IALA

IALA GUIDELINE

G1174
RADAR REFLECTORS ON MARINE AIDS TO NAVIGATION

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DOCUMENT REVISION

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1. INTRODUCTION

Navigational radar equipment plays an important role for the safe navigation of vessels by providing reliable, safety related traffic information to the mariner. Radar enables the surveillance of the traffic situation around the vessel, including landmarks, other vessels and Marine 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 has the advantage that it can detect objects which are not equipped with a radar system themselves. The probability of detection of an object by radar is highly dependent on the magnitude of the reflected radar wave from the object 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-metallic materials 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 consistent and measurable, a structure 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, mechanical and construction aspects have to be considered.

It is recommended to consider equipping AtoN with radar reflectors to make them more detectable to vessels using 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:

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

This Guideline is intended to help maritime administrations and manufacturers to select and to define a suitable sized radar reflector for an AtoN. Among other things, it describes:

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

Racons and Radar Search and Rescue Transponder (SART) are excluded from this guideline.

- For racons see IALA Recommendation *R0101 Marine Radar Beacons (Racons)* [1] and IALA Guideline *G1010 Racon Range Performance* [2].
- Radar SART are subject to ITU Recommendation *ITU-R M.628-3* [3].

Luneberg reflectors are excluded from this guideline.

Luneberg reflectors are applications of the so-called Luneberg lens. Luneberg lenses are radiolucent, inhomogeneous dielectric spheres [4]. 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 AtoN. 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 a 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 Radar Cross Section (RCS, explanation see section 5.6) size (order of magnitude 10 m²).

Note: This guideline focuses on the 9 GHz radar (X-band) as it provides better azimuthal resolution and is more commonly used compared to the 3 GHz radar (S-band). The 9 GHz radar is the preferred radar on board of vessels. Therefore, the radar reflectors are optimized for the 9 GHz radar.

3. NOTES ON THE APPLICATION OF THIS GUIDELINE

As described in the scope, this Guideline is intended to help to find an appropriate radar reflector for a particular application. Using the Guideline, this can be done by the following steps.

3.1. THEORETICAL BASICS

Sections 4, 5 and 6 give an understanding to the theoretical principles of radar waves and their reflection.

3.2. HORIZONTAL AND VERTICAL REFLECTION BEHAVIOUR

The desired horizontal reflection pattern 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 reflection directions could be necessary for buoys with a fixed orientation to the waterway (2).
- Often an omnidirectional reflection behaviour is needed for buoys in the open sea or fixed structures (3).

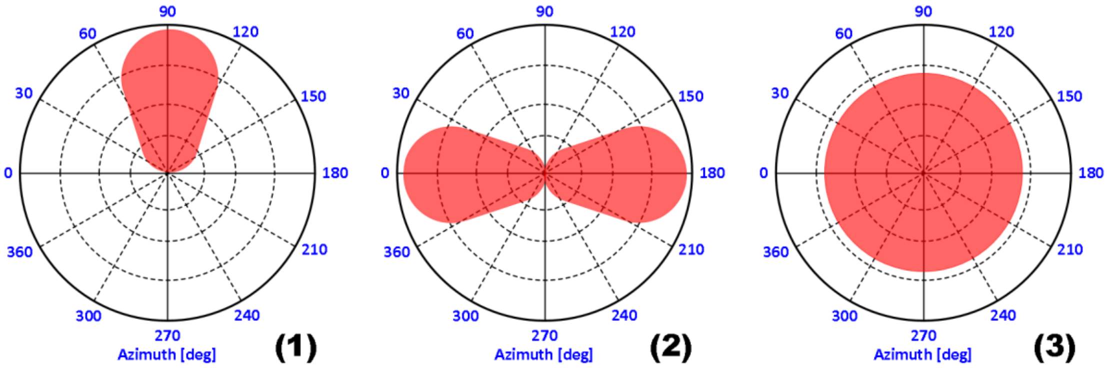


Figure 1 Examples of different horizontal reflection properties

Also the vertical reflection angles have to be considered. If the radar reflector is for the use on buoys, their maximum tilt angle has to be taken into account, see Figure 2. This could be from -30° to 0° to +30° for example.

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

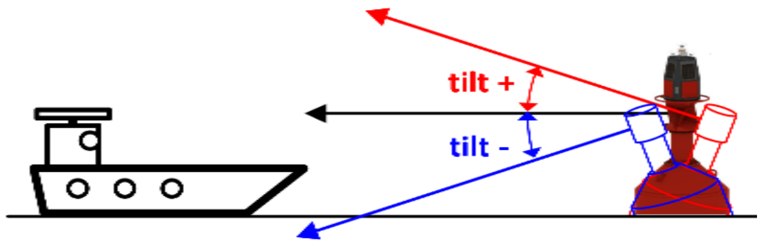


Figure 2 Tilt angle of buoys

3.3. PRE-SELECTION OF POTENTIALLY SUITABLE RADAR REFLECTORS

Section 7.4 and ANNEX A give a brief overview of potentially suitable radar reflectors. Environmental conditions, installation possibilities and maintenance requirements should also be taken into account in accordance with sections 12, 13, 14 and 15.

3.4. RANGE DETERMINATION

Section 8 explains the theory for the (not quite trivial) calculation of the reflector range. The maximum reflector range can be derived from the RCS, see section 5.6. Table 8 of section 8 helps to determine it.

3.5. FINAL RADAR REFLECTOR REQUIREMENTS

Based on the pre-selection according to section 3.3 and the required RCS value, the final design of the radar reflector results. It is important to note here:

- For a given design, the RCS value is directly related to the reflector size.
- For simple corner reflectors, this value can be easily calculated according to section 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 an example for designing a radar reflector 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 MAXIMUM 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):

$$v = \frac{1}{\sqrt{\mu_0 \mu_r \varepsilon_0 \epsilon_r}} = \frac{c}{\sqrt{\varepsilon_r \mu_r}} \tag{1}$$

where:

- v = speed of propagation (m/s);
- μ_0 = $4\pi \times 10^{-7}$ H/m, vacuum permeability;
- μ_r = relative permeability;
- ϵ_0 ≈ 8.8542×10^{-12} F/m, permittivity of free space, electric constant;
- ϵ_r = relative permittivity;
- c ≈ 299 792 458 m/s, speed of light.

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

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

Given the above, this means that the radar wave propagates in air very close to the speed of light.

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

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

where:

- R = radar to target range (m);
- P_t = transmitted signal power (W);
- G_t = transmitting antenna gain;
- G_r = receiving antenna gain;
- σ = radar cross section (m^2);
- λ = wavelength (m);
- 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;
- P_r = received signal power (W).

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 and super- and sub-refraction due to ducting etc. have an impact on the propagation of radar waves and the maximum 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, 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 backscattering of the electromagnetic wave from objects. The strongest form of backscattering is the "directional reflection", also known as "specular reflection", see Figure 4.

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

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.

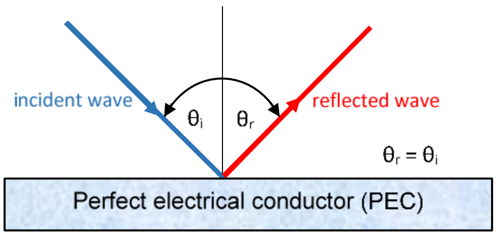


Figure 4 Directional reflection

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.

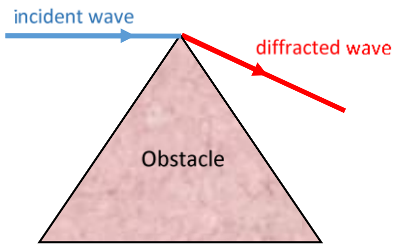


Figure 5 Diffraction

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 reflection θ_r is equal to the angle of incidence θ_i 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.

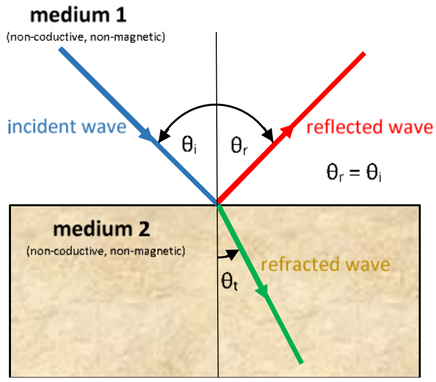


Figure 6 Refraction

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.

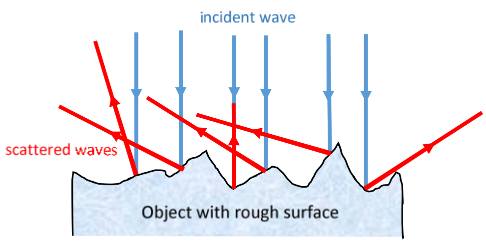


Figure 7 Scattering

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.

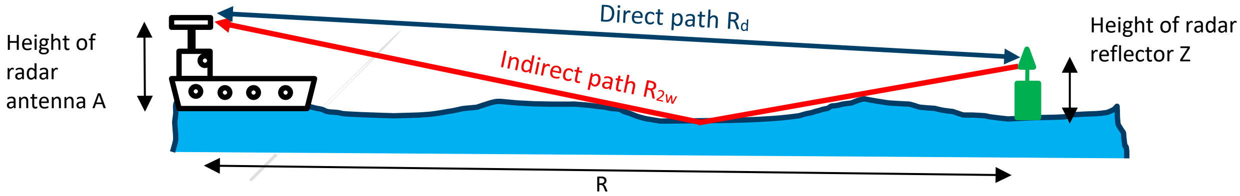


Figure 8 Multipath propagation

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 maximum 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):

$$\Delta R_{max.degradation} = n \cdot \frac{\lambda}{2} \; with \; n = 1, 3, 5 \; etc. \tag{3}$$

where:

ΔR = difference in distance between R_{2w} and R_d (m);

n = sequential number;

λ = wavelength (m);

R_{2w} = length of indirect path (m);

R_d = length of direct path (m).

For navigational radars, operating in the X-band, the free space wavelength is about 3.19 cm.

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

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

where:

ΔR = difference in distance between R_{2w} and R_d (m);

R_{2w} = length of indirect path (m);

R_d = length of direct path (m);

R = distance between radar antenna and target (m);

A = height of radar antenna (m);

Z = height of radar reflector on target (m).

5.6. RADAR CROSS SECTION

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 to *Radar Handbook* [5] 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.

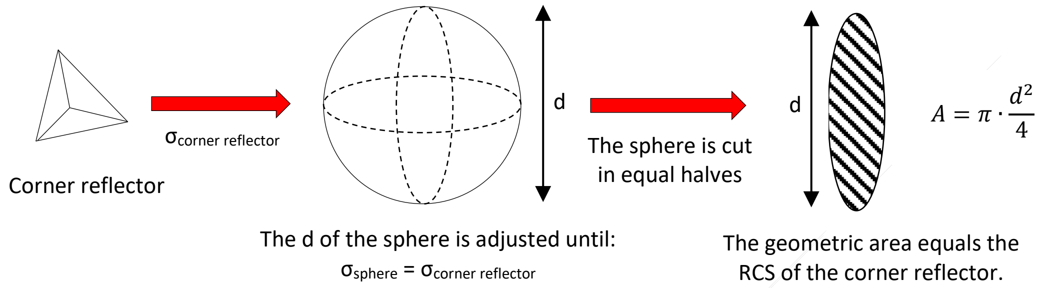


Figure 9 Radar cross section

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 maximum RCS (in the range of several thousand m²).

According to *Radar Handbook*, the formal definition of radar cross section is as shown in Equation (5):

$$\sigma = \lim_{R\to\infty} 4\pi R^2 \frac{|E_s|^2}{|E_0|^2} \tag{5}$$

where:

- σ = radar Cross Section (m²);
- π ≈ 3.14159, mathematical constant;
- R = range from radar to target (m);
- E_S = electric field strength of the scattered wave at the radar (V/m);
- E_0 = electric field strength of the incident wave impinging on the target (V/m).

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 determined according to Equation (6):

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

where:

- σ = radar cross section (m^2);
- π ≈ 3.14159, mathematical constant;
- P_r = received signal power (W);
- R = radar to target distance (range) (m);
- P_t = transmitted signal power (W);
- G_t = transmitting antenna gain;
- G_r = receiving antenna gain;
- λ = wavelength (m);
- 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.

Note: In the following, the maximum RCS is usually referred to when describing the radar reflectors. But looking at the maximum RCS is not sufficient for assessing the overall reflective quality. What is important is the highest possible RCS with a uniform distribution in the spatial angle intended for use.

