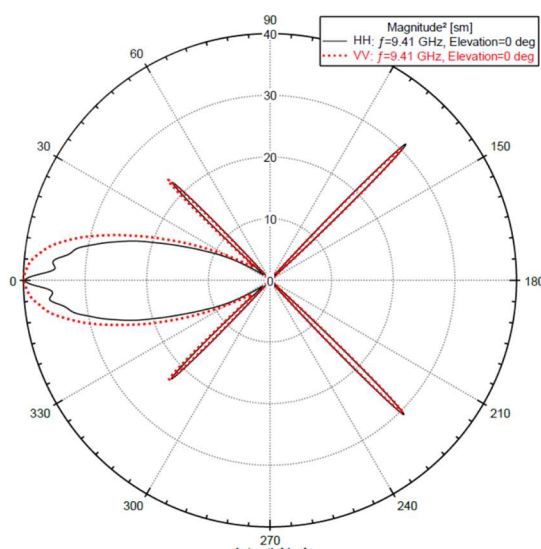
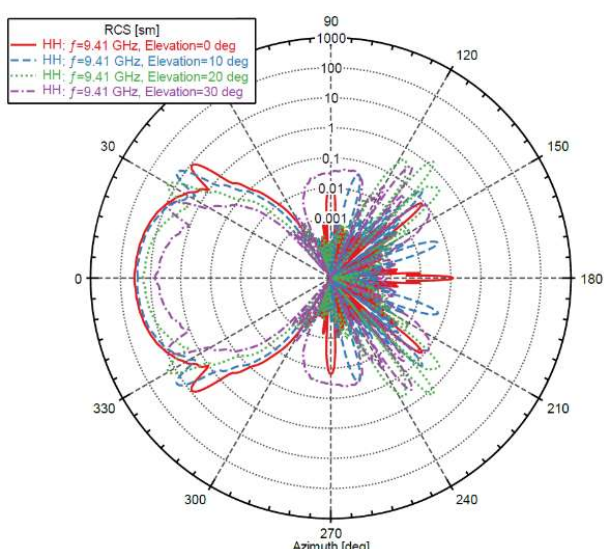


Figure 14: Corner reflector on a bridge

Table 5: radar wave reflection of a corner reflector

Dimensions of simulated corner reflector (mm)	Max. RCS (m ²)	Short description
width: 429 / height: 303 / depth: 217	40	scatters back the radar wave into one spatial sector.
3D-view 		3D-reflection diagram (rectangular) 
2D reflection diagram, different tilt angles, linear 		2D reflection diagram, different tilt angles, logarithmic 

Beside the corner reflector, other sectorial reflective radar reflectors with different characteristics are in use. This can be multi- or omnidirectional reflectors as shown in the following.

7.4.2. MULTIDIRECTIONAL RADAR REFLECTORS

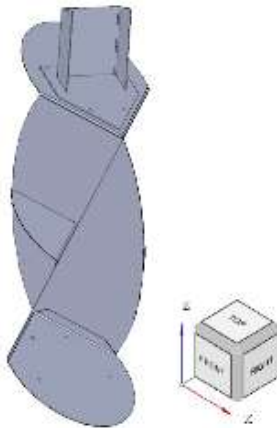
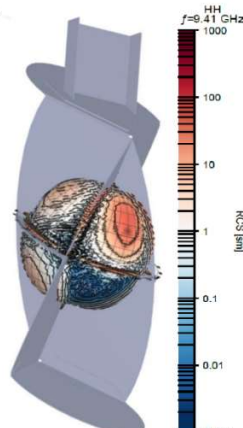

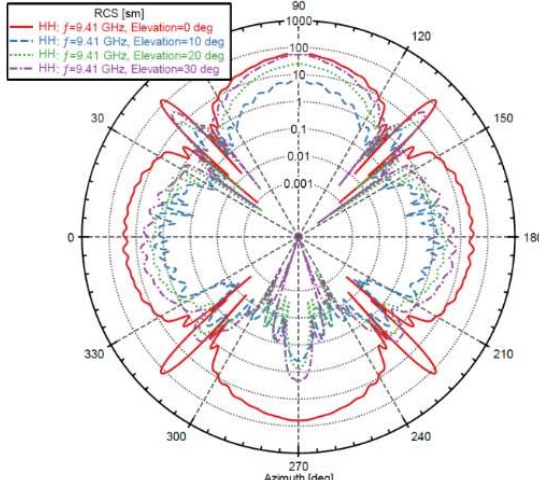
For reflections in several directions, a multiple arrangement of individual corner reflectors is usually chosen. In this case, corner reflectors are combined with each other in such a way that the superimposition of the reflections of the individual corner reflectors results in the desired overall reflection behavior.

For buoys, who have a fixed orientation to the waterway by the design of their mooring, reflection in two main directions may be sufficient. An application example for this are plastic buoys on rivers with currents according to Figure 15. The radar reflector is mounted internally. The impact of the surrounding plastic hull is described in chapter 11. Table 6 shows the relevant parameters of a reflector with two main reflection directions based on a simulation.



Figure 15: buoy with fixed orientation to the waterway

Table 6: bidirectional double corner reflector / 180°

Dimensions of simulated corner reflector (mm)	Max. RCS (m ²)	Short description
Ø: 250mm / height: 700mm	?	2 main reflection directions designed for plastic buoys (mounted inside, protected)
<div>3D-view</div> <div></div>	<div>3D-reflection diagram (rectangular)</div> <div></div>	
<div>2D reflection diagram, different tilt angles, linear</div> <div></div>	<div>2D reflection diagram, different tilt angles, logarithmic</div> <div></div>	

7.4.3. OMNIDIRECTIONAL RADAR REFLECTORS

Often an almost constant reflection in the horizontal plane (omnidirectional) is needed, e.g. for buoys at the open sea. A good omnidirectional radar reflector has an almost equal reflection pattern with a high RCS that remains approximately the same at different tilt angles. To achieve this, typically 5, 6, 8 or 10 individual corner reflectors are combined. However, developing a closed reflection pattern is a difficult task, because the sidelobes of multiple reflectors have both constructive and destructive interference. This can lead to more or less large dips in the reflection pattern. The six tightly packed corner reflectors of the type "SR6" has proven to be a good compromise of all properties. Figure 16 shows a plastic buoy with an internal "SR6"-reflector, Table 7 illustrates the reflection properties. The impact of the surrounding plastic hull is described in chapter 11.

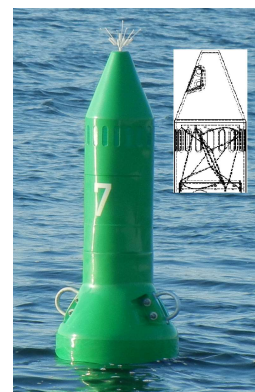
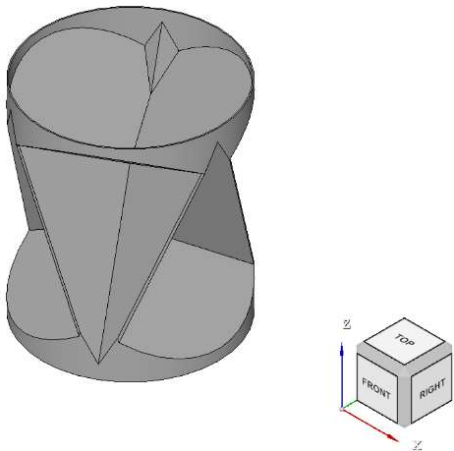
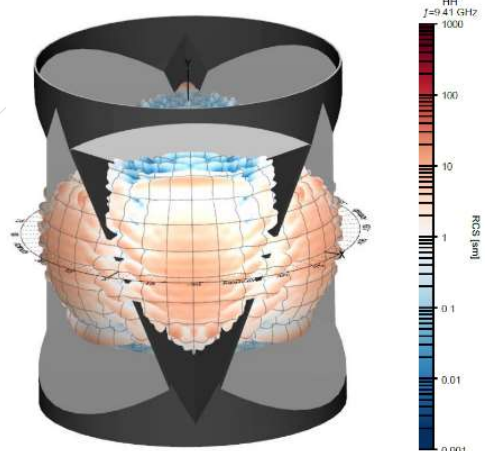
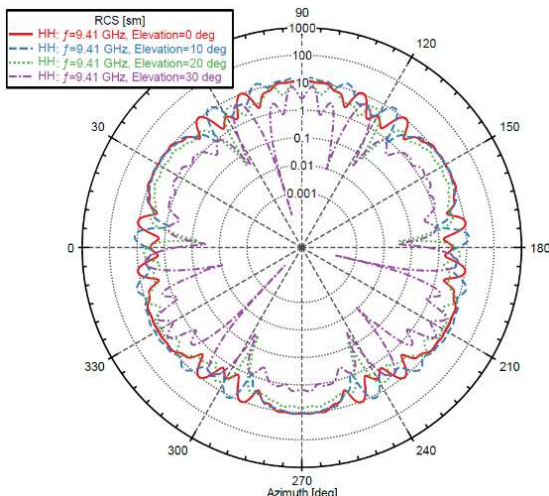


Figure 16: plastic buoy

Table 7: omnidirectional 6 corner reflector "SR6-330"

Dimensions of simulated reflector (mm)	Max. RCS (m ²)	Short description
Ø: 330mm / height: 385mm	10	<ul style="list-style-type: none"> - six tightly packed corner reflectors - good uniformity - different diameters available
3D-view 	3D-reflection diagram (rectangular) 	
2D reflection diagram, different tilt angles, linear	2D reflection diagram, different tilt angles, logarithmic 	

8. DETECTION RANGE OF RADAR REFLECTORS

8.1. OVERVIEW

The detection range of a radar reflector depends on a lot of parameters. Figure 17 provides a non conclusive list of the most important values.

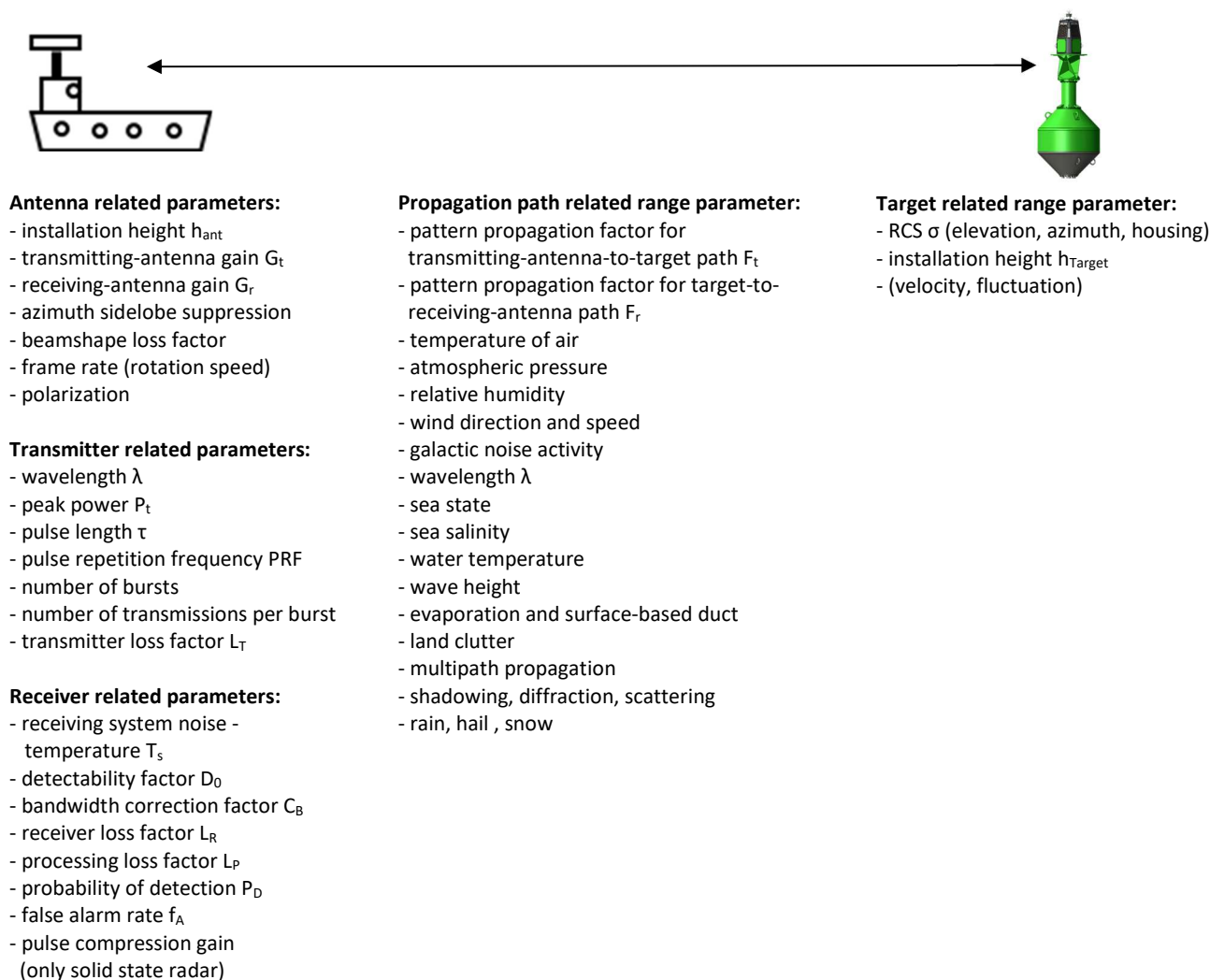


Figure 17: Range parameters

The maximal radar range for pulsed radars can be calculated according [2] with the following Equation (8):

$$R_{max} = \sqrt[4]{\frac{P_t \tau G_t G_r \sigma \lambda^2 F_t^2 F_r^2}{(4\pi)^3 k T_s D_0 C_B L}} \quad (8)$$

where:

- R = radar-to-target distance (range);
- P_t = transmitted-signal power;
- τ = pulse length of radar signal;
- G_t = transmitting-antenna gain;
- G_r = receiving-antenna gain;
- σ = radar target cross section (RCS);
- λ = wavelength;
- F_t = pattern propagation factor for transmitting-antenna-to-target path;
- F_r = pattern propagation factor for target-to-receiving-antenna path;
- π ≈ 3,14159; mathematical constant;
- k = Boltzmann's constant (1.38 x 10⁻²³ Ws/K);
- T_s = receiving system noise temperature;
- D₀ = detectability factor;
- C_B = bandwidth correction factor;
- L = system loss factor.

- Note 1: For a target in free space and in the maxima of both the transmit and receive antenna patterns, F_t = F_r = 1.
- Note 2: For solid-state radars, comprising intra pulse modulation, the pulse compression gain has to be considered.

To double the radar range, the radar cross section of an object has to be increased by factor of 16!

8.2. KEY PARAMETERS FOR CALCULATING THE MAXIMUM DETECTION RANGE

8.2.1. TARGET PARAMETERS

The following section describes the parameters for calculating the maximum detection range of a radar reflector in detail.

8.2.1.1. Elevation

Regarding the maximal possible radar range, any static object is finally characterized by its RCS value(s) σ. However, it is important to understand, that an object does not have only one radar cross section; it has one RCS for each azimuth and elevation angle of the incident radar wave and for each wavelength of the radar. Normally, radar reflectors are optimized to have the maximum RCS at an elevation angle of 0°. Any inclination of the radar reflector will result to different, usually lower RCS values.

Note that in the literature, radar range calculations are normally based on the maximum RCS of an object. However, the degradation due to the non-uniform RCS property of an object or reflector have to be taken into account.

8.2.1.2. Wavelength optimization

Radar reflectors used on AtoN are optimized for X-band radar (wavelength λ approx. 3,2 cm). For S-band radar (wavelength λ approx. 10 cm) these reflectors are less effective, i.e. the RCS of a reflector is about 10 times higher at X-band than at S-band.

8.2.1.3. Installation height h_{Target}

Beside the RCS value(s) of a reflector, its installation height is important. Very low installation heights may lead to shadowing of the object in heavy sea state. Especially for radar detection over long ranges, the installation height is significant due to the curvature of the earth.

8.2.1.4. Velocity and swerling case (fluctuation)

The relative velocity between radar installation and target as well as the “swerling case” should be considered. There are four „swerling cases“, defining different mathematical models for the fluctuation of a target.

8.2.1.5. Plastic housings

For AtoN made of steel, the radar reflector is usually mounted on the outside. Plastic buoys generally have an internal radar reflector. The surrounding plastic has an impact on the radar cross section of the target.

Figure 18 shows a plastic buoy for inland waterways type “B7”.

Figure 19 shows a big coastal plastic buoy type “LB3000”.

The impact of a surrounding plastic cover is explained in chapter 11.



Figure 18: Plastic buoy type “B7” with internal radar reflector

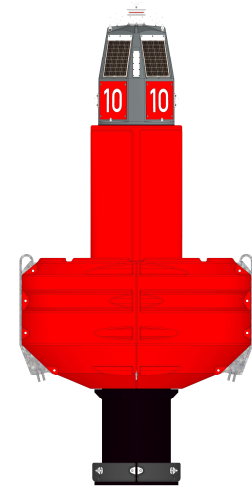


Figure 19: Plastic buoy type “LB3000-WSV” with internal radar reflector

8.2.2. PROPAGATION PARAMETERS

8.2.2.1. Atmosphere

The atmosphere has some influence on the propagation of radar waves. Relevant parameters are the temperature, the atmospheric pressure, the relative humidity, the wind direction and the galactic noise activity. Attenuation due to losses in the atmosphere is frequency dependent. The X-band radar suffers from slightly higher absorption losses than the S-band radar.

8.2.2.2. Propagation over sea

Propagation over sea introduces some more parameters of interest: sea state, wind speed, sea salinity, water temperature and average wave height. Of greater importance is super- and sub-refraction due to ducting, which can be classified as “evaporation duct” and “surface-based duct”.

According [6], “Ducting may occur almost anywhere (...). For most parts of the world evaporation ducting tends to persist most of the time, giving extended range, especially for low mounted antennas. The effect will give average improvement in detection performance and may therefore be very useful in respect to security applications, if required. The effect is usually not stable enough to be calculated in safety applications.” Although “ducting will influence VTS radars more than ships’ radars”, it is important to be aware of this effect.

8.2.2.3. Propagation over land

For propagation over land, the land temperature, the water content of the soil, the surface roughness and the soil type have an impact on the maximal detectable range. Although the relevance is low, high land reflectivity can cause significant land clutter in the radar picture.

8.2.2.4. Multipath propagation

Depending on the phase shift of the received waves from different spatial return paths, the summing signal may be strongly degraded or even completely cancelled. Multipath conditions regularly occur in calm sea. At certain distances, objects like AtoN may disappear completely from the radar screen. Chapter 5.5 of this document gives more information.

8.2.2.5. Shadowing, diffraction, scattering

The propagation of electromagnetic waves follows quasi-optical laws, presuming normal conditions, i.e. a uniform and constant medium. However, effects such as absorption, diffraction, scattering, total reflection etc. have an impact on the propagation of radar waves. Even partial shadowing of a radar reflector by a small object can significantly reduce its performance.

Since there is no ideal reflection without any loss, each reflection results in a degradation of the maximal detectable range. In case the radar wave is reflected by multiple objects, each radar cross section of all involved objects have to be considered. Diffraction and scattering are explained in more detail in Chapter 5.2 and 5.4 of this document.

8.2.3. CLUTTER PARAMETERS

8.2.3.1. Rain

The rainfall rate and the range of a rain area have important impact of the probability of detection of a target with radar.

8.2.3.2. Hail and snow

Although hail and snow are not as frequent as rain, the impact on radar detection of targets is significantly high.

8.2.4. RADAR EQUIPMENT

8.2.4.1. General

Any shipborne radar, falling under SOLAS Convention, has to fulfil the minimum performance requirements of IMO MSC. 192(79) [2] and IEC 62288 [7]. However, shipborne radar installations may differ in design and specification.

8.2.4.2. Transmitter parameters

The following transmitter parameters should be considered regarding the maximal detectable range:

- frequency f / wavelength λ and peak power P_t ;
- pulse length τ and pulse repetition frequency PRF;
- number of bursts and number of transmissions per burst;
- transmitter losses L_T ;
- white phase noise density and colored noise power and jitter.

For solid state radars, in addition the pulse compression factor has to be considered.

8.2.4.3. Receiver parameters

The following receiver parameters should be considered:

- noise figure;
- bandwidth of receiver;
- receiver losses L_R ;
- processing losses L_P ;
- probability of detection P_D ;
- false alarm probability f_A and jitter.

8.2.4.4. Antenna parameters

The following radar antenna parameters should be considered:

- type of antenna;
- vertical illumination;
- polarization;
- transmit gain and receive gain;
- azimuth bandwidth and elevation bandwidth;
- azimuth sidelobe level;
- beamshape losses (if applicable);
- other losses and
- frame rate (speed of rotation).

In addition, the installation height and the tilt of the radar antenna is important for the detectable range of an object, especially over long ranges.

Note: Almost all shipborne radar installations use horizontal polarized radar waves. The polarization plane may be changed by certain spatial structures of a target, resulting in a degradation of the maximal range.

8.3. TYPICAL ACHIEVABLE MAXIMUM RADAR RANGES

The typical maximal detectable ranges, presented in Table 8, are calculated on basis of the parameters listed in **Fehler! Verweisquelle konnte nicht gefunden werden.** . The calculations were performed using the software programme CARPET [sw.sw.1]. Note, that the variation of the parameters could have a deep impact on the results. The following parameters were applied:

- the target is modelled as a single-point-target with no physical dimensions;
- evaporation duct has not been included;
- X-band radar with $P=25\text{ kW}$ / 7 ft antenna / pulse length 400 ns / PRF 1400 Hz / false alarm rate 10^{-6} ;
- S-band radar with $P=30\text{ kW}$ / 12 ft antenna / pulse length 400 ns / PRF 1400 Hz / false alarm rate 10^{-6} ;
- seastate 3, no rain, hail or snow;
- detection probability 90%;
- multipath propagation has not been included.

To give an impression of the impact of various parameters, the followings figures show the detection probability of a target under different conditions.

Figure 20 shows as an example the detection probability of a target with a RCS of 10 m^2 . The height of the target is 5 m, the antenna of the shipborne x-band radar is set to 10 m.

Up to a distance of about 5 NM, a target can be detected with a probability of 90 %. In the close vicinity around the own position, the detection probability is lower since seastate 3 causes significant high water waves.

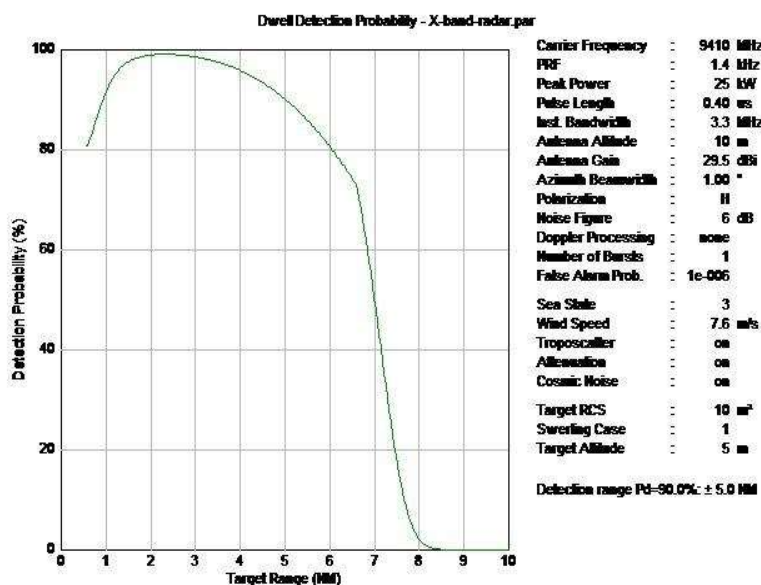


Figure 20: Detection probability of a target with RCS = 10 m^2 , seastate 3

Figure 26 shows the same scenario, but with consideration of multipath effects (see Chapter 5.5). In a distance of about 0.9 NM and 1.8 NM the target is not detected at all by the radar due to multipath propagation. However, multipath effect leads to a slightly higher range.

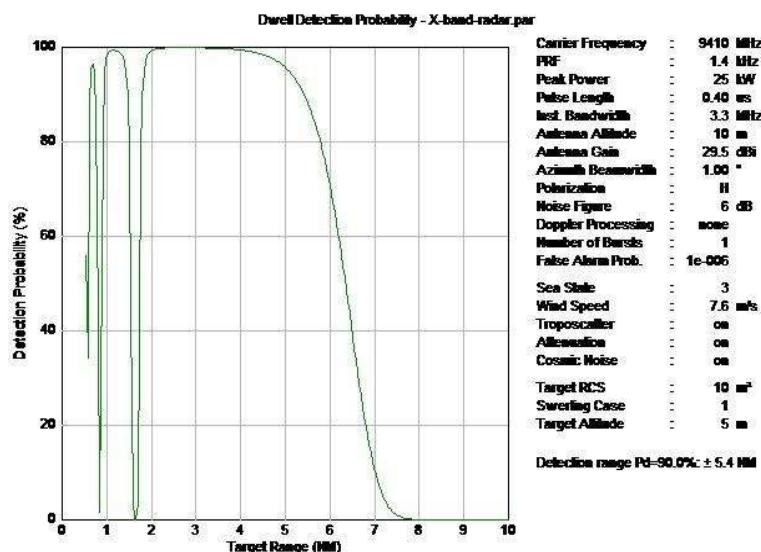


Figure 21: Detection probability of a target with RCS = 10 m^2 , seastate 3, with multipath propagation

Figure 27 shows the same scenario as Figure 20 with seastate 7 instead of seastate 3.

Reliable visual detection of a target in heavy storms and high water waves is a difficult task for the captain of any vessel. This is also true for radar detection. As Figure 27 shows, it is not possible to detect the target on every radar rotation cycle.

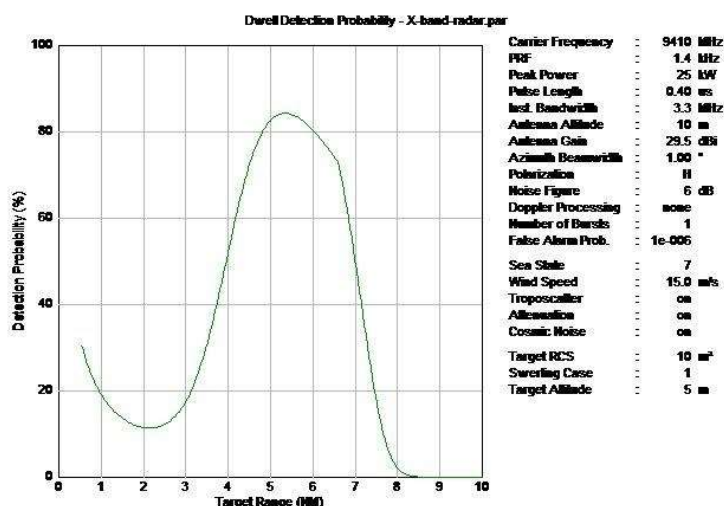


Figure 22: Detection probability of a target with $RCS = 10 \text{ m}^2$, seastate 7

Figure 28 shows the same scenario as Figure 20, but with consideration of evaporation duct. Although in this particular case the nominal range for a detection probability of 90 % is not so much higher, there is a certain probability to see targets far more away (even in more than twice the distance).