6. RADAR WAVE REFLECTION ON OBJECTS

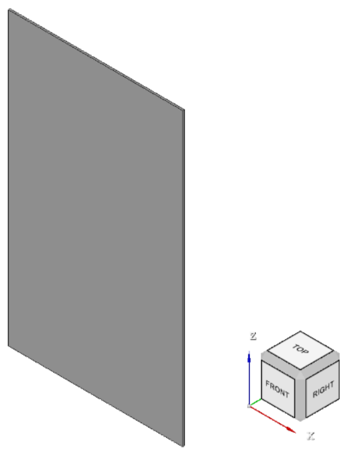
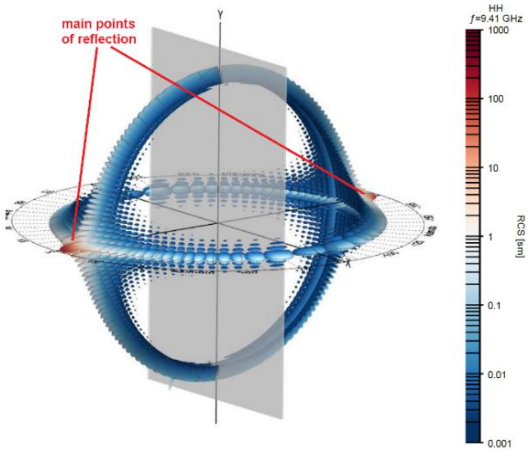
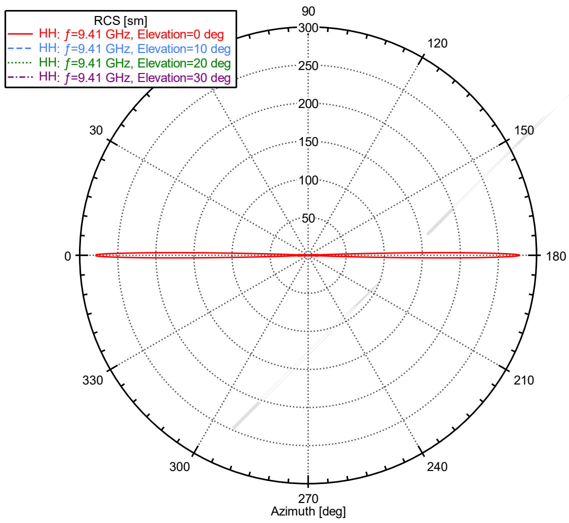
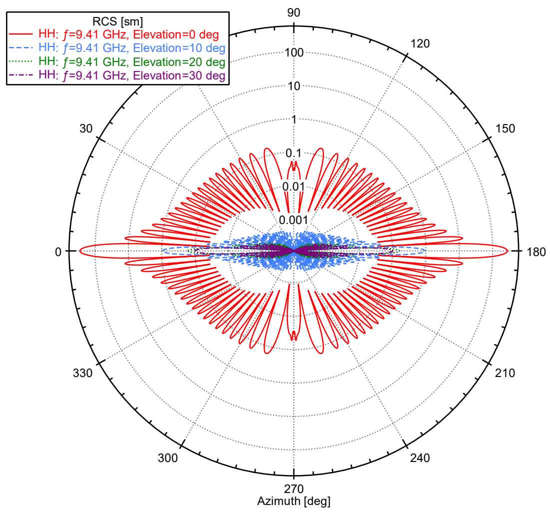
6.1. RADAR WAVE REFLECTION ON SIMPLE OBJECTS

Objects made of metal are generally capable of reflecting incident radar waves. Depending on their shape, the respective reflection changes. 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 adopted is described in section 9, where “sm” means “square metre” in the 3D-reflection diagrams.

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 scattered back due to diffraction, see Table 1. A single metal sheet is therefore not suitable as a radar reflector in practice.

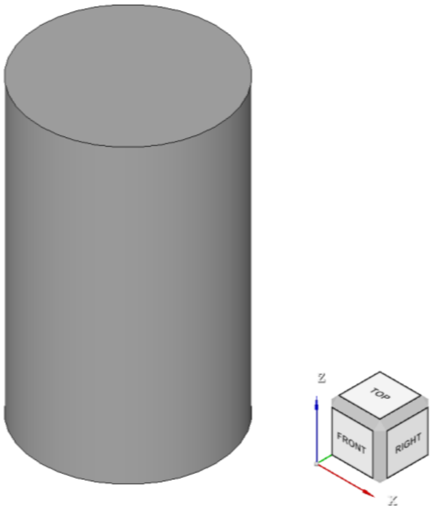
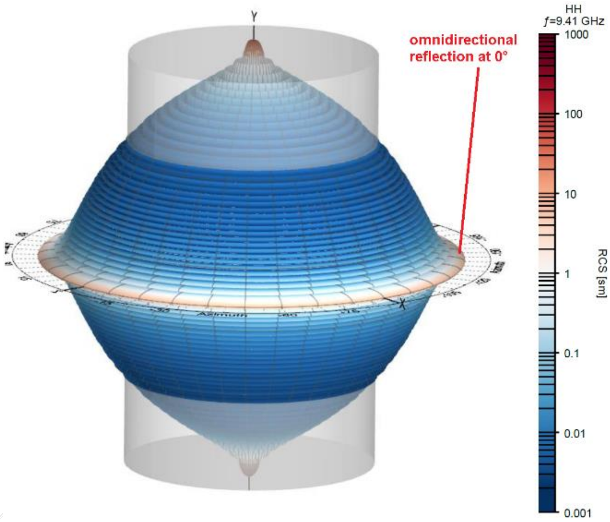
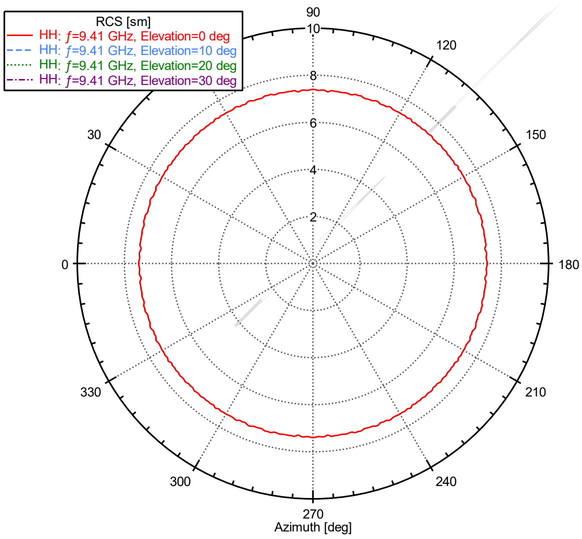
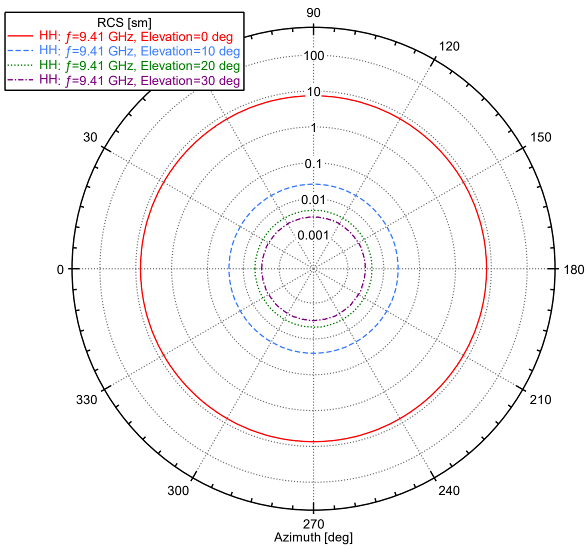
Table 1 Radar wave reflection of a metal sheet

<table>
<tr><th>Dimensions of simulated sheet (mm)</th><th>Max. RCS (m^2)</th><th>Short description</th></tr>
<tr><td>Width: 300; Height: 500
Thickness: 3</td><td>275</td><td>- Not suitable as a radar reflector in practice.
- High reflection only in two small spatial angles.</td></tr>
<tr><td colspan="2">3D-view

</td><td>3D-reflection diagram (rectangular)

</td></tr>
<tr><td colspan="2">2D reflection diagram, different tilt angles, linear

</td><td>2D reflection diagram, different tilt angles, logarithmic

</td></tr>
</table>

6.1.2. CYLINDER

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

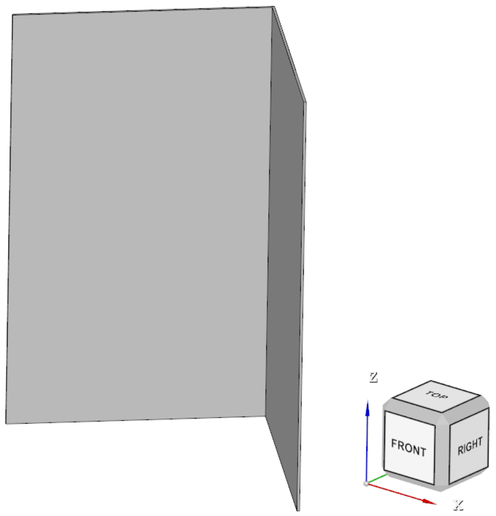
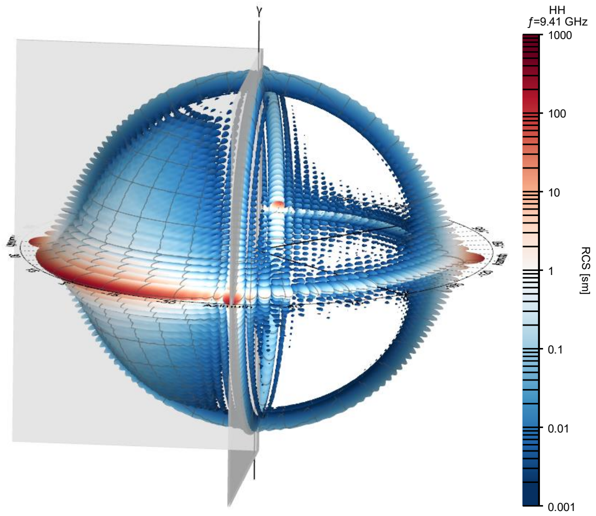
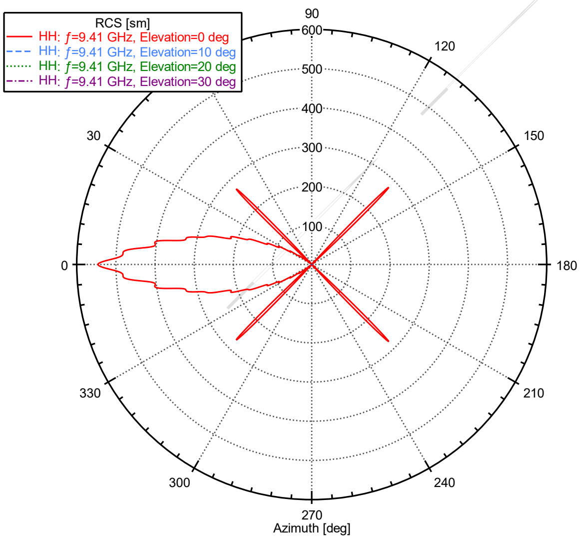
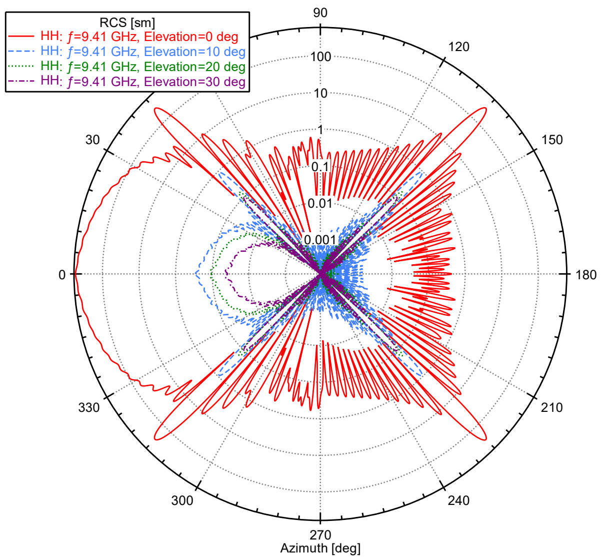
Table 2 Radar wave reflection of a metal cylinder

<table>
<tr><th>Dimensions of simulated cylinder (mm)</th><th>Max. RCS (m^2)</th><th>Short description</th></tr>
<tr><td>Diameter: 300; Height: 500</td><td>7.5</td><td>- Not suitable as a radar reflector in practice.
- Perfect omnidirectional reflection, but only for an elevation of 0°.</td></tr>
<tr><td colspan="2">3D-view

</td><td>3D-reflection diagram (rectangular)

</td></tr>
<tr><td colspan="2">2D reflection diagram, different tilt angles, linear

</td><td>2D reflection diagram, different tilt angles, logarithmic

</td></tr>
</table>

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°

<table>
<tr><th>Dimensions of simulated bent sheet (mm)</th><th>Max. RCS (m^2)</th><th>Short description</th></tr>
<tr><td>Width: 425; Height: 500</td><td>550</td><td>- Not suitable as a radar reflector in practice.
- High reflection only in a spatial angle of ≈ 30° and at an elevation of 0°.</td></tr>
<tr><td colspan="2">3D-view

</td><td>3D-reflection diagram (rectangular)

</td></tr>
<tr><td colspan="2">2D reflection diagram, different tilt angles, linear

</td><td>2D reflection diagram, different tilt angles, logarithmic

</td></tr>
</table>

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

7.1. TASK OF A RADAR REFLECTOR

A radar reflector improves the probability of detection by radar significantly by increasing the intensity of the returned radar wave. This is especially true when a radar reflector is mounted on an AtoN, which is made of non-conductive material such as plastic, this will 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 will be predictable.

As an example, Figure 11 shows a steel buoy, which by itself has a reflection behaviour. In order to obtain a defined and consistent reflection behaviour, the buoy was additionally equipped with a radar reflector.

Figure 11 Steel buoy 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 radar reflector) or sector (sectoral radar reflector);
- reasonable reflection up to an elevation of about 30°; and
- 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 section 12.

7.2.3. REGULATIONS BY INTERNATIONAL BODIES

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 performance (in terms of a RCS value) for AtoN, in order 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)*[6], 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[2]
X-band radar	10 m²	4.9 NM
S-band radar	1 m²	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: 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}.

IMO *International Convention for the Safety of Life at Sea (SOLAS)* [7], Chapter V (Safety of Navigation), 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“ .

In addition, the International Organization for Standardization specifies in *ISO 8729-2010* [8] 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 [8]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 280 ° 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, *ISO 8729-2010* 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 280°”.

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° to each other. This arrangement ensures that the incident radiation is returned almost exactly to the sender of the radiation, see Figure 12.

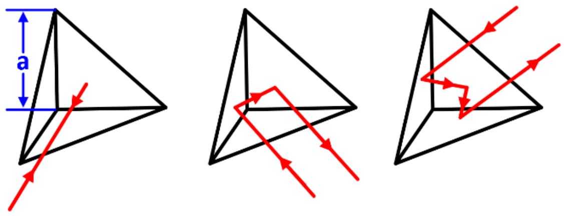


Figure 12 Reflection principle of a corner reflector

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 (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.

$$\sigma_{corner\ reflector} \approx \frac{4\pi \cdot a^4}{3 \cdot \lambda^2} \tag{7}$$

where:

- σ = radar cross section (m^2);
- π ≈ 3.14159, mathematical constant;
- a = inner length (m) of edge as shown in Figure 13;
- λ = wavelength (m).

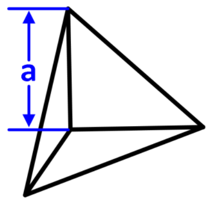


Figure 13 Corner reflector

Example:

A radar reflector with an inner edge length of 0.42 m achieves a reflection area of approx. 128 m^2 at a radar frequency of 9.41 GHz (λ = 3.19 cm).

The maximum RCS of the corner reflector is proportional to the fourth power of its inner 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.

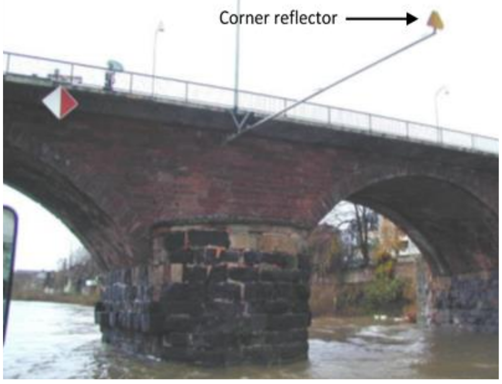
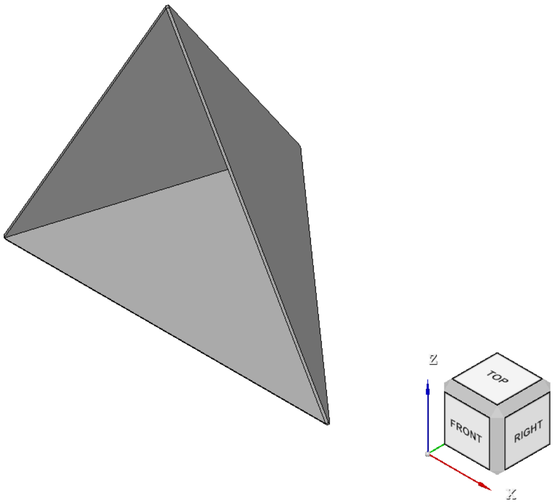
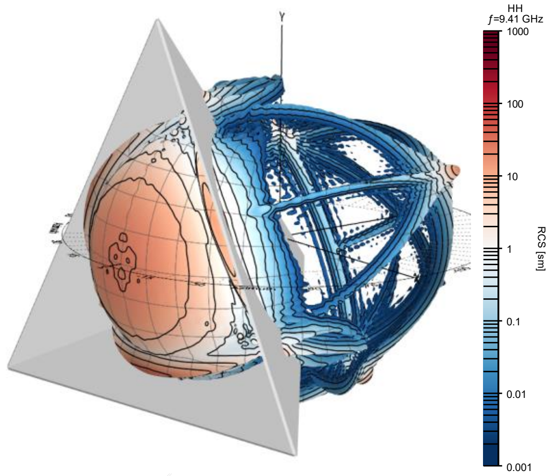
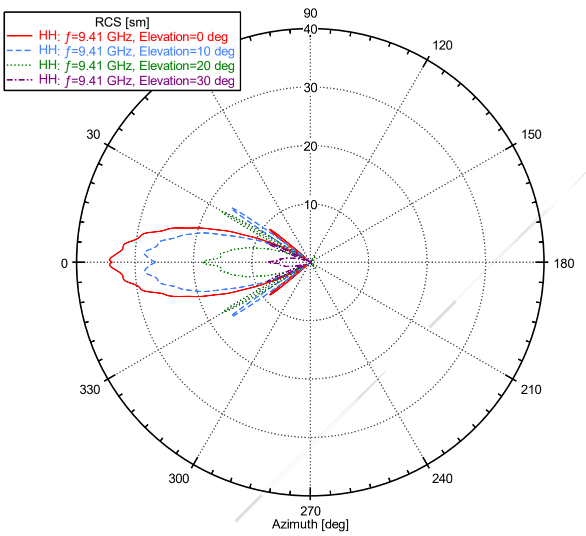
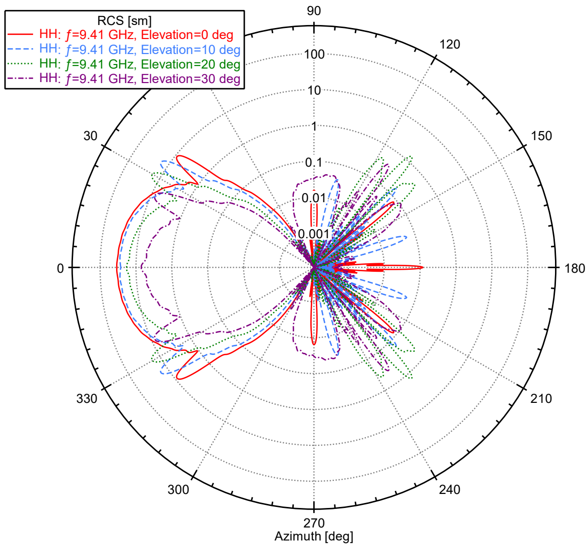


Figure 14 Corner reflector on a bridge

Table 5 Radar wave reflection of a corner reflector

Dimensions of simulated corner reflector (mm)	Max. RCS (m^2)	Short description
Width: 429; Height: 371	34	- Suitable as a radar reflector in practice. - Consistent reflection in reasonable spatial and elevation angles.
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 sections.

7.4.2. MULTIDIRECTIONAL RADAR REFLECTORS

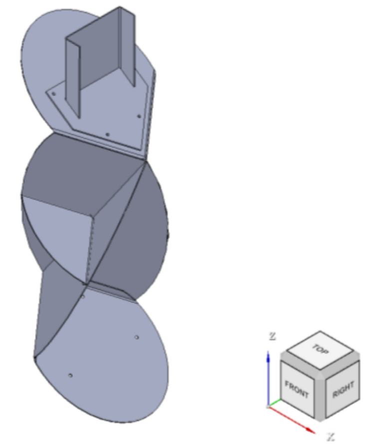
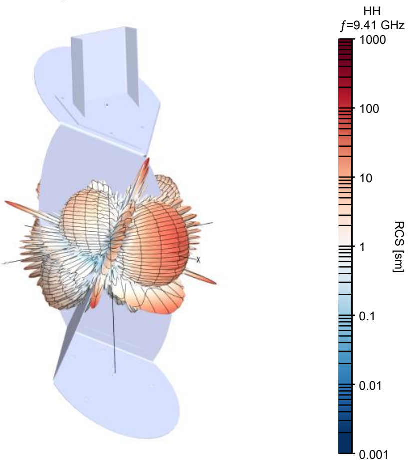
For reflections in several directions, a multiple arrangement of individual corner reflectors is usually chosen. In this case, corner reflectors are combined with each other in such a way that the superimposition of the reflections of the individual corner reflectors results in the desired overall reflection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

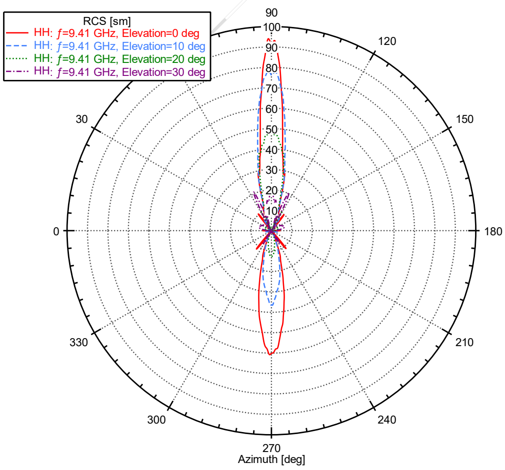
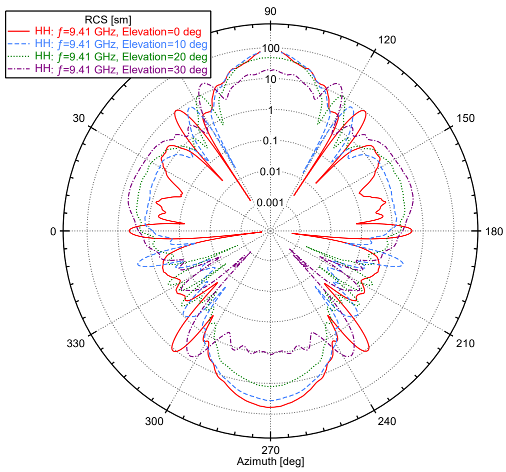
For buoys, who have a fixed orientation to the waterway by the design of their mooring, reflection in two main directions may be sufficient. An example of this application are plastic buoys on rivers with currents as shown in Figure 15. The radar reflector is mounted internally. The impact of the surrounding plastic hull is described in section 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

Dimensions of simulated corner reflector (mm)	Max. RCS (m^2)	Short description
Diameter: 250; Height: 700	95	- Two main reflection directions with high RCS over a restricted spatial angle. - Designed for plastic buoys (mounted inside, protected).

3D-view	3D-reflection diagram (rectangular)
	

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

7.4.3. OMNIDIRECTIONAL RADAR REFLECTORS

Often an almost constant reflection in the horizontal plane (omnidirectional) is needed, e.g., for buoys in 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 six, eight or ten individual corner reflectors are combined. However, developing a consistent reflection pattern is a difficult task, because the overlap of the reflections of multiple reflectors can cause 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 section 11.

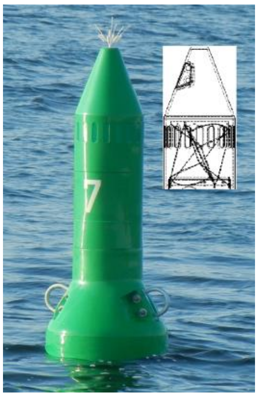
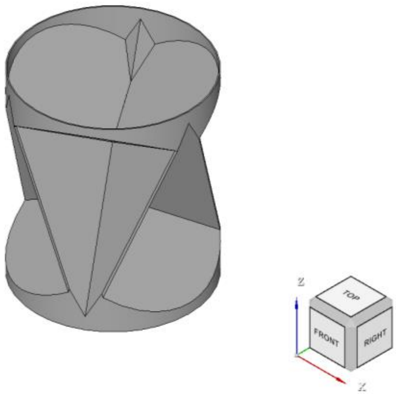
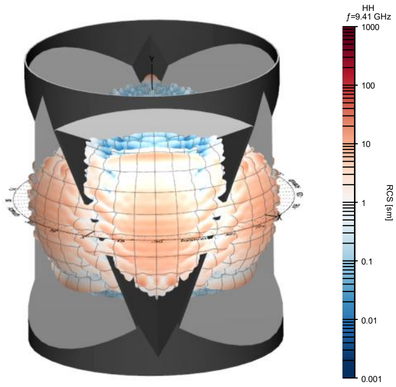
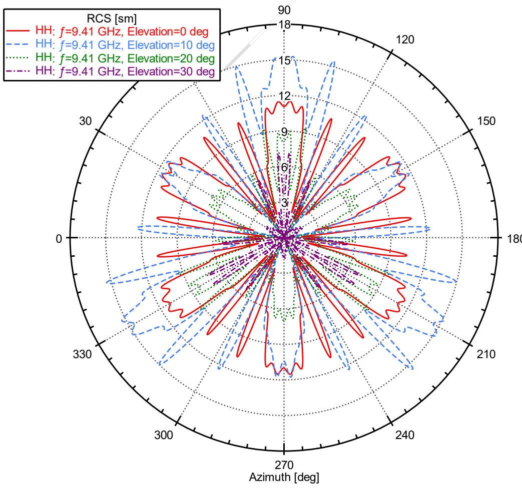
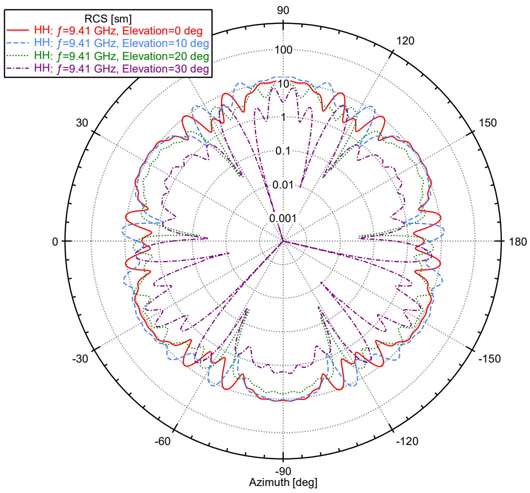


Figure 16 Plastic buoy

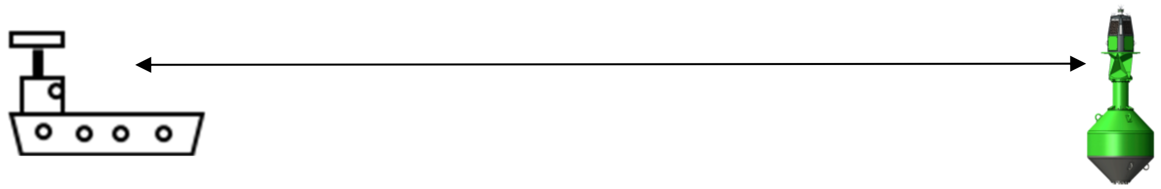
Table 7 Omnidirectional 6 corner reflector SR6-330

<table>
<tr><th>Dimensions of simulated reflector (mm)</th><th>Max. RCS (m^2)</th><th>Short description</th></tr>
<tr><td>Diameter: 330; Height: 385</td><td>15</td><td>- Six tightly packed corner reflectors.
- Good uniformity.
- Different diameters available.</td></tr>
<tr><td colspan="2">3D-view
</td><td>3D-reflection diagram (rectangular)

</td></tr>
<tr><td colspan="2">2D reflection diagram, different tilt angles, linear

</td><td>2D reflection diagram, different tilt angles, logarithmic

</td></tr>
</table>

8. DETECTION RANGE OF RADAR REFLECTORS

8.1. OVERVIEW

The radar equation within section 4 gives information about the theoretical radar range calculation under ideal conditions for a target in free space. In practice a lot of different parameters affect the maximum range. Figure 17 provides a list of the most common parameters. With the help of software-based simulation tools it is possible to refine the maximum detection range accounting for these parameters. For the following simulations the software tool *CARPET* [SW.1] was used.