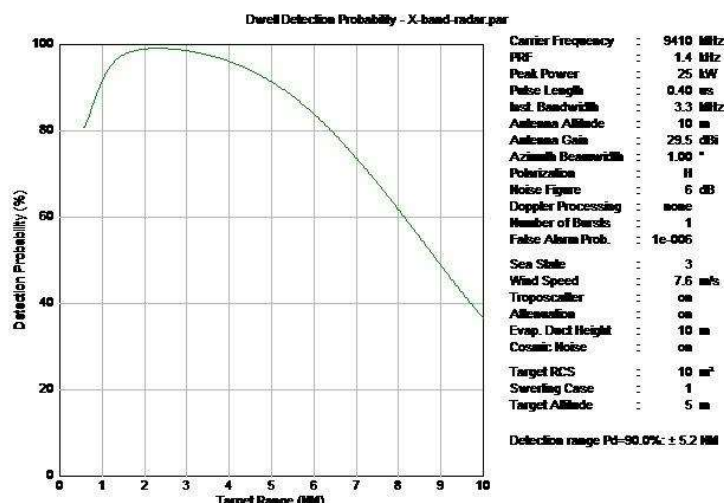


Figure 23: Detection probability of a target with $RCS = 10 \text{ m}^2$, with evaporation duct (height 10 m)

Fehler! Verweisquelle konnte nicht gefunden werden. shows the same scenario as Figure 20, but with rainfall at a rate of 4 mm / hr at a distance of 3 NM to 10 NM from the radar antenna. The simulation with CARPET shows that in the area of rainfall under these conditions no reliable detection of a target of 10 m^2 is possible. However, radar equipment provides rain suppression functionality (often called FTC – fast time constant) to improve the detection of targets in heavy rain. This cannot be simulated by CARPET.

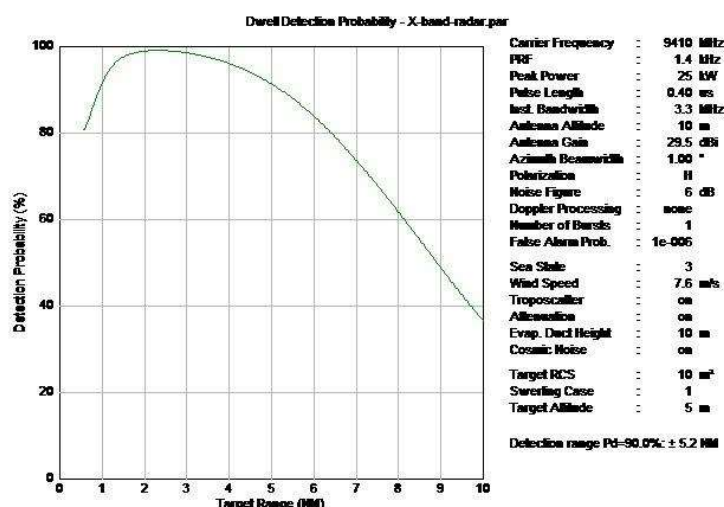


Figure 24: Detection probability of a target with $RCS = 10 \text{ m}^2$, with rainfall (4 mm/hr)

Figure 25 shows the same scenario as Figure 20, but with a typical non-SOLAS radar. The performance of a non-SOLAS radar is inferior compared to professional SOLAS radar equipment. Typically, non-SOLAS radar have less output power (e.g. 10 kW) and shorter antennas (e.g. 6 ft) with less gain. For the simulation, in addition the pulse length was set to 160 ns.

The detection range is significant lower compared to the result that can be achieved with a SOLAS radar.

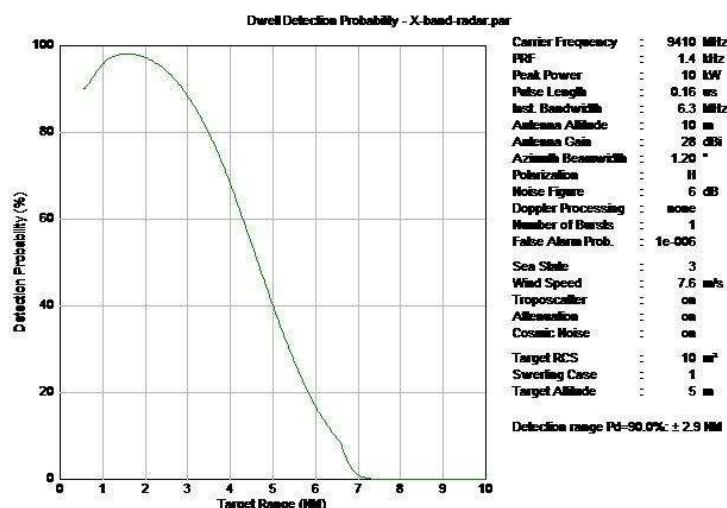


Figure 25: Detection probability of a target with $RCS = 10 \text{ m}^2$ with a typical non-SOLAS radar

Table 8: Typical achievable maximum radar ranges

Shipborne radar antenna installation height	Target height	X-band		S-band	
		RCS	Detectable range (90% DetProb)	RCS	Detectable range (90% DetProb)
5 m	1,0 m	10 m ²	3,7 NM	1 m ²	2,9 NM
		50 m ²	4,2 NM	5 m ²	3,5 NM
		300 m ²	4,9 NM	30 m ²	4,1 NM
		1000 m ²	5,3 NM	100 m ²	4,6 NM
	3,5 m	10 m ²	4,5 NM	1 m ²	3,5 NM
		50 m ²	5,2 NM	5 m ²	4,1 NM
		300 m ²	5,9 NM	30 m ²	4,9 NM
		1000 m ²	6,4 NM	100 m ²	5,5 NM
	7,5 m	10 m ²	5,0 NM	1 m ²	3,7 NM
		50 m ²	5,8 NM	5 m ²	4,9 NM
		300 m ²	6,6 NM	30 m ²	5,8 NM
		1000 m ²	7,2 NM	100 m ²	6,5 NM
10 m	1,0 m	10 m ²	4,8 NM	1 m ²	3,7 NM
		50 m ²	5,5 NM	5 m ²	4,4 NM
		300 m ²	6,2 NM	30 m ²	5,2 NM
		1000 m ²	6,7 NM	100 m ²	5,7 NM
	3,5 m	10 m ²	5,0 NM	1 m ²	3,7 NM
		50 m ²	6,4 NM	5 m ²	5,1 NM
		300 m ²	7,2 NM	30 m ²	6,0 NM
		1000 m ²	7,8 NM	100 m ²	6,6 NM
	7,5 m	10 m ²	5,0 NM	1 m ²	3,7 NM
		50 m ²	7,4 NM	5 m ²	5,6 NM
		300 m ²	8,4 NM	30 m ²	6,9 NM
		1000 m ²	9,1 NM	100 m ²	7,6 NM
15 m	1,0 m	10 m ²	5,0 NM	1 m ²	3,7 NM
		50 m ²	6,5 NM	5 m ²	5,3 NM
		300 m ²	7,3 NM	30 m ²	6,1 NM
		1000 m ²	7,8 NM	100 m ²	6,7 NM
	3,5 m	10 m ²	5,0 NM	1 m ²	3,7 NM
		50 m ²	7,4 NM	5 m ²	5,6 NM
		300 m ²	8,3 NM	30 m ²	6,8 NM
		1000 m ²	8,9 NM	100 m ²	7,5 NM
	7,5 m	10 m ²	5,0 NM	1 m ²	3,7 NM
		50 m ²	7,5 NM	5 m ²	5,6 NM
		300 m ²	9,5 NM	30 m ²	7,8 NM
		1000 m ²	10,2 NM	100 m ²	8,5 NM
20 m	1,0 m	10 m ²	5,0 NM	1 m ²	3,7 NM
		50 m ²	7,4 NM	5 m ²	5,6 NM
		300 m ²	8,2 NM	30 m ²	6,9 NM
		1000 m ²	8,8 NM	100 m ²	7,5 NM
	3,5 m	10 m ²	5,0 NM	1 m ²	3,7 NM
		50 m ²	7,5 NM	5 m ²	5,6 NM
		300 m ²	9,2 NM	30 m ²	7,6 NM
		1000 m ²	9,9 NM	100 m ²	8,4 NM
	7,5 m	10 m ²	5,0 NM	1 m ²	3,7 NM
		50 m ²	7,5 NM	5 m ²	5,6 NM
		300 m ²	10,5 NM	30 m ²	8,5 NM
		1000 m ²	11,2 NM	100 m ²	9,3 NM

Note 1: since the radar reflectors are usually optimized for the use in x-band, these reflectors are less effective in s-band., i.e. the RCS of a reflector is about 10 times lower at s-band than at x-band.

Note 2: the values provided in this table are calculated values under the conditions stated above. Under different conditions (e.g. using a small non-SOLAS radar), the result can differ significantly!

9. SIMULATION

9.1. POSSIBILITIES AND BENEFITS

Nowadays, computer-based simulation programmes can be a good help to support the relatively complex measurements on radar reflectors according to chapter 10 or even to avoid them.

In particular, this method helps in the selection of a suitable radar reflector or in the verification of in-house developments.

Simulations were also used in the preparation of the present guideline. Almost all illustrations of the reflection behaviour of different radar reflectors are based on simulations with the software “CST MICROWAVE STUDIO”. For more detailed information see [MARCH report].

9.2. PROCEDURE, REQUIRED DATA

As a rule, a 3D design (3-model) of the radar reflector to be examined must be available in a CAD environment. Then a suitable 3D model is exported from the 3D software (e.g. 3D step files). The software used for simulation imports the 3D model and calculates the reflection behaviour to be expected in reality.

The simulation can be carried out using different methods, for example:

- Multi-Level Fast Multipole Method (MLFMM): This matrix method is accurate but can be memory and time intensive.
- Shooting and Bouncing Rays (SBR). This method is based on ray-tracing techniques. It is very fast and more suitable to calculate the 3D RCS needed here. It includes multiple reflections and edge diffraction by using either independent rays or ray-tubes.

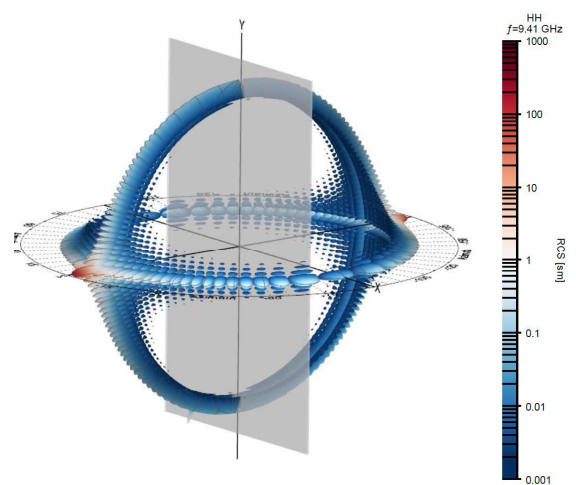


Figure 26: RCS-simulation for a metal sheet

For the purposes of this guideline the SBR-method is accurate enough, so it was used for the 3D RCS calculations.

The calculation requires the input of various simulation parameters, such as frequency, (9.41 GHz and/or 3.05 GHz), polarisation (HH), etc.

Figure 26 shows the RCS-simulation of a 3 mm metal sheet with the dimensions of 300 mm × 500 mm at a frequency of 9.41 GHz. The expected RCS for each room angle was calculated and is presented in a logarithmic scale (see bar at the right).

10. MEASUREMENT OF THE REFLECTION PROPERTIES OF RADAR REFLECTORS

10.1. CONCEPT FOR THE MEASUREMENT

The measurement of radar reflectors should be based on ISO 8729-1 which concerns passive reflectors and gives specifications for the construction, performance, testing, inspection and installation of them. The measuring methods and requirements for the measuring chamber are described in chapter 6.4 of ISO 8729-1.

The reflective performance tests can be conducted in a free-field environment or a fully anechoic chamber. Typically the fully anechoic microwave test chamber is used for carrying out the measurements. Before use, the reflector test range shall be calibrated using a precision sphere of known RCS.

Table 9: typical test concept

parameter	value
frequency	9,41 GHz (X-band) and 3,050 GHz (S-band)
polarisation	horizontal (H)
rotation angle	360°
angle resolution	0,5°
inclination to the front	0°, 10°, 20°, 30°

The tests should be carried out at both X-Band (9.410 GHz) and S-band (3.050 GHz) with the same power density at the EUT (equipment under test) turntable that was used for the chamber calibration. The radar reflector shall have a minimum RCS of 7.5 m² at X-band and 0.5 m² at S-band. Based on the demands of the ISO 8729-1 a typical test concept could be as shown in section 10.2.