Antenna related parameters:
- installation height h_{ant}
- transmitting-antenna gain G_t
- receiving-antenna gain G_r
- azimuth sidelobe suppression
- beamshape loss factor
- frame rate (rotation speed)
- polarization

Transmitter related parameters:
- wavelength λ
- peak power P_t
- pulse length τ
- pulse repetition frequency PRF
- number of bursts
- number of transmissions per burst
- transmitter loss factor L_T

Receiver related parameters:
- receiving system noise - temperature T_s
- detectability factor D_0
- bandwidth correction factor C_B
- receiver loss factor L_R
- processing loss factor L_P
- probability of detection P_D
- false alarm rate f_A
- pulse compression gain (only solid state radar)

Propagation path related range parameter:
- pattern propagation factor for transmitting-antenna-to-target path F_t
- pattern propagation factor for target-to-receiving-antenna path F_r
- temperature of air
- atmospheric pressure
- relative humidity
- wind direction and speed
- galactic noise activity
- wavelength λ
- sea state
- sea salinity
- water temperature
- wave height
- evaporation and surface-based duct
- land clutter
- multipath propagation
- shadowing, diffraction, scattering
- rain, hail , snow

Target related range parameter:
- RCS σ (elevation, azimuth, housing)
- installation height h_{Target}
- (velocity, fluctuation)

Figure 17 Range parameters

8.2. KEY PARAMETERS FOR CALCULATING THE MAXIMUM DETECTION RANGE

8.2.1. TARGET PARAMETERS

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

8.2.1.1. Elevation

Regarding the maximum possible radar range, any 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 in 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. 3.19 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 swirling case (fluctuation)

The relative velocity between radar installation and target as well as the "swirling case" should be considered. There are four "swirling 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.

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

Figure 18 shows a plastic buoy with internal radar reflector.

Figure 19 shows a big coastal plastic buoy type LB3000-WSV with internal radar reflector.

Figure 18 Plastic buoy with internal radar reflector

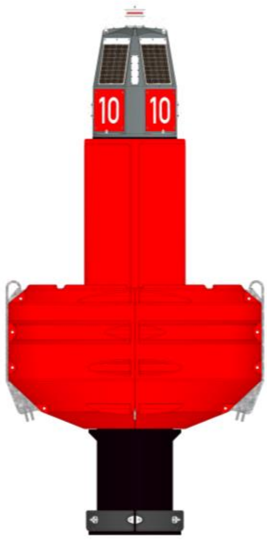


Figure 19 Plastic buoy type LB3000-WSV with internal radar reflector

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 (higher frequency) suffers from slightly higher absorption losses and hence attenuation than the lower frequency 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 to IALA Recommendation *R0128 Operational and Technical Performance of VTS Systems* [9],

> “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 maximum 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. Section 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 maximum 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 section 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)* and IEC Standard EN 62388 *Maritime navigation and radiocommunication equipment and systems – Shipborne radar – Performance requirements, methods of testing and required test results* [10] as captured in section 7.2.

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 Pt;
- pulse length τ and pulse repetition frequency PRF;
- number of bursts and number of transmissions per burst;
- transmitter losses L_T; and
- 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; and
- 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 aperture;
- 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 ANNEX B. The calculations were performed using the software programme *CARPET*. 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 kW; 7 ft antenna; pulse length 400 ns; PRF 1400 Hz; false alarm rate 10^{-6};
- S-band radar with P=30 kW; 12 ft antenna; pulse length 400 ns; PRF 1400 Hz; false alarm rate 10^{-6};
- sea state 3, no rain, hail or snow;
- detection probability 90%; and
- 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 m². 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 sea state 3 causes significant high water waves.

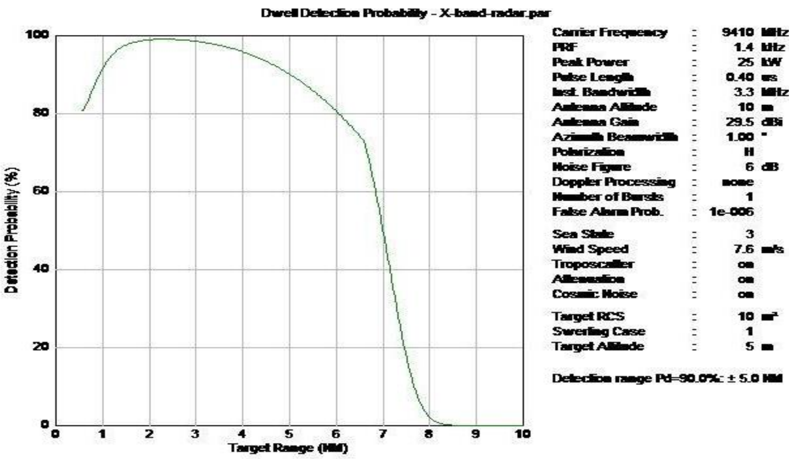


Figure 20 Detection probability with a sea state of 3

Figure 21 shows the same scenario, but with consideration of multipath effects (see section 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.

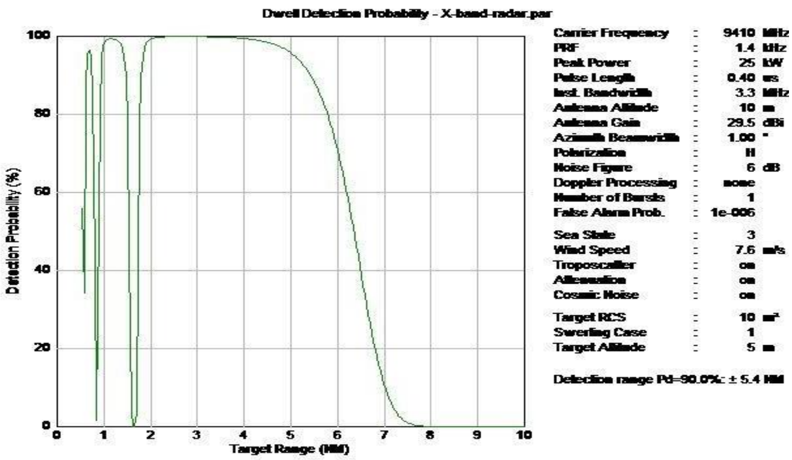


Figure 21 Detection probability with a sea state of 3, with multipath propagation

Figure 22 shows the same scenario as Figure 20 with sea state 7 instead of sea state 3.

Reliable visual detection of a target in heavy storms and high 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.

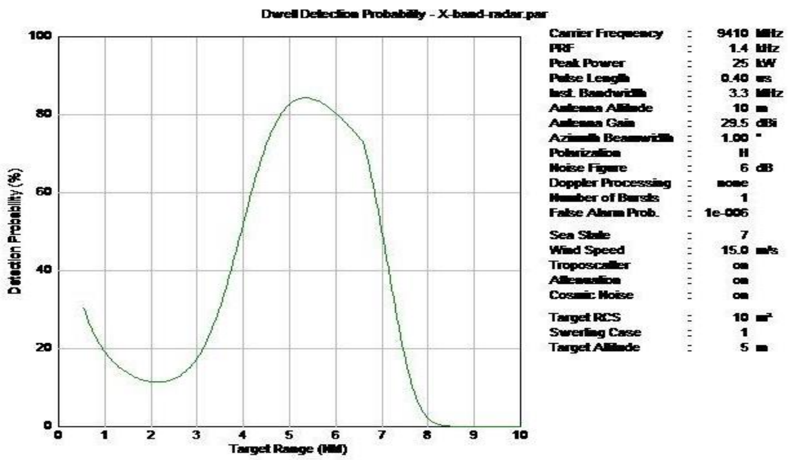


Figure 22 Detection probability with a sea state of 7

Figure 23 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 only a little higher, however there is a certain probability of seeing targets further away (potentially up to twice the distance).

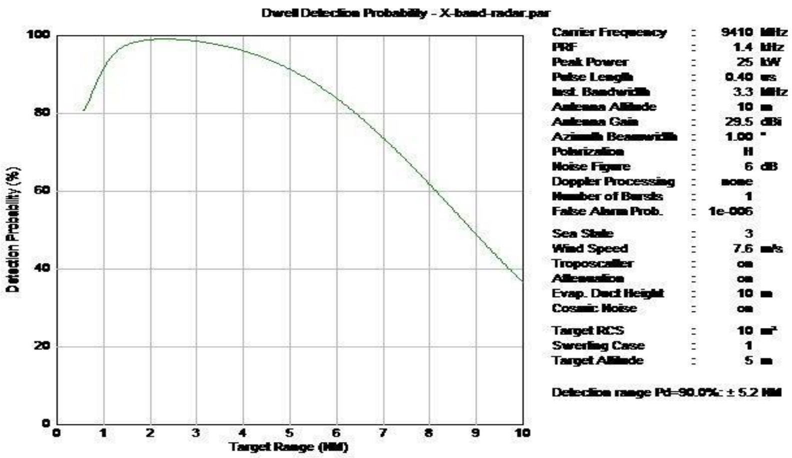


Figure 23 Detection probability with evaporation duct (height 10 m)

Figure 24 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 m² 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*.

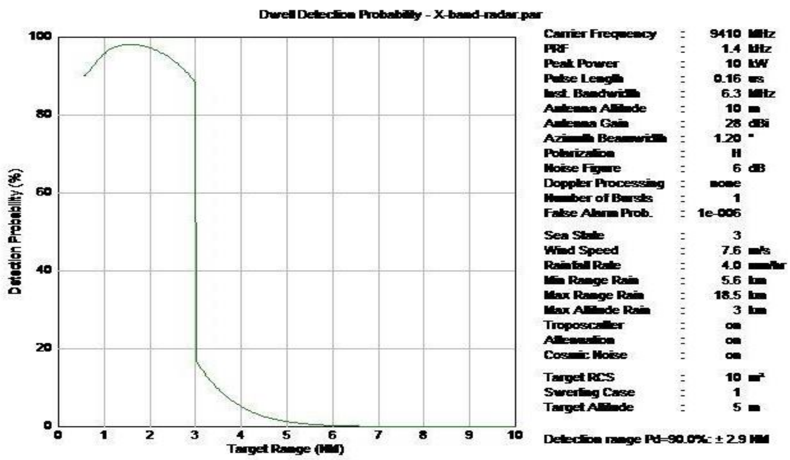


Figure 24 Detection probability with rainfall (4 mm/hr)

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.

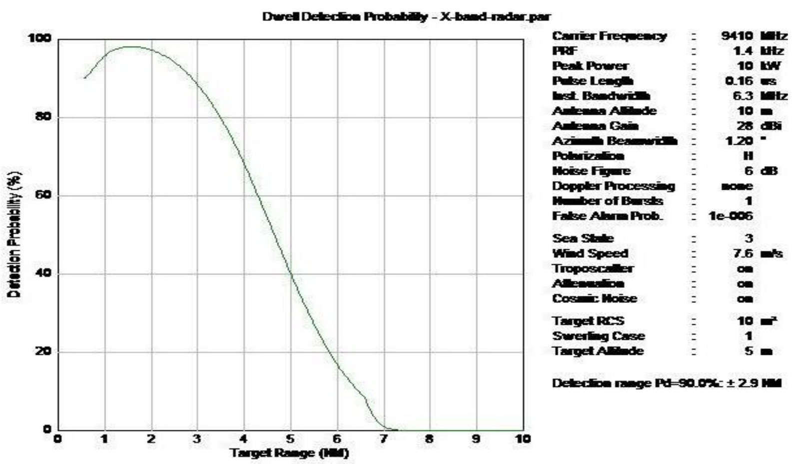


Figure 25 Detection probability with a typical non-SOLAS radar

Table 8 Typical achievable maximum radar ranges

Shipborne radar antenna height	Target height	X-band		S-band
		RCS	Detection range	Detection range
5 m	1.0 m	10 m²	3.7 NM	2.9 NM
		50 m²	4.2 NM	3.5 NM
		300 m²	4.9 NM	4.1 NM
		1000 m²	5.3 NM	4.6 NM
	3.5 m	10 m²	4.5 NM	3.5 NM
		50 m²	5.2 NM	4.1 NM
		300 m²	5.9 NM	4.9 NM
		1000 m²	6.4 NM	5.5 NM
	7.5 m	10 m²	5.0 NM	3.7 NM
		50 m²	5.8 NM	4.9 NM
		300 m²	6.6 NM	5.8 NM
		1000 m²	7.2 NM	6.5 NM
10 m	1.0 m	10 m²	4.8 NM	3.7 NM
		50 m²	5.5 NM	4.4 NM
		300 m²	6.2 NM	5.2 NM
		1000 m²	6.7 NM	5.7 NM
	3.5 m	10 m²	5.0 NM	3.7 NM
		50 m²	6.4 NM	5.1 NM
		300 m²	7.2 NM	6.0 NM
		1000 m²	7.8 NM	6.6 NM
	7.5 m	10 m²	5.0 NM	3.7 NM
		50 m²	7.4 NM	5.6 NM
		300 m²	8.4 NM	6.9 NM
		1000 m²	9.1 NM	7.6 NM
15 m	1.0 m	10 m²	5.0 NM	3.7 NM
		50 m²	6.5 NM	5.3 NM
		300 m²	7.3 NM	6.1 NM
		1000 m²	7.8 NM	6.7 NM
	3.5 m	**10 m²**	**5.0 NM**	**3.7 NM**
		50 m²	7.4 NM	5.6 NM
		300 m²	8.3 NM	6.8 NM
		1000 m²	8.9 NM	7.5 NM
	7.5 m	10 m²	5.0 NM	3.7 NM
		50 m²	7.5 NM	5.6 NM
		300 m²	9.5 NM	7.8 NM
		1000 m²	10.2 NM	8.5 NM
20 m	1.0 m	10 m²	5.0 NM	3.7 NM
		50 m²	7.4 NM	5.6 NM
		300 m²	8.2 NM	6.9 NM
		1000 m²	8.8 NM	7.5 NM
	3.5 m	10 m²	5.0 NM	3.7 NM
		50 m²	7.5 NM	5.6 NM
		300 m²	9.2 NM	7.6 NM
		1000 m²	9.9 NM	8.4 NM
	7.5 m	10 m²	5.0 NM	3.7 NM
		50 m²	7.5 NM	5.6 NM
		300 m²	10.5 NM	8.5 NM
		1000 m²	11.2 NM	9.3 NM

Note 1: The detection ranges are based on a detection probability of 90%.