Devices which may have to be provided for realizing the inclinations of the measured objects shall be shielded with appropriate absorbers or shall be made of materials which do not influence the radar reflection characteristics.

10.2. MEASUREMENT EXAMPLE OF A RADAR REFLECTOR

The radar reflector to be examined is mounted on a suitable measuring tower and measured at 4 different elevation angles (0°, 10°, 20° and 30°). The respective elevation angle is realised by tilting the measuring tower forward. At each elevation angle the radar reflector shall be rotated 360° (around its vertical axis/tilting tower axis). The rotation takes place in 0.5° steps.

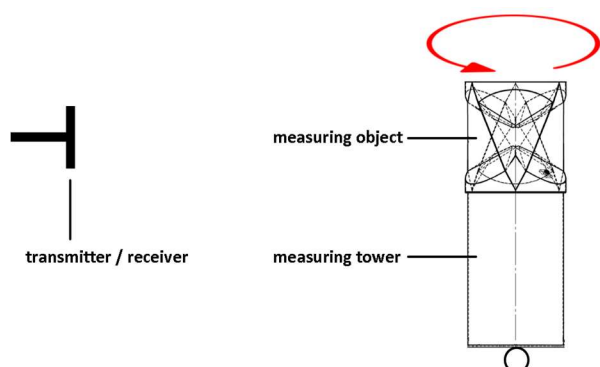


Figure 27: radar reflector on measuring tower, elevation angle 0°

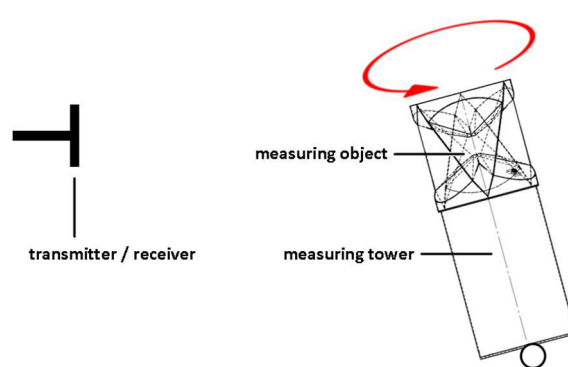


Figure 28: radar reflector on measuring tower, elevation angle 10°

The results of the measurements as described above of three identical radar reflectors (#1, #2, #3) at the frequency of 9.4 GHz are shown in the following figures (polar coordinates):

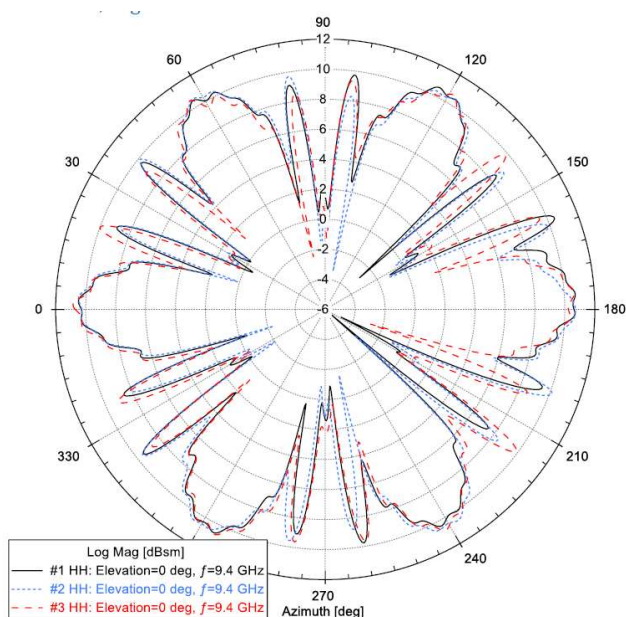


Figure 29: measurement results at 0° elevation

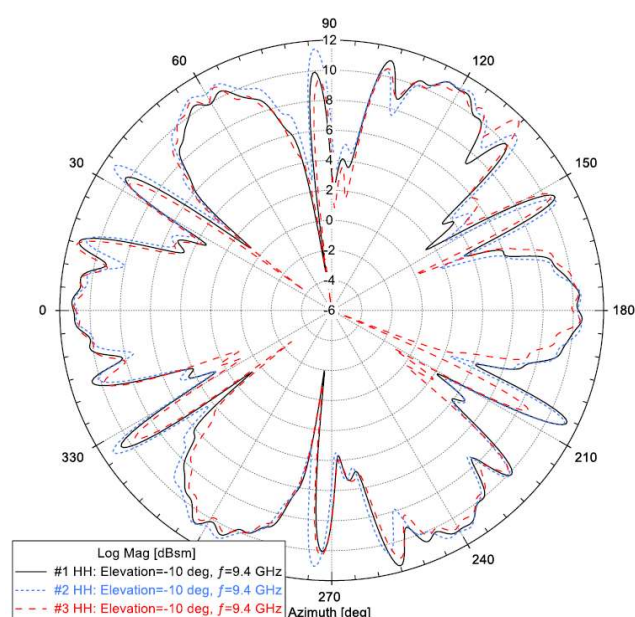


Figure 30: measurement results at -10° elevation

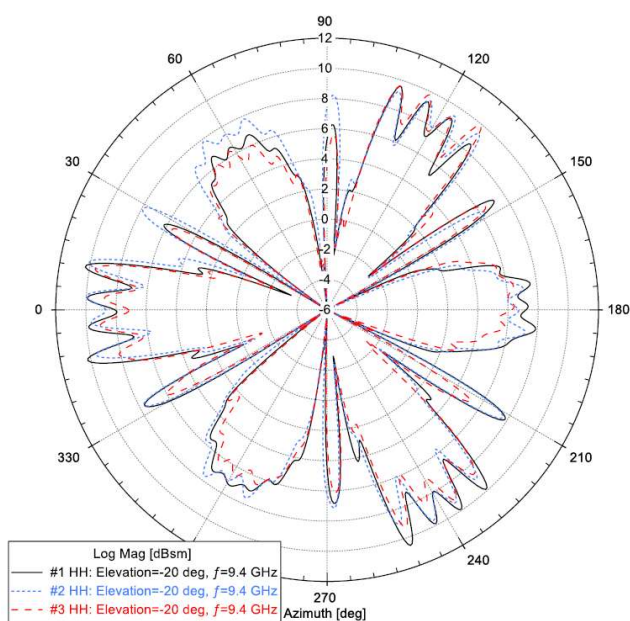


Figure 31: measurement results at -20° elevation

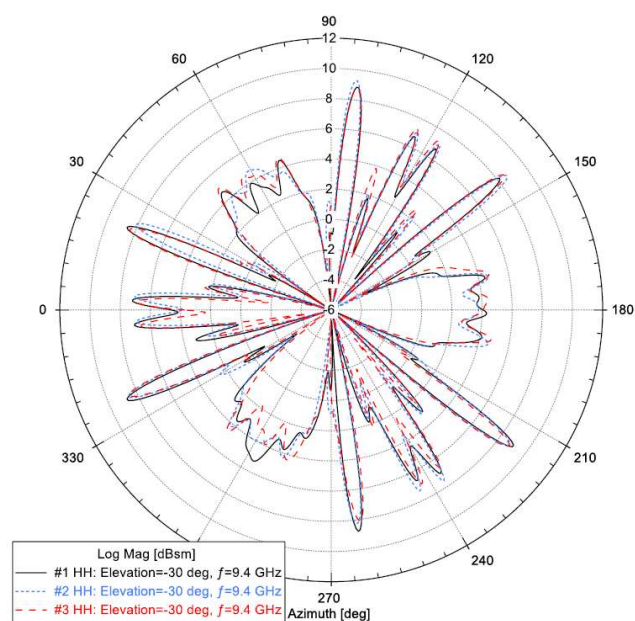


Figure 32: measurement results at -30° elevation

11. INFLUENCE OF PLASTIC BY INSTALLING THE RADAR REFLECTOR IN A PLASTIC HOUSING

11.1. CONSIDERATIONS

It is often necessary to cover radar reflectors. Any cover around the radar reflector affects its reflective properties to a greater or lesser extent. The impairments essentially depend on:

- cover material;
- material thickness;
- distance between cover and radar reflector and
- geometry of the cover (bending radius, cylindrical or conical, etc.).

Often the cover is made of plastic, e.g. when installing the radar reflector in an ice-proof plastic buoy. Therefore, the possible effects of the surrounding plastic in relation to the radar reflection properties were investigated. The test are described in ANNEX E.

11.2. SUMMARY OF MEASUREMENT AND TEST RESULTS ON THE INFLUENCE OF PLASTIC COVERS ON THE REFLECTION BEHAVIOUR OF RADAR REFLECTORS

The laboratory measurements do not show any significant impairment due to plastic cover. The real tests on land and on the water also confirm this. The results can be summarised as follows:

- the investigated plastic (polyethylene) is suitable from a radar technology point of view;
- the colouring of the PE has no negative influence and
- eventual reflections and interferences had no significant influence.

Not investigated were the following points:

- the behaviour of other plastics than polyethylene;
- the influence of different wall thicknesses;
- the influence of different distances between the radar reflector and the plastic cover and
- plastic covers of other shapes, e.g. conical shapes, etc.

11.3. PRILIMINARY RESULTS

Any cover in front of a reflector has a certain impact on its effectiveness. Therefore, the material of the cover, its dimensions and the position related to the reflector have to be chosen carefully and individually for a given application.

As a general rule, the material should be capable to pass electromagnetic waves best possible (non metallic, not magnetic, permittivity close to 1). In addition, the thickness should be much smaller than the wavelength of the radar wave, if possible, or at least some adverse conditions should be avoided (further investigations have to done to determine the best thickness).

To compensate the unavoidable electromagnetic losses in the cover, a bigger radar reflector should be used in applications where radar reflectors are placed inside a buoy (e.g. replace a SR6-300 of a steel buoy by a SR6-330 in a plastic buoy).

12. CONSTRUCTION

12.1. GENERAL

The materials used for radar reflectors shall be of sufficient strength and quality so as to make the reflector capable of maintaining reflection performance under the conditions of stress due to seastates, vibration, humidity and change of temperature likely to be experienced in the marine environment and capable of withstanding the environmental conditions.

ISO 8729:1 [Reference]:

Radar reflectors are consisting from good electric conductivity materials such as metal. In practice aluminium and mild steel/stainless steel are typically used.

Even a very thin layer of metal can make an object strongly radar reflective. From a radar point of view only a thin metallic layer is required for a perfect reflection. Thus, a plastic material like GRP with a metallized surface or with a metallized nylon mesh embedded in it yields has similar good results.

Manufacturing processes include bending and welding. Holes are drilled to attach and hold the radar reflectors on the buoy (AtoN). Deviating from this, brackets can be welded to the radar reflectors with which the radar reflector can be attached.

12.2. MATERIALS

As described above, radar reflectors are usually made of aluminium or steel. When using aluminium, marine grade aluminium should be used. If steel is used, mild (construction) steel or stainless steel can be used.

When using different metals (e.g. aluminium and mild steel) electrochemical corrosion can cause heavy damages. To prevent a direct electrical connection of two different metals, e.g. insulating bushes can be used (Figure 35).

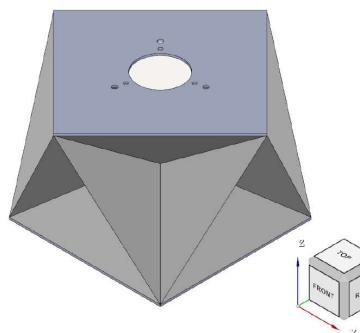


Figure 33: welded radar reflector



Figure 34: radar reflector consisting of single corner reflectors mounted on a structure



Figure 35 plastic insulation between different metals

12.3. SURFACE PROTECTION

If the radar reflector is mounted inside the buoy body (e.g. plastic buoy made of polyethylene) there is no protection needed. However, the buoy body must be watertight and airtight. Figure 36 shows a plastic buoy with an integrated radar reflector.

If the radar reflector is mounted outside, surface protection is needed. Figure 37 shows a steel buoy with an outside mounted radar reflector.

The coating and rust-proofing must be saltwater-proof. Thin layers' of paint which are directly applied for this purpose to the reflecting surface do not degrade the performance of the radar reflector.

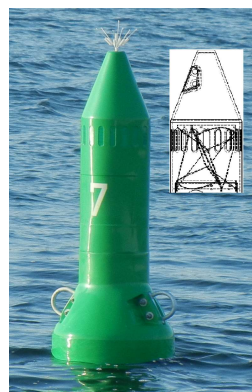


Figure 36: plastic buoy



Figure 37: steel buoy

12.4. MANUFACTURING QUALITY

As with all types of cluster reflectors the individual reflecting elements (i.e. the corner reflectors) have to be manufactured to close tolerances, otherwise the reflected wave will diverge from the exact direction back to the illuminating radar (see also section 7.3).

For best results all three plates of each corner reflector must be perfectly flat, and the corner angles must be exactly at right angles (rectangularity). In a production process some deviations are unavoidable and result in certain loss of performance. Unfortunately, the allowable rectangular tolerance and deviations from perfect flatness become smaller as the size of the reflector gets larger. The tolerances shown in Table 10 should not be exceeded:

Table 10: tolerances	
reflector diameter	maximum angular tolerance
0,5 m	$\pm 1^\circ$
1 m	$\pm 0,5^\circ$
reflector diameter	maximum flatness tolerance
0,5 m	$\leq 1 \text{ mm}$
1 m	$\leq 2 \text{ mm}$

Even under these conditions a noticeable loss of performance can occur if all tolerances of a corner reflector accumulate (all tolerances of the same sign).

The quality of the mechanical finish is important to the quality of the response from the radar reflector as variation will degrade the effectiveness of the radar reflector.

12.5. INCOMING GOODS INSPECTION

In the procurement process the incoming goods inspection is very important to achieve the specified quality and tolerances. The manufacturer should deliver an acceptance report. An example is shown in ANNEX D.

12.6. FURTHER REQUIREMENTS

Depending on the application, a radar reflector should meet further requirements:

- low weight
- low manufacturing costs
- protection against icing

The low weight could be important for the swimming stability of floating AtoN. In regions where ice can form, the radar reflector must be built or protected so that no damages occur (flatness, angularity).

13. MAINTENANCE

Rust and mechanical damages (damaging the flatness of the plates, damaging the rectangularity) reduces the radar detectability. Then the radar reflectors should be repaired or replaced.

13.1. MAINTENANCE FOR OUTSIDE MOUNTED RADAR REFLECTORS

It is important that the coating is in a good condition. Figure 38 shows refurbished radar reflectors. These have been sandblasted and newly coated in the colour of the buoy on which they will be mounted.

13.2. MAINTENANCE FOR COVERED RADAR REFLECTORS

If the radar reflector is mounted inside and covered, there is no maintenance required.



Figure 38: surface protected with colour

14. PROCUREMENT OF RADAR REFLECTORS

14.1. MARKET AVAILABLE RADAR REFLECTORS

The market offers a variety of different radar reflectors. As a rule, these are offered for equipping small boats or yachts. Only a few products are offered for use on AtoN. Nearly all well-known manufacturers of AtoN and particular manufacturers of buoys have radar reflectors in their product portfolio.

Their suitability must be checked intensively, e.g. on the basis of the manufacturer's data sheets. The parameters and technical data given therein are primarily to be compared with the nautical requirements. In the second step, it must be checked whether the reflector is suitable for the intended environmental conditions. Important data are:

- radar reflection properties: horizontal and vertical diagrams including RCS values;
- materials and
- protection.

14.2. MANUFACTURING BASED ON GIVEN SPECIFICATIONS

As an alternative to commercially available radar reflectors, radar reflectors can also be procured according to own specifications or manufactured in-house. This can be the case in particular if the radar reflector is a load-bearing component, e.g. of a buoy, and must be integrated accordingly.

Platzhalter: Ggf. Konstruktionszeichnungen von Reflektoren seitens Seezeichenverwaltungen als Annex und hier der Verweis darauf.

15. MOUNTING

An important parameter regarding the effectiveness of a radar reflector is the mounting height, see also chapter 8. A mounting location as high as possible, e.g. on a buoy, optimises the radar range. Figure 37 gives a good example for this.

Furthermore, care should be taken to ensure that there is no constructive shadowing, e.g. by parts mounted in front of the reflector.

The radar reflector must be mounted according to the procedure recommended by the manufacturer, which should be described in detail in the operating instructions.

The AtoN itself shall have appropriate mounting points to allow the reflector to be mounted in the correct orientation. The mounting points must be capable of withstanding stresses due to wind, waves and vibration.

16. ACRONYMS

dBsm	dB square meter
HH	Horizontal polarization receive and transmit. See VV, VH and HV.
HV	Horizontal polarization transmit, vertical receive. See VV, VH and HH.
MLFMM	Multi-Level Fast Multipole.
RCS	Radar Cross Section
RF	Radio frequency
SBR	Shooting and Bouncing Rays
VH	Vertical polarization transmit, horizontal receive. See VV, HV and HH.
VV	Vertical polarization receive and transmit. See VH, HV and HH.

17. REFERENCES

18. ABBREVIATIONS

CARPET	Computer Aided Radar Performance Evaluation Tool
IMO	International Maritime Organization
ISO	International Organization for Standardization

19. SOFTWARE TOOLS

- [sw.1] CARPET Computer Aided Radar Performance Tool
TNO (Toegepast Natuurkundig Onderzoek) Physics and Electronics Laboratory,
P.O.Box 96864,
2509 JG The Hague,
Netherlands, <http://www.tno.nl>

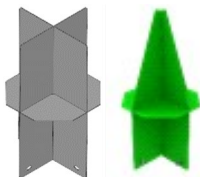
20. LITERATURE


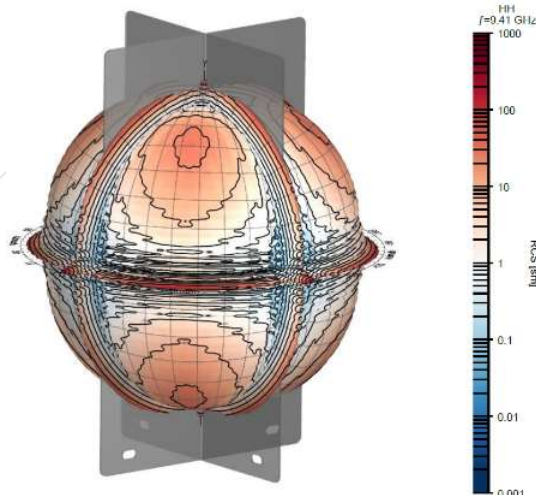
- [1] SKOLNIK
- [2] IMO Resolution MSC.192(79)
- [3] SOLAS Chapter V (Safety of Navigation)
- [4] ISO 8729-2010
- [5] MARCH Report
- [6] IALA V.128 Ed.3.0
- [7] IEC 62288
- [8] Beitrag zur Musterspezifikation für Kunststofftonnen der deutschen Nord- und Ostseeküste, FVT, Mario Walterfang, 2017

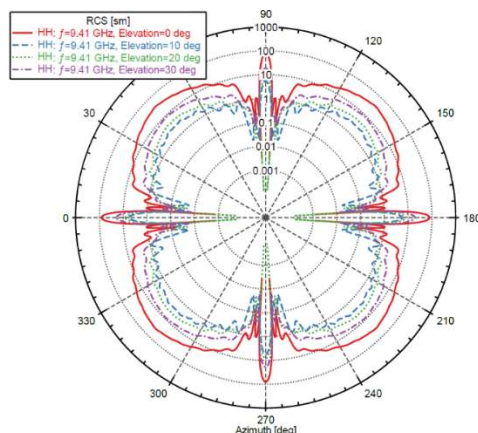
ANNEX A TYPICAL DESIGNS

From a global perspective, a wide variety of radar reflectors is used in the field of AtoN. In preparing this guideline, the most common types used by maritime administrations were identified. For these, the resulting reflection diagrams have been simulated on the base of 3D models. The following tables present the different radar reflectors and their use cases. Note: The inventory is not conclusive.

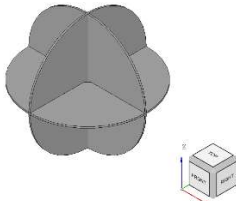

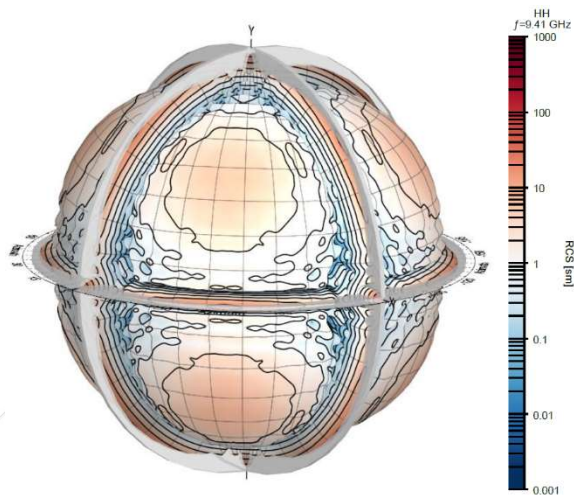
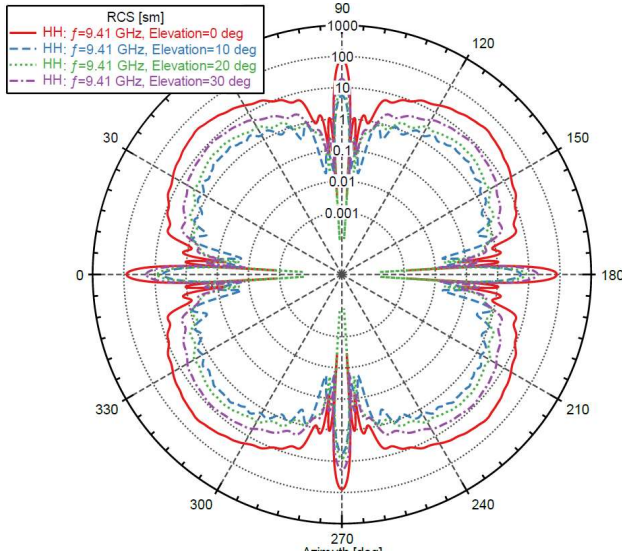
A.1. OCTAHEDRAL REFLECTOR (RECTANGULAR AND TRIANGLE)

Type	multidirectional	Name	octahedral reflector (rectangular and triangle)
Origin	German waterways and shipping administration	Purpose	In use for steel or plastic buoys on German inland waterways as top marks, different shapes
Dimensions simulated reflector (mm)	width: 350 / height: 600 / depth: 350	3D-view	Short description / Special properties <ul style="list-style-type: none">- Simple construction- easy to manufacture
Max. RCS (m²)			
???			

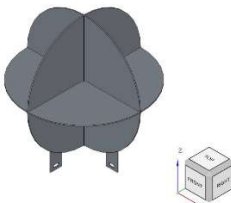

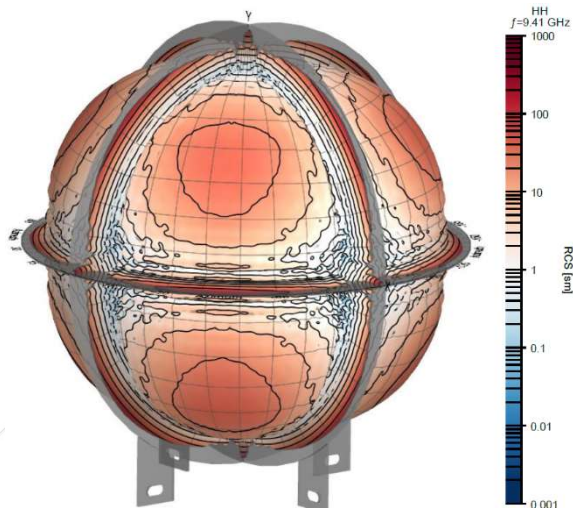

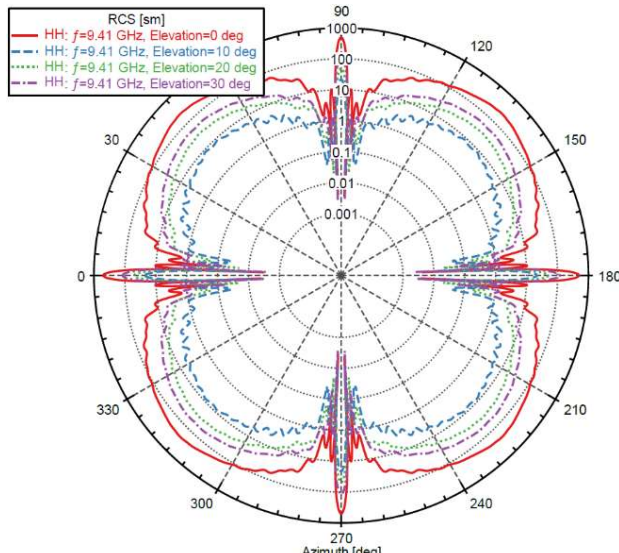
Application example(s)	3D-reflection diagram (rectangular)
	

2D reflection diagram, different tilt angles, linear	2D reflection diagram, different tilt angles, logarithmic
	

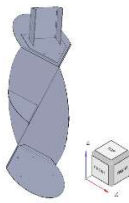

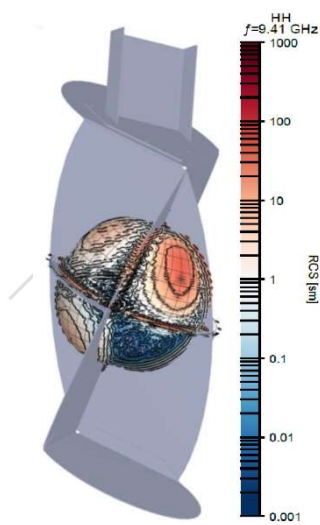

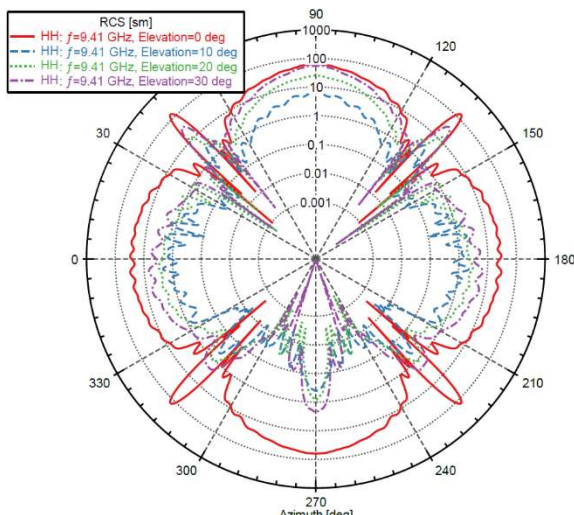
A.2. 12,5 OCTAHEDRAL REFLECTOR, BALL TYPE