Note 2: 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 3: 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!

Note 4: The values marked in red correspond to the minimum reference detection ranges published by the IMO as mentioned in section 7.2. Table 4.

9. SIMULATION OF THE REFLECTION BEHAVIOUR

9.1. POSSIBILITIES AND BENEFITS

Nowadays, computer-based simulation programmes significantly help to support the relatively complex measurements on radar reflectors according to section 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* [SW.2], executed by MARCH Microwave Systems B. V., Netherlands.

9.2. PROCEDURE, REQUIRED DATA

As a rule, a 3D design (3-model) of the radar reflector to be simulated must be available in a CAD environment. Then a suitable 3D model is exported from the CAD 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.

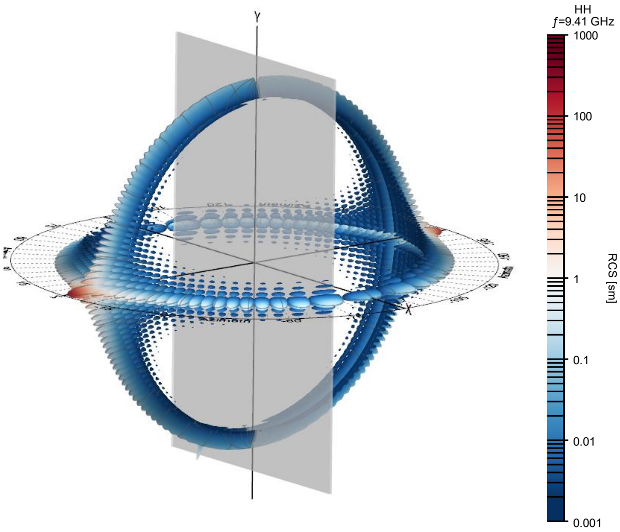


Figure 26 RCS simulation for a metal sheet

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), polarization, 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 spatial 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 *ISO 8729-1*, chapter 6.4.

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 3.05 GHz (S-band)
Polarization	Horizontal (H)
Rotation angle	360°
Angle resolution	0.5°
Elevation to the front	0°, -10°, -20°, -30°

The tests should be carried out at both X-band (9.41 GHz) and S-band (3.05 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 m^2 at X-band and 0.5 m^2 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 four different elevation angles (0°, -10°, -20° and -30°). The respective elevation angle is realized 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.

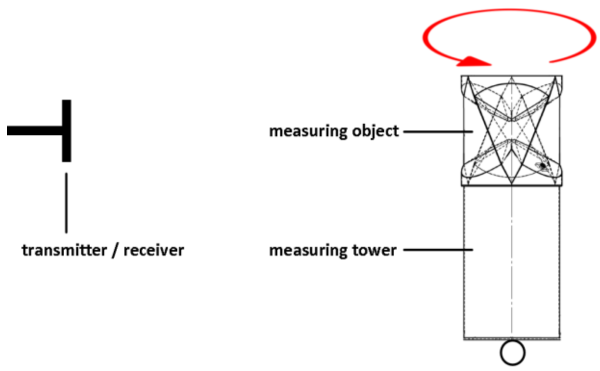


Figure 27 Radar reflector on measuring tower, elevation angle 0°

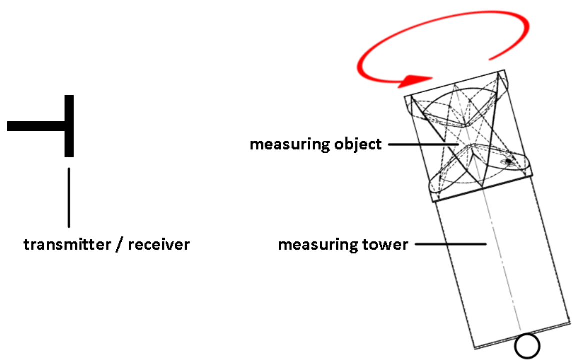


Figure 28 Radar reflector on measuring tower, elevation angle -10°

The results of the measurements as described above of three identical radar reflectors (#1, #2, #3) at the frequency of 9.41 GHz are shown in the following figures (polar coordinates):

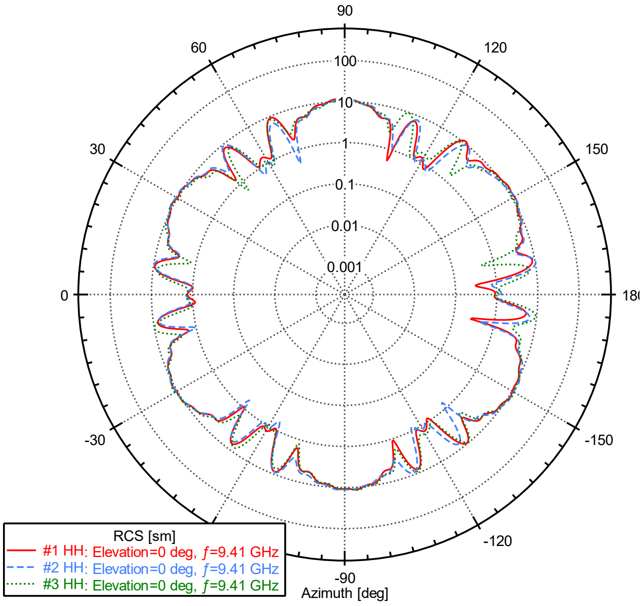


Figure 29   Measurement results at 0° elevation

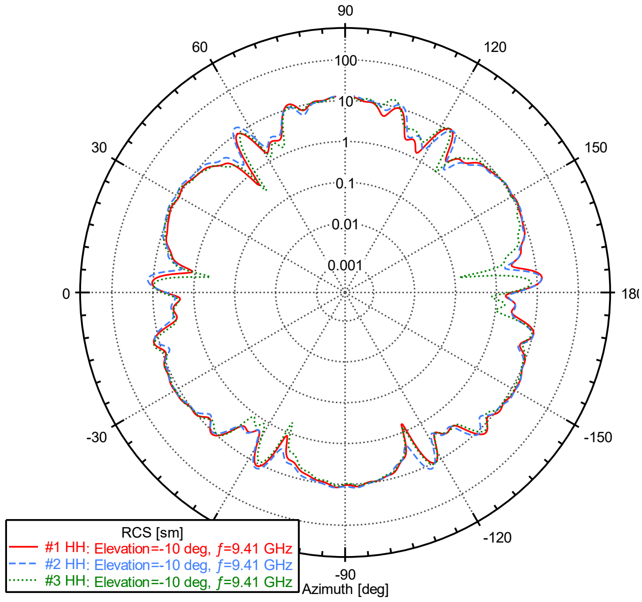


Figure 30   Measurement results at -10° elevation

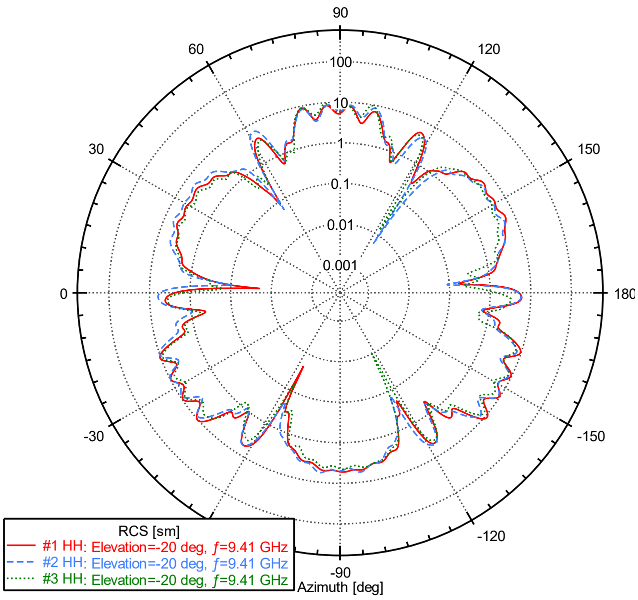


Figure 31   Measurement results at -20° elevation

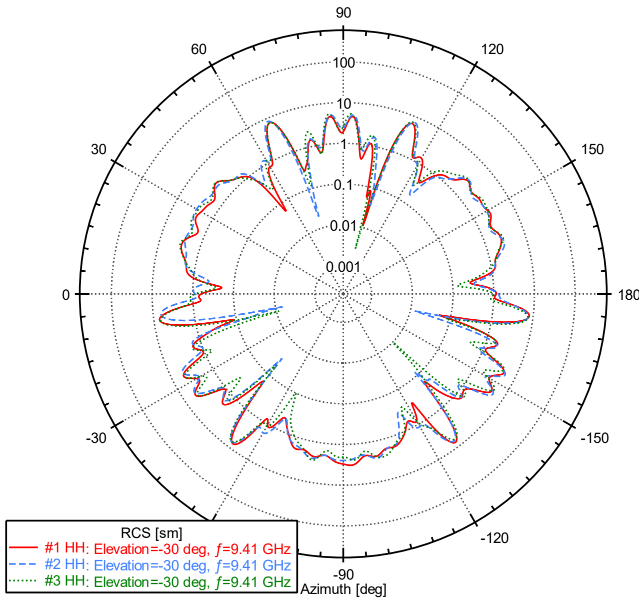


Figure 32   Measurement results at -30° elevation

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

11.1. CONSIDERATIONS

Radar reflectors fitted inside of plastic buoys are covered by surrounding plastic. Any cover around the radar reflector affects its reflective properties to a greater or lesser extent. These 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 tests 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 summarized as follows:

- the investigated plastic (polyethylene, PE) 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. PRELIMINARY 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 as best as 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, so that some adverse conditions are 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 reflector with a 300 mmm diameter on a steel buoy by a SR6 reflector with a diameter of 330 mm 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 sea states, vibration, humidity and change of temperature likely to be experienced in the marine environment and capable of withstanding the environmental conditions.

Radar reflectors are manufactured 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 of sheet metal (Figure 33). It is also possible to attach individual corner reflectors to a supporting structure (Figure 34). In some cases, the radar reflector is part of the daymark of an AtoN (Figure 35) or fully integrated into the buoy body (Figure 36).

Figure 33 Welded radar reflector

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

Figure 35 Radar reflector as part of the daymark

Figure 36 Radar reflector integrated into the buoy body

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, insulating bushes can be used (Figure 37).

Figure 37 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 38 shows a plastic buoy with an integrated radar reflector.

If the radar reflector is mounted outside, surface protection is needed. Figure 39 and Figure 40 show outside mounted radar reflectors.

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.

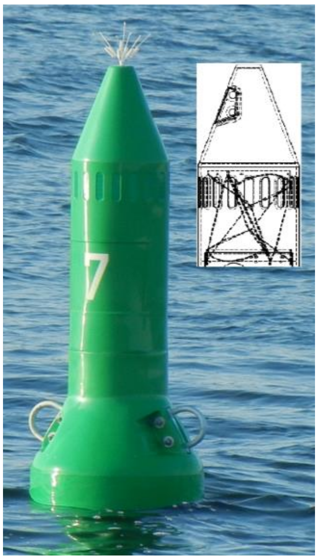


Figure 38 Plastic buoy

Figure 39 Steel buoy

Figure 40 Corner reflectors on a LANBY

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 becomes smaller as the size of the reflector gets larger. The tolerances shown in Table 10 should not be exceeded:

Table 10 Manufacturing tolerances

Reflector diameter	Maximum angular tolerance
0.5 m	± 1°
1 m	± 0.5°
Reflector diameter	**Maximum flatness tolerance**
0.5 m	≤ 1 mm
1 m	≤ 2 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 the following further requirements:

- low weight;
- low manufacturing costs; and
- protection against icing, if needed.

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 41 shows the coating of aluminium corner reflectors which has been severely attacked by the adverse marine environment. Also bird droppings can contribute to a damage of the coating.

Figure 42 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 41 Damaged coating

Figure 42 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 one’s own specifications or manufactured in-house. This can be the case in particular if the radar reflector is a load-bearing component of a buoy and must be integrated accordingly.

15. MOUNTING

An important parameter regarding the effectiveness of a radar reflector is the mounting height, see also section 8. A mounting location as high as possible, e.g., on a buoy, optimizes the radar range. Figure 39 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. REFERENCES

[1] IALA. Recommendation R0101 Marine Radar Beacons (Racons).

[2] IALA. Guideline G1010 Racon Range Performance.

[3] ITU Recommendation ITU-R M.628-3.

[4] Dr. Zeininger, S. Luneberglinsen und ihre Verwendung, Sonderdruck der Grünzweig + Hartmann AG.

[5] Skolnik, M.I. (1990) Radar Handbook.

[6] IMO. Resolution MSC.192 (79).

[7] IMO. International Convention for the Safety of Life at Sea (SOLAS).

[8] ISO. Standard ISO 8729-2010.

[9] IALA. Recommendation R0128 Operational and Technical Performance of VTS Systems.

[10] IEC. Standard EN 62388 Maritime navigation and radiocommunication equipment and systems – Shipborne radar – Performance requirements, methods of testing and required test results.