Type	multidirectional	Name	12,5 octahedral reflector, ball type
Origin	Commercial, different diameters available	Purpose	leisure boats
Dimensions simulated reflector (mm)	width: 320 / height: 320 / depth: 320	3D-view 	Short description / Special properties <ul style="list-style-type: none">- relatively simple construction of 8 corner reflectors- good radar visibility for a broad range of both Elevation and Azimuth angles- breakdowns around the maxima at multiples of 90°
Max. RCS (m²)			
???			
Application example(s) 		3D-reflection diagram (rectangular) 	
2D reflection diagram, different tilt angles, linear		2D reflection diagram, different tilt angles, logarithmic 	

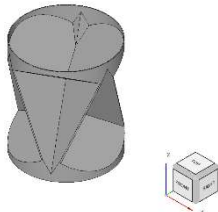

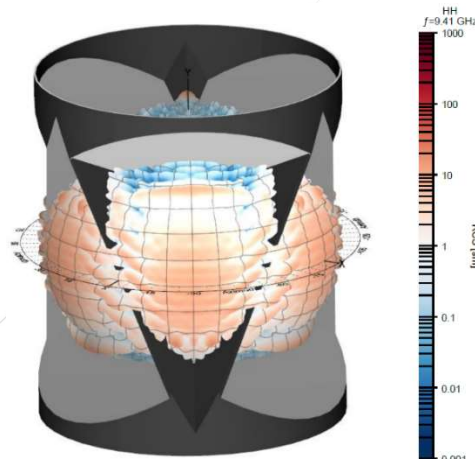
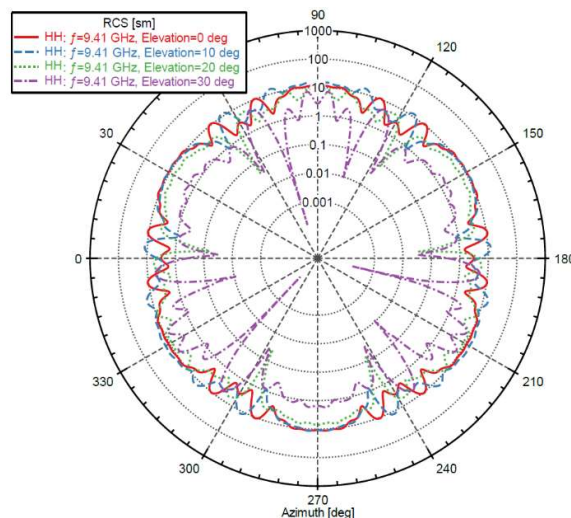
A.3. OCTAHEDRAL REFLECTOR, BALL TOP MARK

Type	multidirectional	Name	octahedral reflector, ball top mark
Origin	German waterways and shipping administration	Purpose	used on steel or plastic buoys on German inland waterways as top marks
Dimensions simulated reflector (mm)		Short description / Special properties <ul style="list-style-type: none">- bigger version of "12,5 octahedral reflector"- higher RCS but nulls in the response	
width: 500 / height: 530 / depth: 500			
Max. RCS (m²)			
???			
Application example(s)		3D-reflection diagram (rectangular)	
			
2D reflection diagram, different tilt angles, linear		2D reflection diagram, different tilt angles, logarithmic	
			

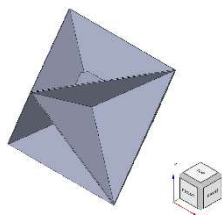

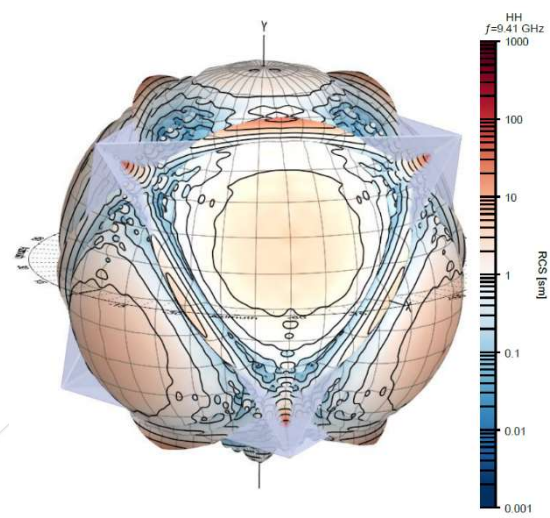

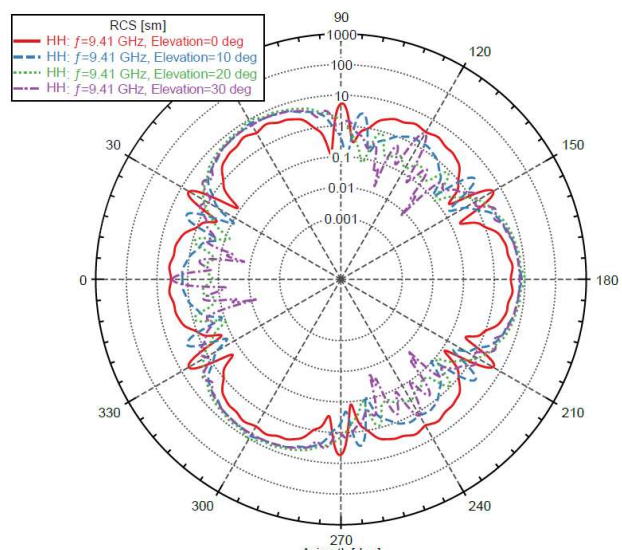
A.4. 2 CORNER REFLECTOR / 180°

Type	bidirectional	Name	2 corner reflector / 180°	
Origin	German waterways and shipping administration	Purpose	Used in plastic buoys on German inland waterways, buoys have fixed orientation to the waterway	
Dimensions simulated reflector (mm)	Ø: 250mm / height: 700mm	3D-view		Short description / Special properties <ul style="list-style-type: none">- 2 main reflection directions- designed for plastic buoys (mounted inside, protected)
Max. RCS (m²)	???			
Application example(s)			3D-reflection diagram (rectangular)	
				
2D reflection diagram, different tilt angles, linear			2D reflection diagram, different tilt angles, logarithmic	
				

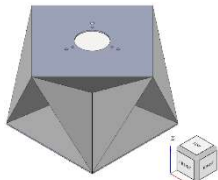

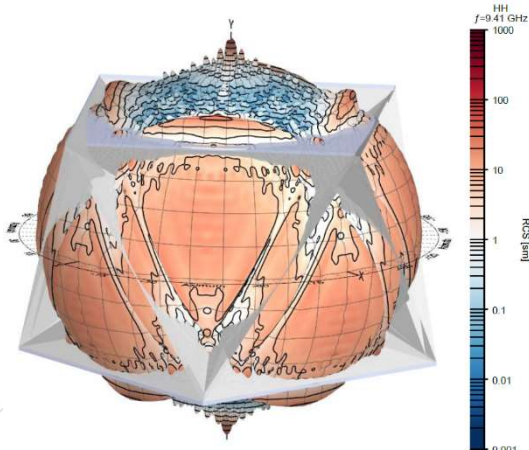

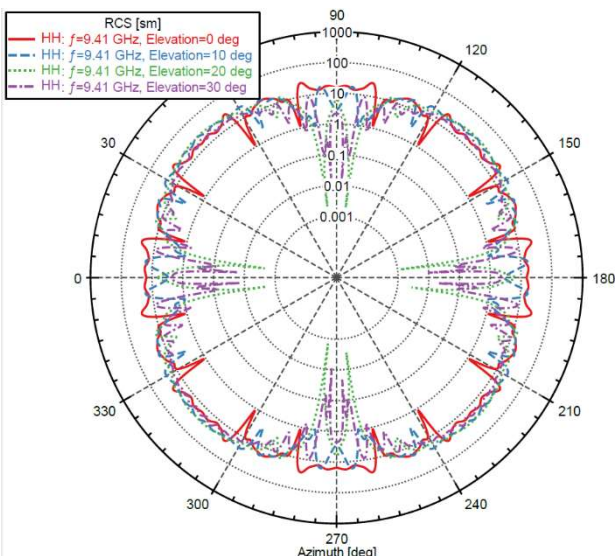
A.5. 6 CORNER REFLECTOR “SR6” / DIFFERENT DIAMETERS FOR THE RESPECTIVE REQUIRED RCS

Type	omnidirectional	Name6 corner reflector “SR6-330”			
Origin	German waterways and shipping administration	Purpose <ul style="list-style-type: none">- use on/in steel or plastic buoys on German inland or coastal waterways- use on beacons			
Dimensions simulated reflector (mm) width: 388 / height: 388 / depth: 388		3D-view		Short description / Special properties	
Max. RCS (m²) ???				<ul style="list-style-type: none">- six tightly packed truncated corner reflectors- truncation of the single reflectors reduces the overall RCS- increased uniformity especially for H polarization- in different diameters available	
Application example(s)		3D-reflection diagram (rectangular)			
					
2D reflection diagram, different tilt angles, linear		2D reflection diagram, different tilt angles, logarithmic			
					
Diameter / mm	300	330	480	900	
Max. RCS (m²)		10			

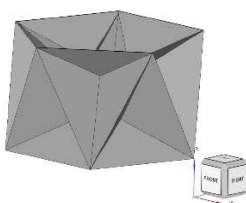
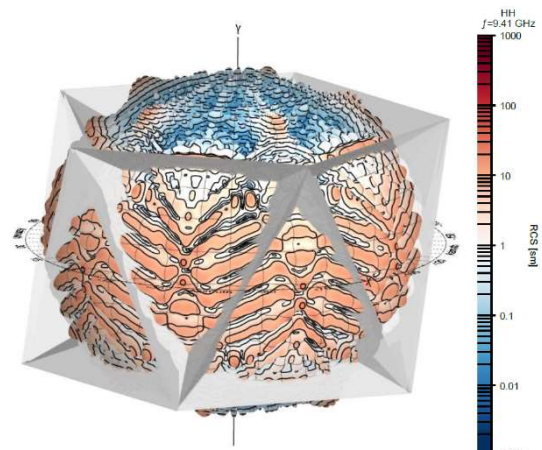
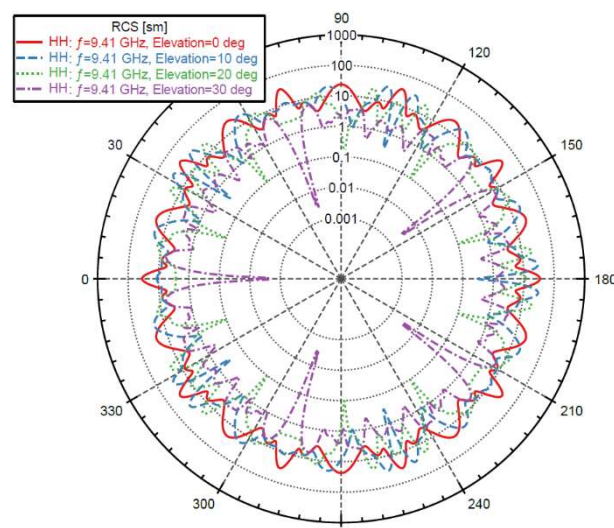
A.6. 8 CORNER REFLECTOR

Type	omnidirectional	Name	6 corner reflector
Origin	Dutch waterways administration	Purpose	Used on buoys and fixed structures
Dimensions simulated reflector (mm)		Short description / Special properties - Best uniformity of the RCS at 3.05 GHz	
width: 302 / height: 247 / depth: 348			
Max. RCS (m²)	???		
Application example(s)		3D-reflection diagram (rectangular)	
			
2D reflection diagram, different tilt angles, linear		2D reflection diagram, different tilt angles, logarithmic	
			

A.7. ENGLISH 8 SIDED REFLECTOR (FIRDELL)

Type	omnidirectional	Name	English 8 sided reflector (Firdell)	
Origin	Trinity House	Purpose	<ul style="list-style-type: none">- Use on buoys- Use on fixed structures	
Dimensions simulated reflector (mm)	width: 573 / height: 342 / depth: 573	3D-view	<div></div>	Short description / Special properties
Max. RCS (m²)	???	<ul style="list-style-type: none">- high RCS response- considerable nulls for H polarization at 9.41 GHz		
Application example(s)		3D-reflection diagram (rectangular)		
<div></div>		<div></div>		
2D reflection diagram, different tilt angles, linear		2D reflection diagram, different tilt angles, logarithmic		
<div></div>		<div><div><div>RCS [sm]</div><div><div>— HH: f=9.41 GHz, Elevation=0 deg</div><div>— HH: f=9.41 GHz, Elevation=10 deg</div><div>— HH: f=9.41 GHz, Elevation=20 deg</div><div>— HH: f=9.41 GHz, Elevation=30 deg</div></div></div><div></div></div>		

A.8. 10 CORNER REFLECTOR

Type	omnidirectional	Name	10 corner reflector
Origin	???	Purpose	Use on buoys
Dimensions simulated reflector (mm)		Short description / Special properties <ul style="list-style-type: none">-similar to the English 8-sided reflector- good uniformity at 3.05 GHz- considerable side lobe interference at 9.41 GHz- ripple in the elevation curves	
Max. RCS (m²)			
Application example(s)		3D-reflection diagram (rectangular)	
			
2D reflection diagram, different tilt angles, linear		2D reflection diagram, different tilt angles, logarithmic	
			

ANNEX B PARAMETERS USED FOR CARPET SIMULATION

X-band radar	S-band radar
[Transmitter Parameters] Mean Carrier Frequency= 9410 MHz Peak Power= 25.000 kW Pulse Length (uncompressed)= 0.400 μ s Instantaneous Bandwidth= 3.3 MHz Pulse Repetition Frequency= 1.400 kHz Transmitted Pulses per Burst= 1 Pulse Bursts= 1 Transmitter Losses= 2.0 dB White Phase Noise Density= -120.0 dBc/Hz Coloured Noise Power= -40.0 dBc Cut-off Frequency= 1.0 Hz StDev Timing Jitter= 0.100 ns	[Transmitter Parameters] Mean Carrier Frequency= 3050 MHz Peak Power= 30.000 kW Pulse Length (uncompressed)= 0.400 μ s Instantaneous Bandwidth= 3.3 MHz Pulse Repetition Frequency= 1.400 kHz Transmitted Pulses per Burst= 1 Pulse Bursts= 1 Transmitter Losses= 2.0 dB White Phase Noise Density= -120.0 dBc/Hz Coloured Noise Power= -40.0 dBc Cut-off Frequency= 1.0 Hz StDev Timing Jitter= 0.100 ns
[Receiver Parameters] MTI none Doppler Filter Bank= f Taper Doppler Filter= Blackman Noise Figure= 6.0 dB Receiver Losses= 1.0 dB Processing Losses= 0.0 dB False Alarm Probability= 1×10^{-6} Fill Pulses= 0 StDev Timing Jitter= 0.100 ns	[Receiver Parameters] MTI none Doppler Filter Bank= f Taper Doppler Filter= Blackman Noise Figure= 6.0 dB Receiver Losses= 1.0 dB Processing Losses= 0.0 dB False Alarm Probability= 1×10^{-6} Fill Pulses= 0 StDev Timing Jitter= 0.100 ns
[Antenna Parameters] Type= rectangular Vertical Illumination= uniform Polarization= horizontal Tracking= none Transmit Gain= 29.5 dBi Receive Gain= 29.5 dBi Azimuth Beamwidth= 1.0 deg Elevation Beamwidth= 20.0 deg Azimuth Sidelobe Level= -35.0 dB Beamshape Losses= 0.0 dB Dissipative Losses= 0.0 dB Tilt= 0.0 deg Height= <value> m Frame Time= 2.5 s	[Antenna Parameters] Type= rectangular Vertical Illumination= uniform Polarization= horizontal Tracking= none Transmit Gain= 26.5 dBi Receive Gain= 26.5 dBi Azimuth Beamwidth= 1.9 deg Elevation Beamwidth= 25.00 deg Azimuth Sidelobe Level= -35.0 dB Beamshape Losses= 0.0 dB Dissipative Losses= 0.0 dB Tilt= 0.0 deg Height= <value> m Frame Time= 2.5 s
Target	
[Target Parameters] Radar Cross Section= <value> m ² Range= 37.0 km Velocity= 0.1 m/s Altitude= <value> m Swerling Case= 1 Circular Polarization RCS Red.= 5.0 dB	



Common parameters			
[Radar Toggles]			
Phase Noise=	t		
Doppler Processing=	f		
Pulse Compression=	f		
Timing Jitter=	t		
Rotating=	t		
[Propagation Toggles]		[Propagation Parameters]	
Troposcatter=	t	Air Temperature=	15.0 degC
Attenuation=	t	Atmospheric Pressure=	1020 hPa
Free Space=	f	Relative Humidity=	70 %
Surface-Based Duct=	f	Surface Refractivity=	328.3 Nunits
Evaporation Duct=	f	Wind Direction=	0 deg
Antenna Noise=	t	K-factor, Refractivity Gradient=	1333.3 Nunits/km
Multipath=	f	Galactic Noise Activity=	average
		Sea State=	3
		Sea Salinity=	35 promille
		Water Temperature=	10.0 degC
		Evaporation Duct Height=	10.0 m
		Surface-Based Duct Height=	100.0 m
		Wind Force=	3 Beaufort
		Land Temperature=	10.0 degC
		Water Content Soil=	60 %
		Surface Roughness=	0.1 m
		Soil Type=	average
[Clutter Toggles]		[Clutter Parameters]	
Sea Clutter=	t	Land Clutter Reflectivity=	-38.0 dBm2/m2
Land Clutter=	f	Rainfall Rate=	4.0 mm/hr
Constant Gamma=	f	Chaff Density=	30 g/km3
Rain=	t/f	Minimum Range Rain/Chaff=	3.0 NM
Chaff=	f	Maximum Range Rain/Chaff=	10.0 NM
		Maximum Altitude Rain/Chaff=	3000 m
		Circular Pol. Power Reduction of Rain Clutter=	20.0 dB
[Jamming Toggles]		[Jamming Parameters]	
Barrage=	f	Power=	10.000 kW
Responsive=	f	Antenna Gain=	12.0 dBi
		Bandwidth Barrage Mode=	600 MHz
		Bandwidth Responsive Mode=	10.0 MHz
		Range=	200 km
		Altitude=	3.0 km
[Layout]			
Performance Parameter=	range		
Minimum Plot Range=	1.0 km		
Maximum Plot Range=	60.0 km		
Range unit=	NM		
Altitude unit=	m		
Probability of Detection=	90.0 %		

ANNEX C EXAMPLE FOR DESIGNING A RADAR REFLECTOR FOR PLASTIC BUOYS

Encouraged by the good correlation between simulation and measurement results, the German Federal Waterways and Shipping Administration (WSV) has incorporated the obtained knowledge into the development of radar reflectors for plastic buoys. In the following, the path from the nautical requirements to the first draft, its simulation, laboratory confirmation up to range measurements in practice is described.

C.1.1. NAUTICAL REQUIREMENTS

For plastic buoys, used at river estuaries and shallow waters in the German North Sea and Baltic Sea an appropriate radar reflector had to be developed. The basic nautical demands were as follows:

- a omnidirectional reflection behaviour;
- b reflection behaviour as constant as possible at tilt angles between -30° to 0° to $+30^\circ$;
- c maximum detection range 5 NM;
- d minimum shipborne antenna height 10 m and
- e minimum mounting height of the radar reflector in the buoy 1 m.

C.1.2. INITIAL DESIGN

The WSV uses the radar reflector type "SR6" (Figure 39) which consists of a 6-fold combination of individual corner reflectors according to section 7.4.3., as standard radar reflector since many years, as it provides omnidirectional reflection characteristic (req. a) and a good tilt behaviour (req. b). Assuming a radar antenna height of 10 m on a vessel (req. d) and a mounting height of the radar reflector in the buoy of approx. 1 m above the waterline (req. e), a max. RCS of approx. 10 m^2 results according to table 8 for the required radar range of 5 NM (req. c).

For an RCS of 10 m^2 , the required edge length of a single corner reflector (Figure 40) can be calculated to approx. 0.22 m according to section 7.4.1.

An average edge length of 0.22 m in the 6-fold arrangement of the SR6 radar reflector can be realized with a diameter of approx. 300 mm. Since the reflector was to be installed in the plastic buoy, the possible attenuation of the surrounding plastic in relation to the radar reflection was investigated, see chapter 11. As a safety margin for any effects due to attenuation, interference, etc., the diameter was increased by 10 %, which leads to an approx. 45 % larger RCS to compensate the potential losses in the plastic cover.

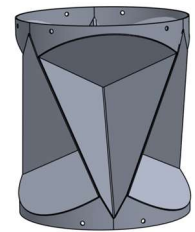


Figure 39: SR6 radar reflector

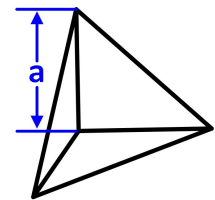


Figure 40: corner reflector

C.1.3. SIMULATION

A 3D design was created, which was then transferred to the simulation software according to chapter 9. The simulation results are shown in Figure 41 and Figure 42.

As roughly calculated before, the maximum RCS value is about 10 m².

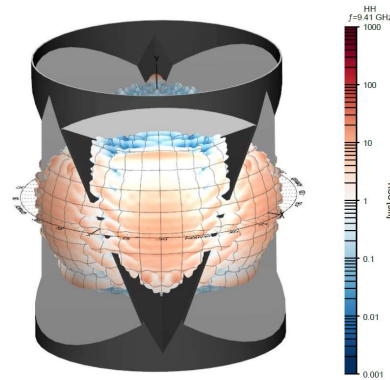


Figure 75. SR6-330 3D RCS at 9.41 GHz, HH.

Figure 41: Spherical 3D RCS plot

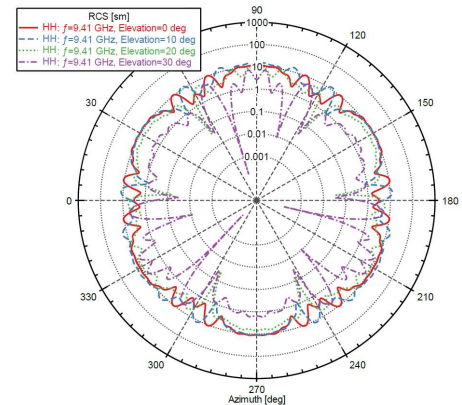


Figure 42: RCS at 0°, -10°, -20° and -30°

C.1.4. LABORATORY MEASUREMENTS

From the 3D design, three real samples were made from aluminium (Figure 43) and measured according to chapter 10. Figure 44 shows the measurement results.

The comparison between simulation and measurement result shows a relative good level of agreement. The differences - especially the deep cuts and the increases in reflectivity- are due to the following factors:

- Manufacturing tolerances
- Blunt edges due to the thickness of the material
- Slits between the sheets due to the production process, as the welding seams could not be made continuous.



Figure 43: first sample

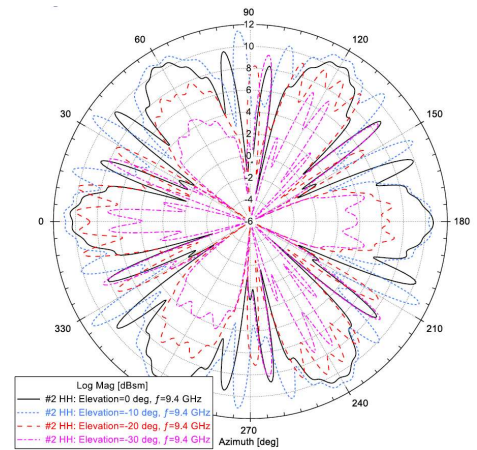


Figure 44: RCS at 0°, -10°, -20° and -30°

20.1.1. MEASUREMENT RESULTS

The radar reflection properties planned in theory, simulated on the basis of a 3D model and measured on a sample of the intended radar reflector have been verified in practice using the radar reflector mounted on a buoy. The results of the real tests with buoys and ship radar systems on the water are described in Annex 0.

In conclusion, the initial considerations, the subsequent simulation, the measurements on the first sample reflectors and the subsequent tests in practice resulted in very good agreements.

ANNEX D EXAMPLE FOR ACCEPTANCE PROTOCOL / INCOMING GOODS INSPECTION

The following is an example of how the incoming goods inspection for radar reflectors manufactured to order can be carried out and documented.

GERMAN FEDERAL WATERWAYS AND SHIPPING ADMINISTRATION

Traffic Technologies Centre



Acceptance protocol for radar reflectors SR 6

Delivery according to order number: _____
 Contractor: _____
 Date of acceptance test: _____
 Reflector type: _____

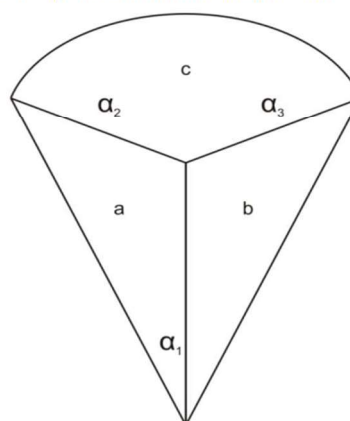
The drawings on which the order is based are decisive for the acceptance of the radar reflectors.
 The following points are examined in detail:

1. The deviation from the flatness
 at each of the 6 corners. The permissible
 tolerances for radar reflectors are
 with a diameter:

up to 500 mm ≤ 1 mm
 and above 500 mm ≤ 2 mm.

The areas a, b and c are measured parallel to the
 neighbouring areas (distance 5 cm) and on the bisector
 between the neighbouring areas. surfaces.

2. The tolerances ($\leq \pm 0,5^\circ$) of the angles α_1 , α_2 and α_3 of
 all 6 corners of, respectively measured in the centre,
 centre and outside.



Corners counted from top
 clockwise

3. The dimensional accuracy including the flatness of the flanges.
4. Check the weld seams for tightness (test pressure 0.2 bar)

Test results see attached tables

 Contractor

 Principal

Corner no. counted from the top clockwise

Test for...		1	2	3	4	5	6
Flatness	Area a						
	Area b						
	Area c						
Corner-area							
Angle tolerance	Angle α_1						
	Angle α_2						
	Angle α_3						

Test for...	Passed	Failed
Tolerances		
Flatness of the flanges		
Weld seams		

Comments:

ANNEX E MEASUREMENTS ON PLASTIC MATERIAL

E.1. INTRODUCTION

To investigate the impact of a plastic cover on the properties of a radar reflector, the German Federal Waterways and Shipping Administration (WSV) conducted a series of measurements.