17. ABBREVIATIONS

AtoN	Marine Aids to Navigation
CAD	Computer Aided Design
CARPET	Computer Aided Radar Performance Evaluation Tool
dBsm	dB Square Meter
HH	Horizontal polarization transmit, Horizontal polarization receive
HV	Horizontal polarization transmit, Vertical polarization receive
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IMO	International Maritime Organization
ISO	International Organization for Standardization
ITU	International Telecommunication Union
LANBY	Large Automatic Navigation Buoy
MLFMM	Multi-Level Fast Multipole Method
PE	Polyethylene
PEC	Perfect Electrical Conductor
Racon	Radar Beacon
Radar	Radio Detection and Ranging
RCS	Radar Cross Section
RF	Radio Frequency
SART	Search and Rescue Radar Transponder
SBR	Shooting and Bouncing Rays
SM	Square Meter
SOLAS	Safety Of Life At Sea
SR	Speckter Reflector
VH	Vertical polarization transmit, Horizontal polarization receive
VTS	Vessel Traffic Service
VV	Vertical polarization transmit, Vertical polarization receive
WSV	German Federal Waterways and Shipping Administration

18. SOFTWARE TOOLS

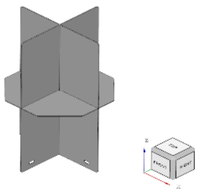
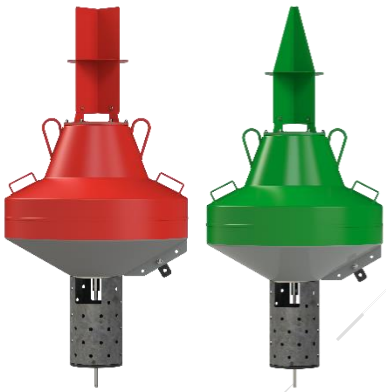
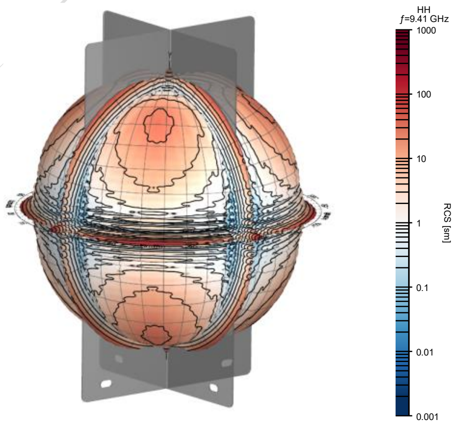
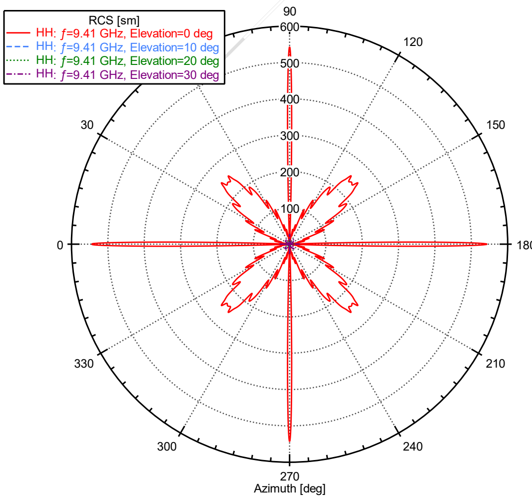
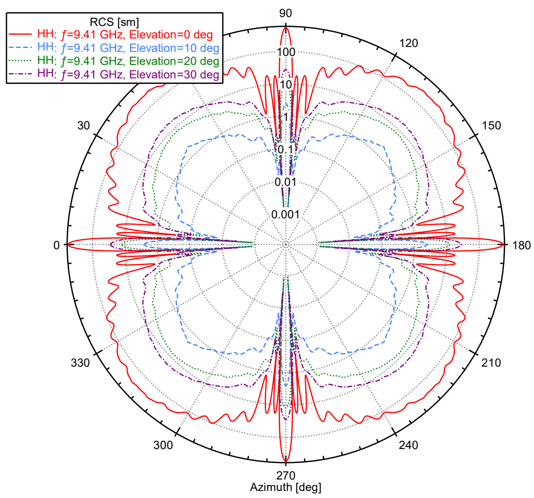
[SW.1] CARPET - Computer Aided Radar Performance Tool
TNO (Toegepast Natuurkundig Onderzoek) Physics and Electronics Laboratory,
P.O.Box 96864,
2509 JG The Hague, Netherlands

[SW.2] CST MICROWAVE STUDIO
Dassault Systèmes
10, Rue Marcel Dassault, 78140 Vélizy-Villacoublay, France

ANNEX A TYPICAL DESIGNS

From a global perspective, a wide variety of radar reflectors are used in the field of AtoN. In preparing this guideline, some of 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)

<table>
<tr><td>Type</td><td>Multidirectional</td><td>Name</td><td colspan="2">Octahedral reflector (rectangular and triangle topmark)</td></tr>
<tr><td>Origin</td><td>German Federal Waterways and Shipping Administration</td><td>Purpose</td><td colspan="2">Joint use as top mark and radar reflector for steel or plastic buoys on German inland waterways, different shapes available</td></tr>
<tr><td colspan="2">Dimensions simulated reflector (mm)
Width: 350; Height: 600</td><td rowspan="2">3D-view
</td><td rowspan="2" colspan="2">Short description / Special properties
- Simple construction, easy to manufacture.
- Consistent lower level RCS makes this reflector suitable for many applications, but high RCS values at elevations of 0°; 90°; 180°; 270° azimuth are not effective due to small spatial angles.</td></tr>
<tr><td colspan="2">RCS (m²)
See simulation diagrams below</td></tr>
<tr><td colspan="2">Application example(s)
</td><td colspan="3">3D-reflection diagram (rectangular)
</td></tr>
<tr><td colspan="2">2D reflection diagram, different tilt angles, linear
</td><td colspan="3">2D reflection diagram, different tilt angles, logarithmic
</td></tr>
</table>

A.2. OCTAHEDRAL REFLECTOR, BALL TOP MARK

Type	Multidirectional	**Name**	Octahedral reflector, ball top mark
Origin	German Federal Waterways and Shipping Administration	**Purpose**	Joint use as top mark and radar reflector for steel or plastic buoys on German inland waterways, different shapes available

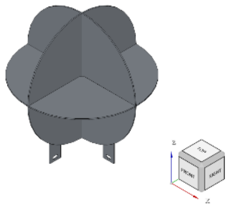
Dimensions simulated reflector (mm)

Width: 500; Height: 500

RCS (m²)

See simulation diagrams below

3D-view

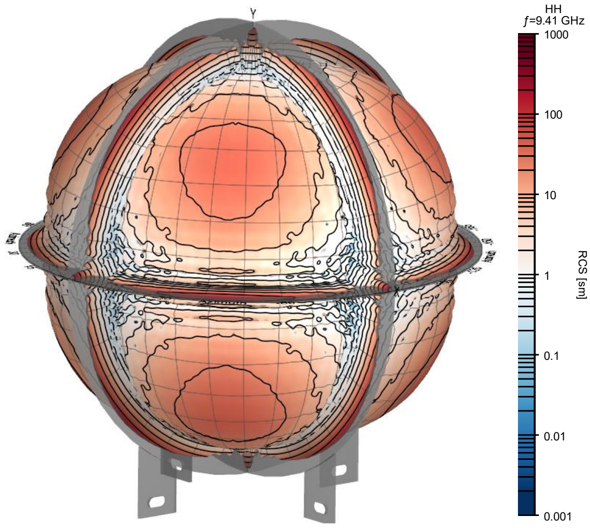


Short description / Special properties

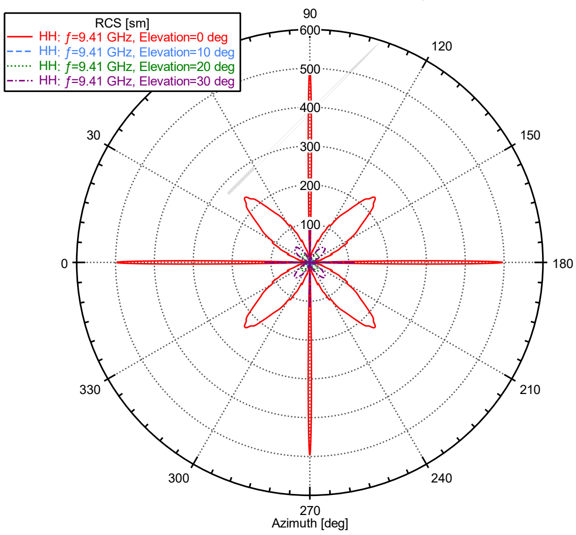
- Simple construction, easy to manufacture.
- Consistent lower level RCS makes this reflector suitable for many applications, but high RCS values at elevations of 0°; 90°; 180°; 270° azimuth are not effective due to small spatial angles.

Application example(s)

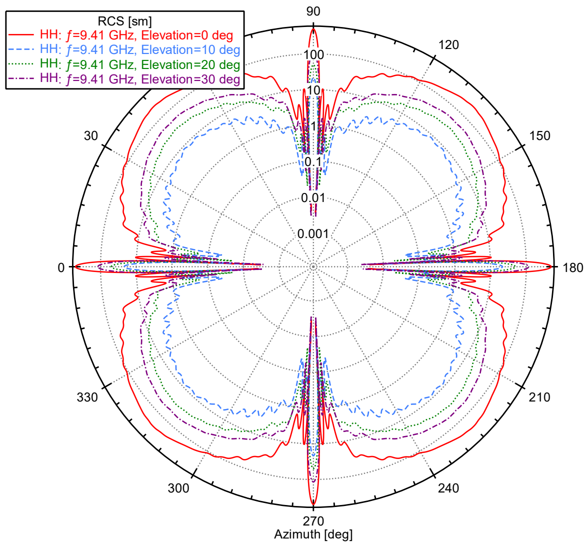
3D-reflection diagram (rectangular)



2D reflection diagram, different tilt angles, linear



2D reflection diagram, different tilt angles, logarithmic



A.3. 2 CORNER REFLECTOR

Type	Bidirectional	**Name**	2 corner reflector
Origin	German Federal Waterways and Shipping Administration	**Purpose**	Used in plastic buoys on German inland waterways, buoys have fixed orientation to the waterway

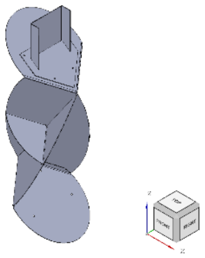
Dimensions simulated reflector (mm)

Diameter: 250; Height: 700

RCS (m²)

See simulation diagrams below

3D-view

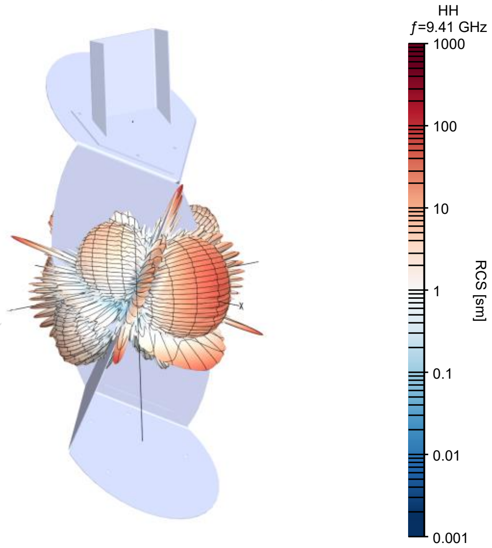


Short description / Special properties

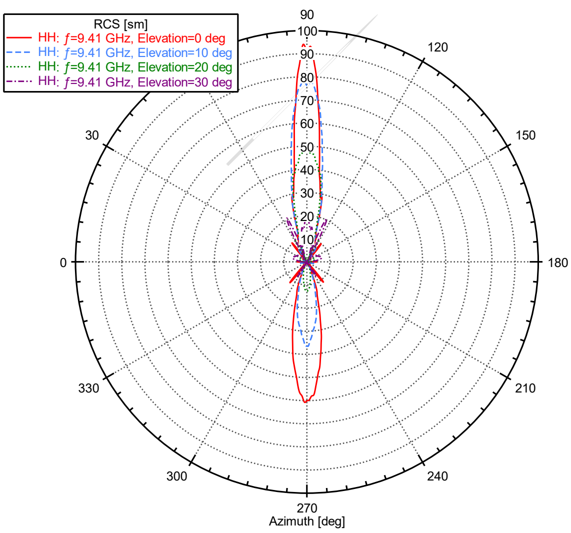
- Two main reflection directions.
- designed for plastic buoys (mounted inside, protected).

Application example(s)

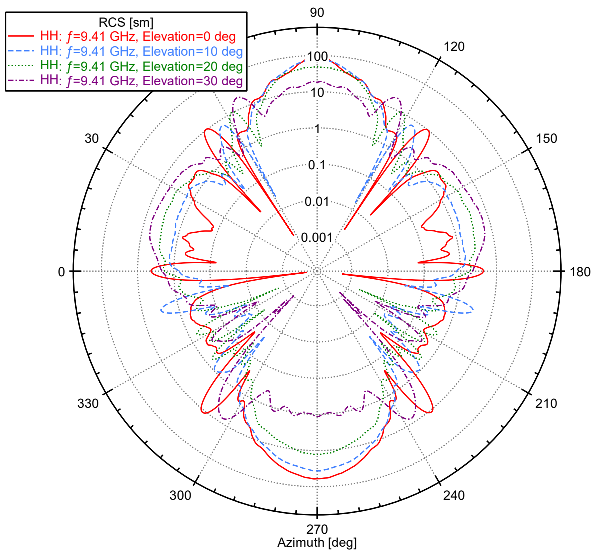
3D-reflection diagram (rectangular)



2D reflection diagram, different tilt angles, linear



2D reflection diagram, different tilt angles, logarithmic



A.4. 6 CORNER REFLECTOR SR6 / DIFFERENT DIAMETERS FOR THE RESPECTIVE REQUIRED RANGE

Type Omnidirectional	**Name** 6 corner reflector type SR6-330
Origin German Federal Waterways and Shipping Administration	**Purpose** - Used on steel or in plastic buoys on German inland and coastal waterways - Use on beacons

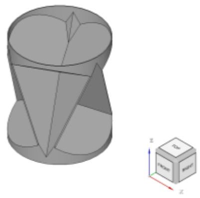
Dimensions simulated reflector (mm)

Diameter: 330; Height: 385

RCS (m²)

See simulation diagrams below

3D-view

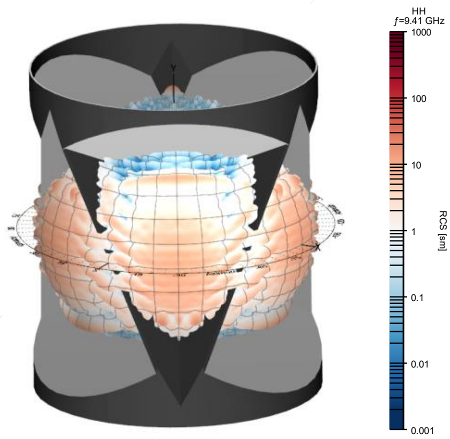


Short description / Special properties

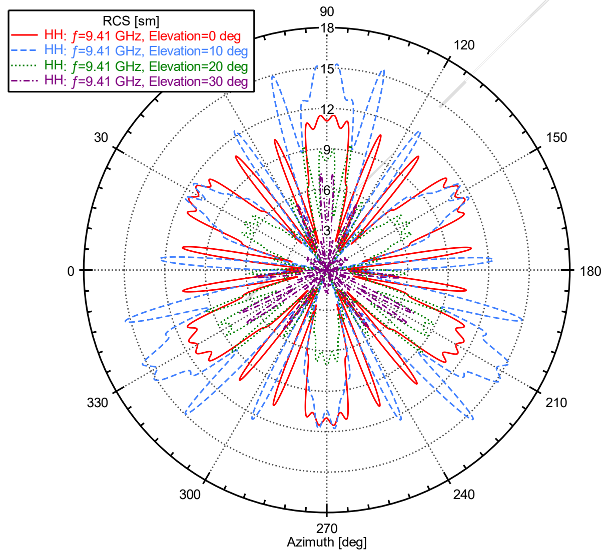
- Six tightly packed corner reflectors.
- Good uniform reflection behaviour, especially at different elevation angles.
- Available in different diameters.

Application example(s)

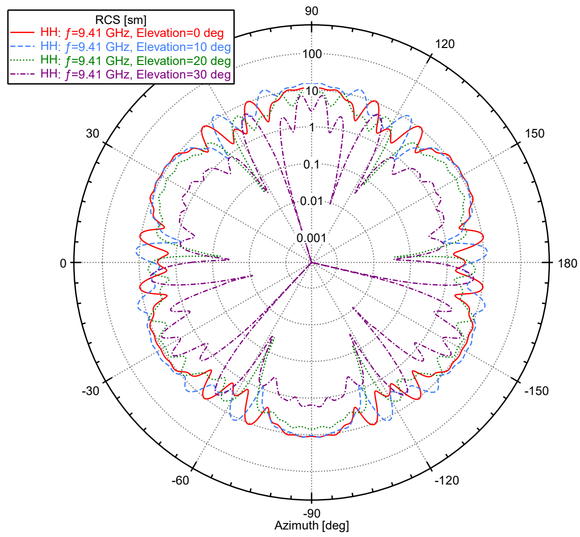
3D-reflection diagram (rectangular)



2D reflection diagram, different tilt angles, linear



2D reflection diagram, different tilt angles, logarithmic



Diameter / mm	300	330	480	900
Max. RCS (m²)	≈ 10	15	≈ 70	≈ 900

A.5. 6 CORNER REFLECTOR

Type	Omnidirectional	**Name**	6 corner reflector
Origin	Netherlands, Rijkswaterstaat	**Purpose**	Used on buoys and fixed structures

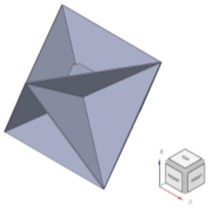
Dimensions simulated reflector (mm)

Width: 302; Height: 247

RCS (m²)

See simulation diagrams below

3D-view

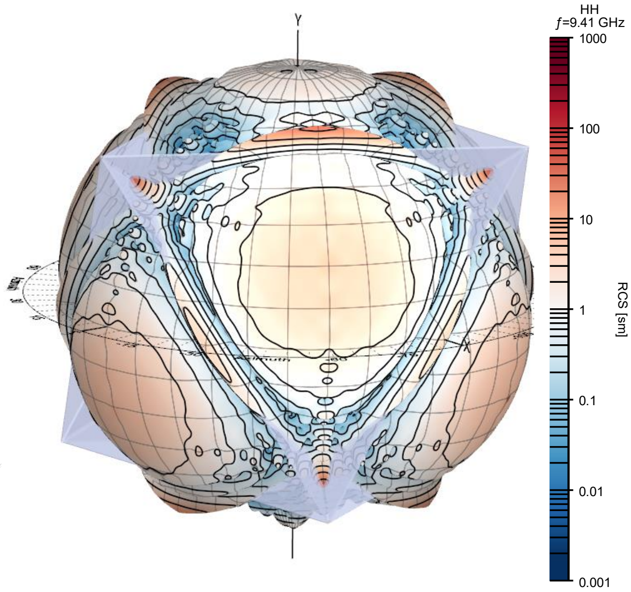


Short description / Special properties

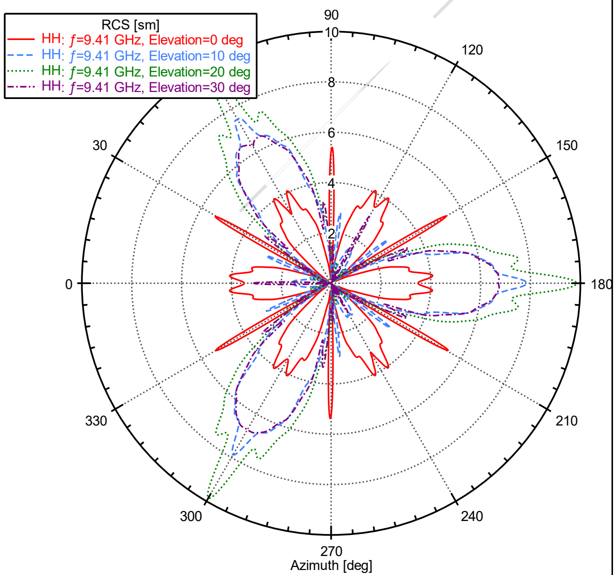
- Good experiences over many years.
- Easy to manufacture.
- Easy to install.

Application example(s)

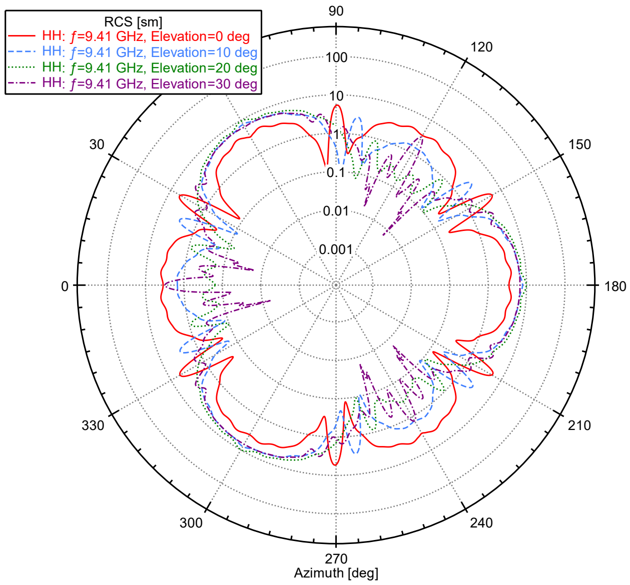
3D-reflection diagram (rectangular)



2D reflection diagram, different tilt angles, linear



2D reflection diagram, different tilt angles, logarithmic



A.6. 8 CORNER REFLECTOR

Type	Omnidirectional	**Name**	English 8 sided reflector
Origin	England, Trinity House	**Purpose**	- Use on buoys - Use on fixed structures

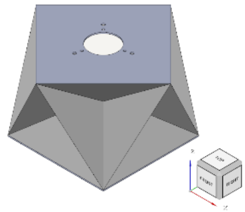
Dimensions simulated reflector (mm)

Width: 573; Height: 342

RCS (m^2)

See simulation diagrams below

3D-view

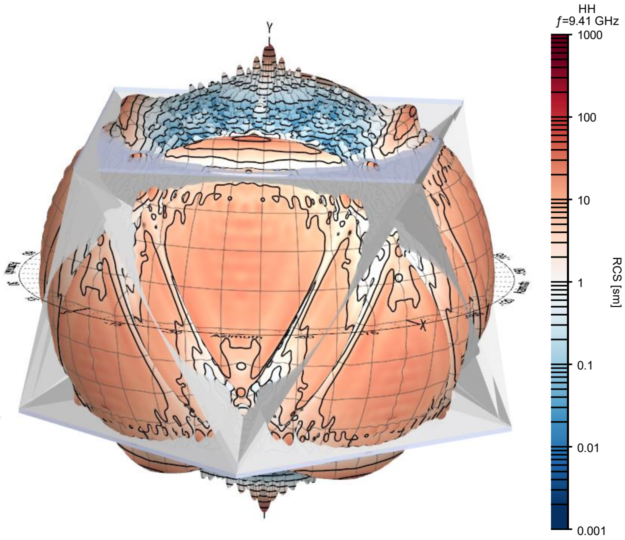


Short description / Special properties

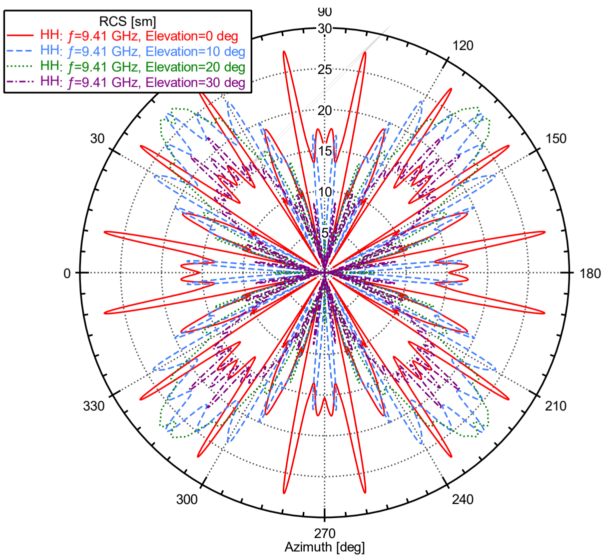
- Eight tightly packed corner reflectors.
- Good uniform reflection behaviour, especially at different elevation angles.

Application example(s)

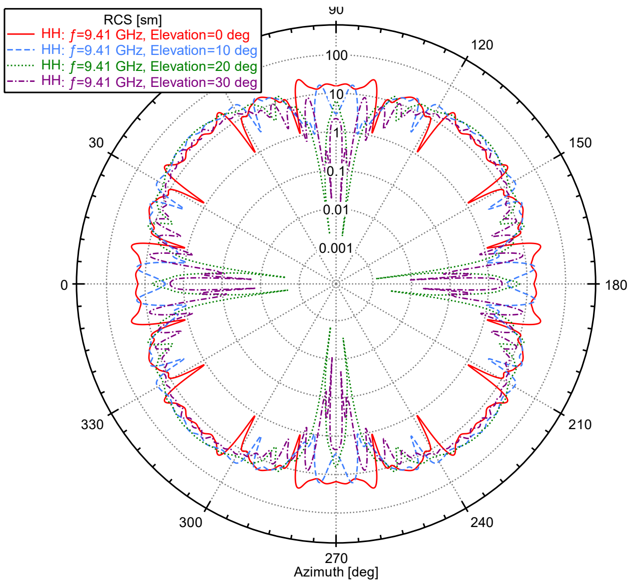
3D-reflection diagram (rectangular)



2D reflection diagram, different tilt angles, linear



2D reflection diagram, different tilt angles, logarithmic



A.7. 10 CORNER REFLECTOR

Type	Omnidirectional	**Name**	10 corner reflector
Origin	German Federal Waterways and Shipping Administration	**Purpose**	- Used on buoys. - Used on fixed structures.

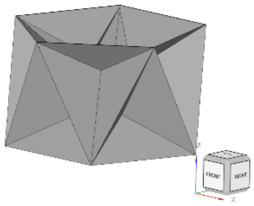
Dimensions simulated reflector (mm)

Width: 482; Height: 300

Max. RCS (m^2)

See simulation diagrams below

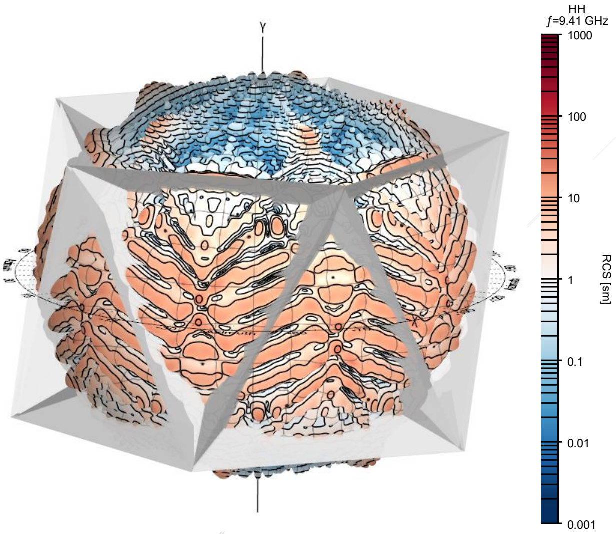
3D-view



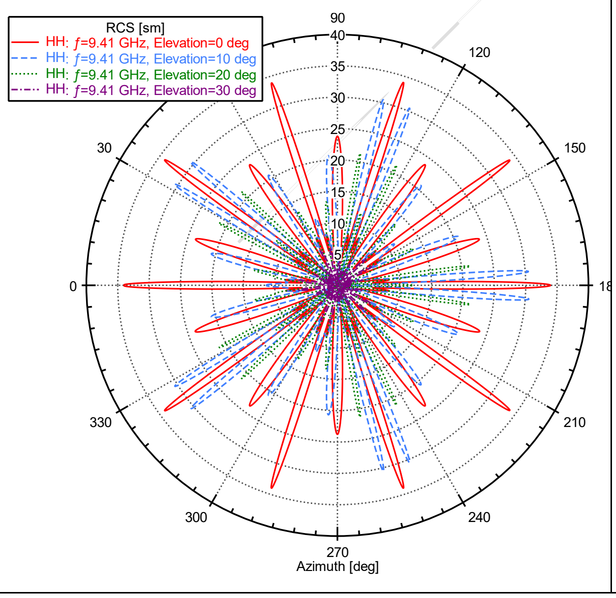
Short description / Special properties

- Similar to the 8 corner reflector.
- Good uniformity.
- Considerable side lobe interference.
- Ripple in the elevation curves.