E.2. SUMMARY OF MEASUREMENT AND TEST RESULTS ON THE INFLUENCE OF PLASTIC COVERS ON THE REFLECTION BEHAVIOUR OF RADAR REFLECTORS

The laboratory measurements do not show any significant impairment due to plastic cover used in the trials. The real tests on land and on the water also confirm this. The results can be summarised as follows:

- the investigated plastic (polyethylene) is suitable from a radar technology point of view;
- the colouring of the PE has no negative influence and
- eventual reflections and interferences had no significant influence.

Not investigated were the following points:

- the behaviour of other plastics than polyethylene;
- the influence of different wall thicknesses;
- the influence of different distances between the radar reflector and the plastic cover and
- plastic covers of other shapes, e.g. conical shapes, etc.

E.3. MEASUREMENTS ON PLASTIC COVERS

E.3.1. LABORATORY MEASUREMENTS ON PLASTIC MATERIAL

In a first step laboratory measurements were carried out by the WSV with the following goals:

- determination of the relative permittivity of the used plastic;
- measurement of the reflexion factor of the plastic as a function of the thickness of the cover and
- measurement of the transmission factor of the plastic as a function of the thickness of the cover.

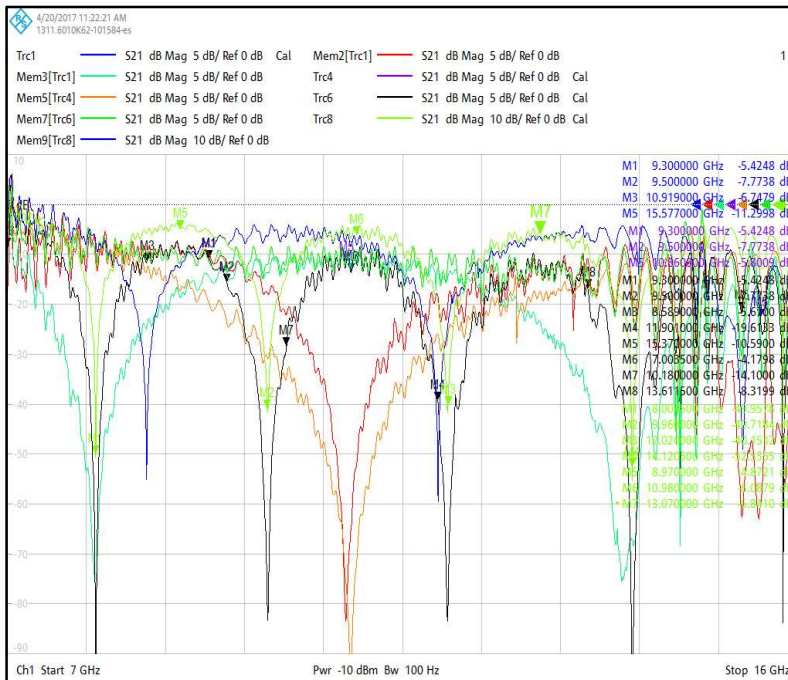


Figure 45: measurement results, attenuation of plastic samples



Figure 46: test setup

The result was that the tested PE plastic is in general suitable for this application. The colouring had no significant impact on the test results. The measurement showed that the transmission of the signal through the plastic depends on the relationship between the thickness and the signal wavelength; to meet the goal to design the plastic cover as transparent as possible (high transmission factor) the thickness of the material has to be chosen appropriate. The trials showed, that best results can be achieved if the thickness of the cover is a multiple of the radar wavelength. As the tests were conducted inside a waveguide, tests with real covers of different thickness should be conducted to confirm this postulation.

Note: for a more detailed description of the conducted tests see [8].

E.3.2. COMPARATIVE LABORATORY MEASUREMENTS WITHOUT AND WITH PLASTIC COVER

In order to assess the effects of a plastic cover in reality, laboratory measurements were carried out on a SR6 radar reflector with a diameter of 330 mm **by MARCH**



Figure 47: radar reflector without cover



Figure 48: radar reflector with plastic cover

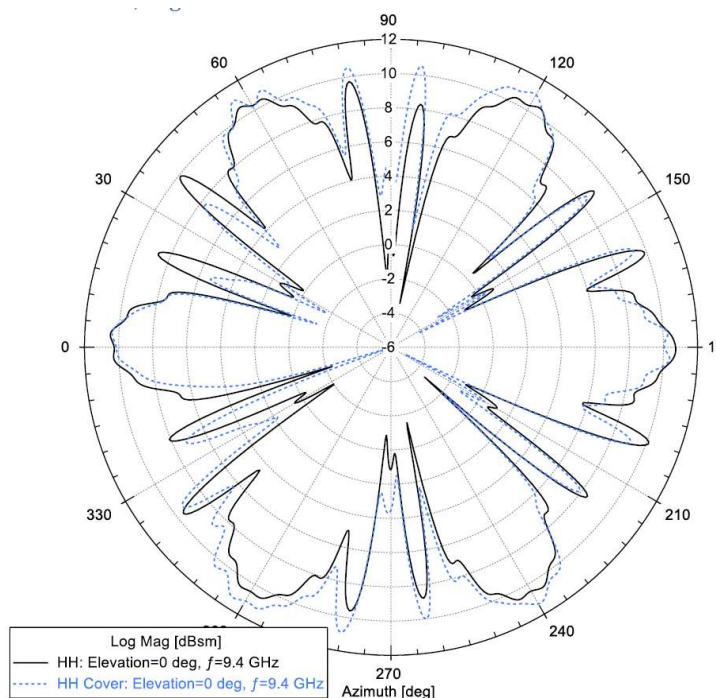


Figure 49: Result of the comparative measurements at 9.4 GHz and 0° elevation:

- without plastic cover (black solid line)
- with plastic cover (blue dashed line)

The measurements were performed according to the same procedure as described in chapter 10.2, first without and then with a plastic cover, see Figure 47 and Figure 48.

The plastic cover was cut out of a commercial available plastic buoy to create the measurement conditions as real as possible. The plastic pipe had an outer diameter of 400 mm and a wall thickness of 12 mm. The polyethylene was dyed-through LDPE (Clariant Remafin).

The result was that the transparency of the plastic is really good and the other expected effects, such as interference, also have only a minor impact. The measurements show that the plastic cover only has a minor impact on the reflection behaviour in this constellation. This can be seen in Figure 49, which shows measurement results without and with plastic cover together in one diagram. Note the linear scaling.

Note: for a more detailed description of the conducted tests see **[X]**.

E.3.3. COMPARATIVE FREE FIELD MEASUREMENTS WITHOUT AND WITH PLASTIC COVER

The German Federal Waterways and Shipping Administration (WSV) conducted a test of a radar reflector with and without plastic cover on an air-field to figure out the impact of the plastic cover in a real life scenario.

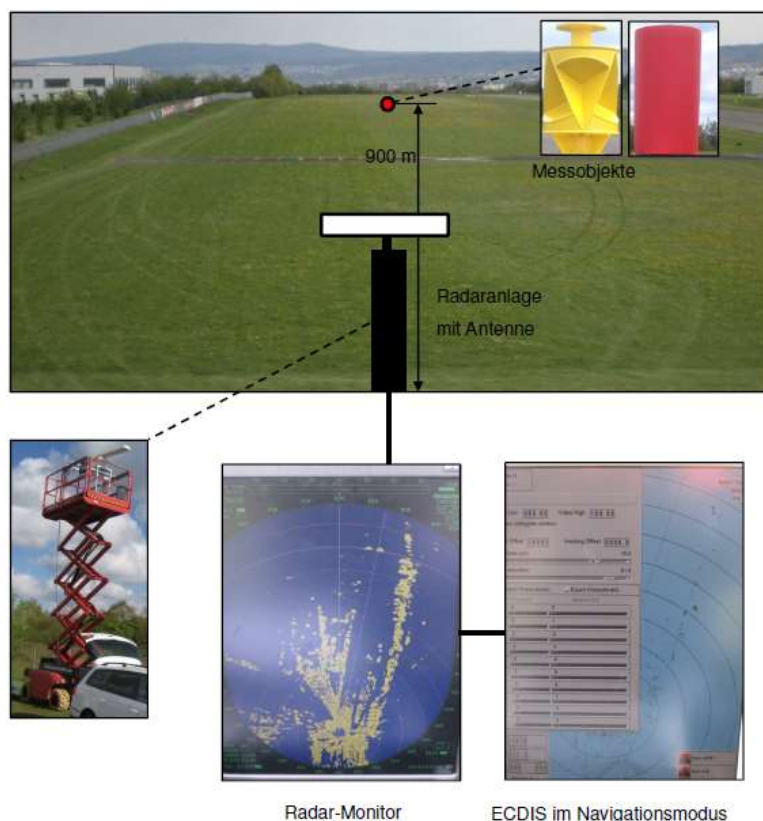


Figure 50: Setup for free field measurements on land



Figure 51: RF absorber

The test was performed with a type approved river radar (JFS Swissradar 364). The radar antenna was installed on a mobile lift truck. A SR6 radar reflector with a diameter of 360 mm was mounted on a stand in a distance of 900 m. Metal parts of the radar reflector installation were covered with RF absorbers (Figure 51).

The detection probability of the radar reflector was tested with and without a plastic cover.

The test showed nearly no impact of the plastic cover in the radar picture.

Note: for a more detailed description of the conducted tests see [X].

E.3.4. REAL ON-SITE TESTS ON THE WATER

E.3.4.1. Measurement concept and setup

The German Federal Waterways and Shipping Administration (WSV) conducted a comparison test of the detecting probability of a steel buoy and a plastic buoy with radar under real conditions in a real life scenario.

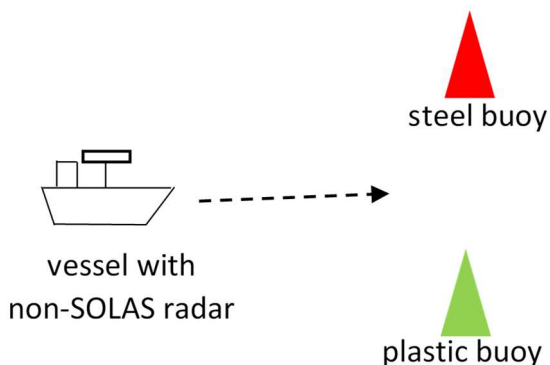


Figure 52: measurement setup



Figure 53: "SZM Bussard"(small buoy tender)

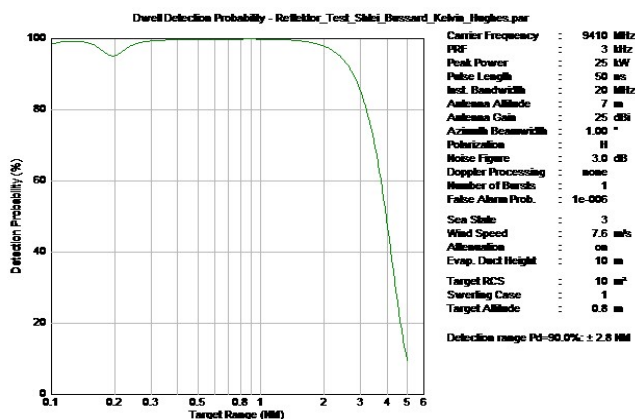


Figure 54: simulated maximum radar range

The vessel "SZM Bussard" was equipped with a non-SOLAS radar. The detectable radar range of a steel buoy and plastic buoy was tested and compared to a simulation performed with the software tool CARPET [X]. Figure 52 shows the test setup.

The plastic buoy and the steel buoy are quite hard to compare directly since the radar reflectors are placed at different heights. In addition, the swimming characteristic of both buoys is different, which has a certain impact on the detecting probability, as there was strong wind and significant high water waves during the tests.

The tests showed that the measured detection ranges match quite well with the simulated results, performed with CARPET. The plastic housing of the used plastic buoy seems to have only a minor impact on the detection probability by radar.

Note: for a more detailed description of the conducted tests see [X].

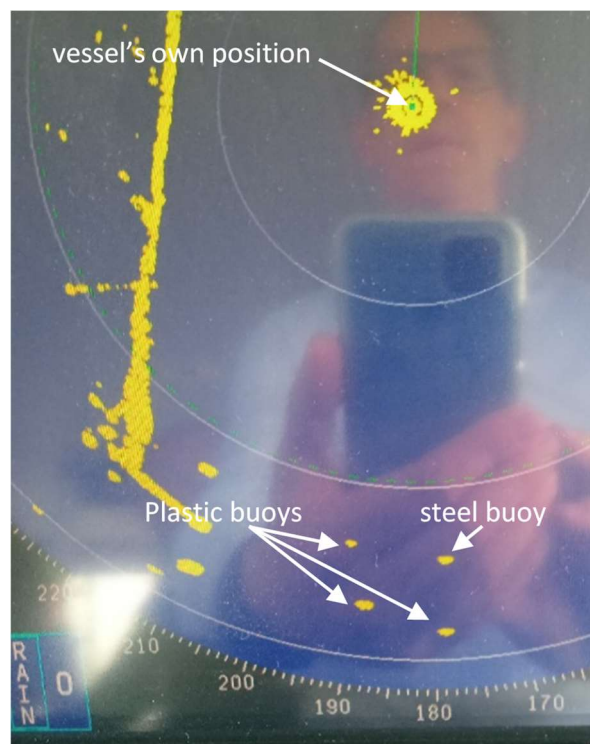


Figure 55: radar picture