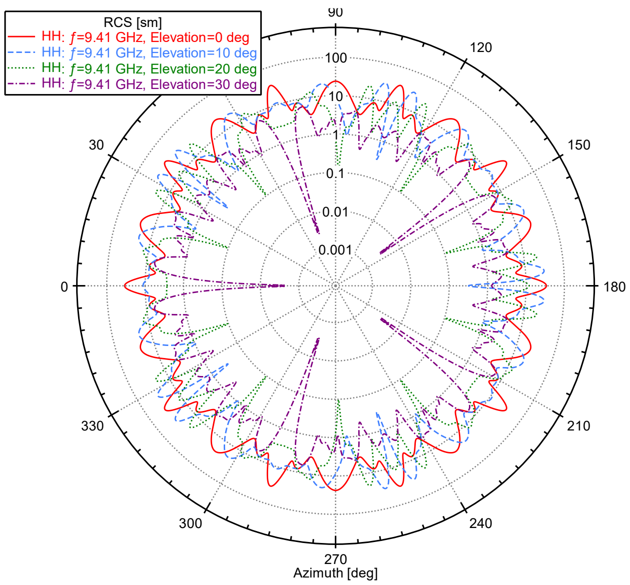
3D-reflection diagram (rectangular)



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 µs 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 µs 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= 1x10^-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= 1x10^-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> m2 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] Troposcatter= t Attenuation= t Free Space= f Surface-Based Duct= f Evaporation Duct= f Antenna Noise= t Multipath= f	**[Propagation Parameters]** Air Temperature= 15.0 degC Atmospheric Pressure= 1020 hPa Relative Humidity= 70 % Surface Refractivity= 328.3 Nunits Wind Direction= 0 deg K-factor, Refractivity Gradient= 1333.3 Nunits/km 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] Sea Clutter= t Land Clutter= f Constant Gamma= f Rain= t/f Chaff= f	**[Clutter Parameters]** Land Clutter Reflectivity= -38.0 dBm2/m2 Rainfall Rate= 4.0 mm/hr Chaff Density= 30 g/km3 Minimum Range Rain/Chaff= 3.0 NM 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] Barrage= f Responsive= f	**[Jamming Parameters]** Power= 10.000 kW 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°;
- 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 43) 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 (X-band) 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 44) 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 section 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.

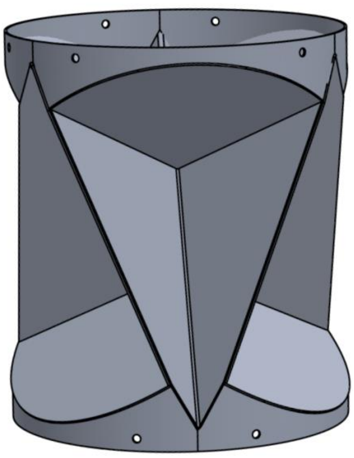


Figure 43 SR6 radar reflector

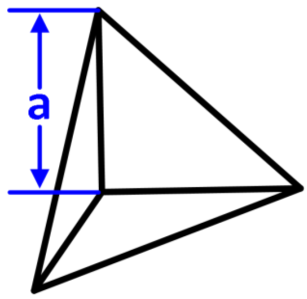


Figure 44 Corner reflector

C.1.3. Simulation

A 3D design was created, which was then transferred to the simulation software according to section 9.

The simulation results are shown in Figure 45 and Figure 46.

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

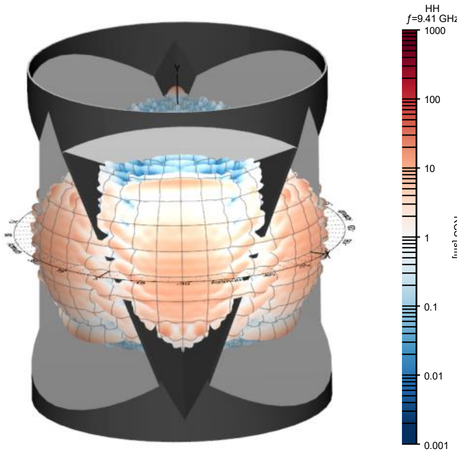


Figure 45 Spherical 3D RCS plot

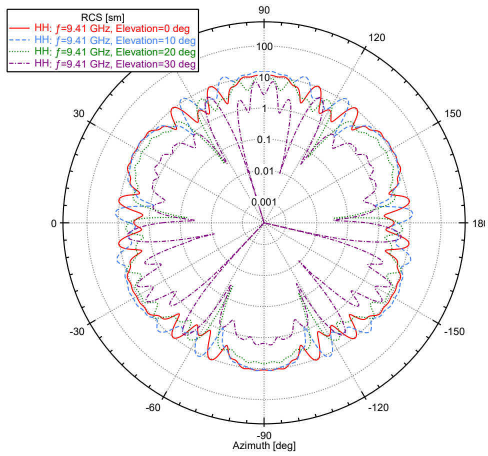


Figure 46 RCS at 0°, -10°, -20° and -30°

C.1.4. Laboratory measurements

From the 3D design, three real samples were made from aluminium (Figure 47) and measured according to section 10. Figure 48 shows the measurement results of the three samples in a diagram.

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:

Figure 47 First sample of SR6-330 radar reflector

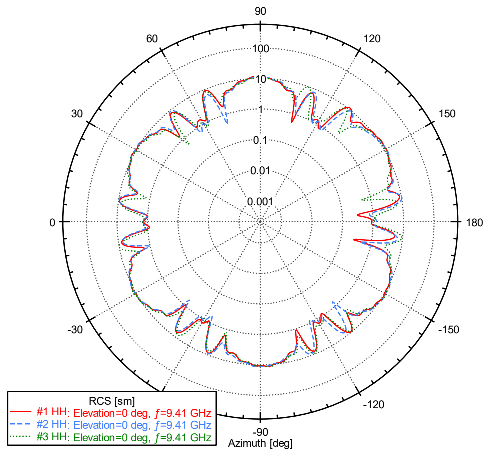


Figure 48 RCS at 0°, -10°, -20° and -30°

- Manufacturing tolerances:
  - The angle between the main reflector plates is not 90° exactly.
  - The flatness of the reflector plates is not perfect.
- Blunt edges due to the thickness of the material.
- Production-related slits between the sheets, as the welding could not be made continuous.

C.1.5. 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 E.

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

WSV.de

Acceptance protocol for radar reflectors SR 6

Delivery according to order number: ....

Contractor: ....

Date of acceptance test: ....

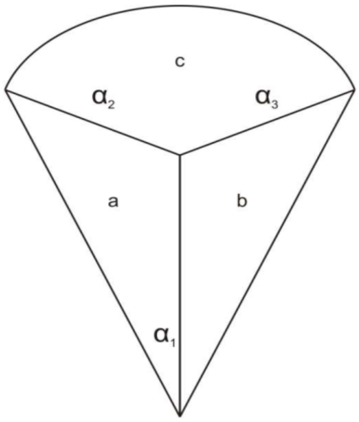
Reflector type: ....

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.



Corners counted from top clockwise

2. The tolerances (≤ ± 0,5°) of the angles α1, α2 and α3 of all 6 corners of, respectively measured in the centre, centre and outside.

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

1/2

GERMAN FEDERAL WATERWAYS AND SHIPPING ADMINISTRATION

Traffic Technologies Centre

WSV.de

Corner no. counted from the top clockwise

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

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

Comments:

2/2

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 summarized as follows:

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

The following points were not investigated:

- 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

A series of 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 reflection 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.

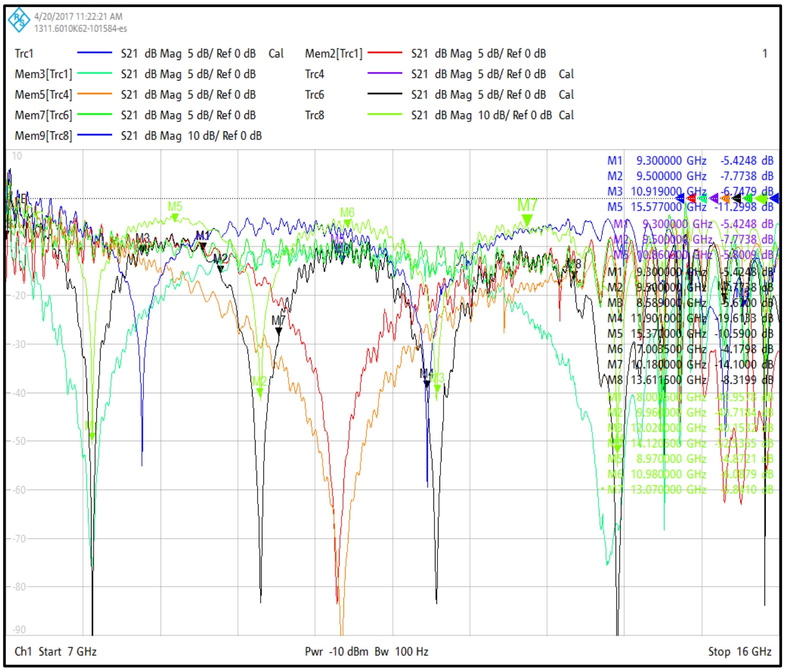


Figure 49 Measurement results, attenuation of plastic samples

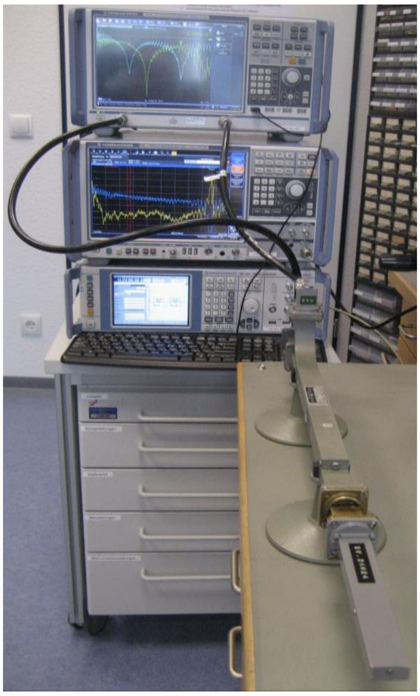


Figure 50 Test setup

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 of designing the plastic cover to be as transparent as possible (high transmission factor) an appropriate thickness of the material has to be chosen. 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.

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.

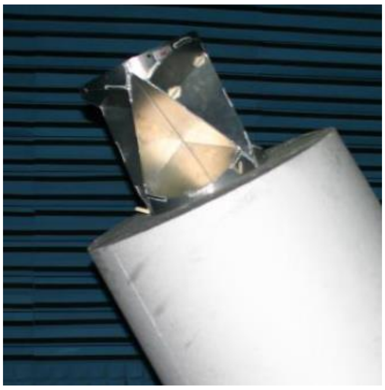


Figure 51 Radar reflector without cover

Figure 52 Radar reflector with plastic cover

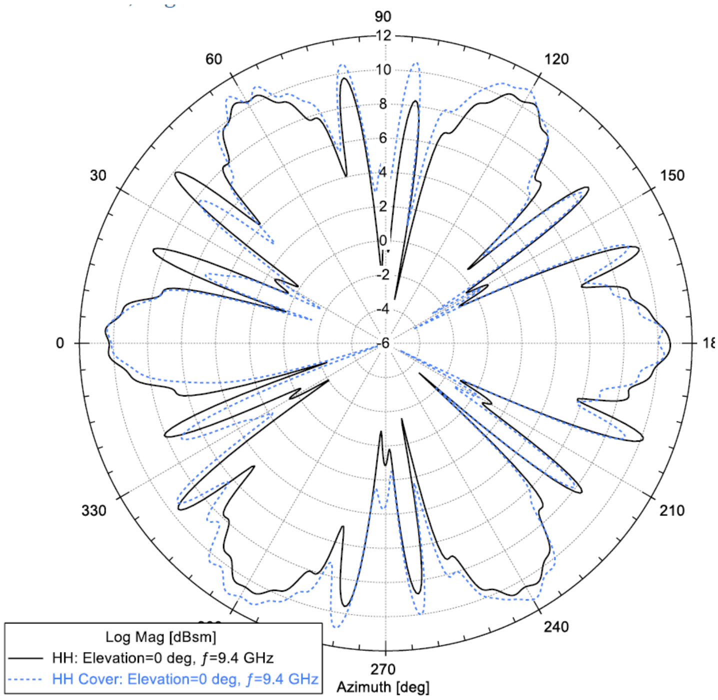


Figure 53 Result of the comparative measurements at 9.4 GHz and 0° elevation

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

The measurements were performed according to the same procedure as described in section 10.2, first without and then with a plastic cover, see Figure 51 and Figure 52.

The plastic cover was cut out of a commercial available plastic buoy to make the measurement conditions as real as possible. The plastic cover had an outer diameter of 400 mm and a wall thickness of 12 mm. The polyethylene was solid coloured.

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 arrangement. This can be seen in Figure 53, which shows measurement results without and with plastic cover together in one diagram. Note the linear scaling.

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.

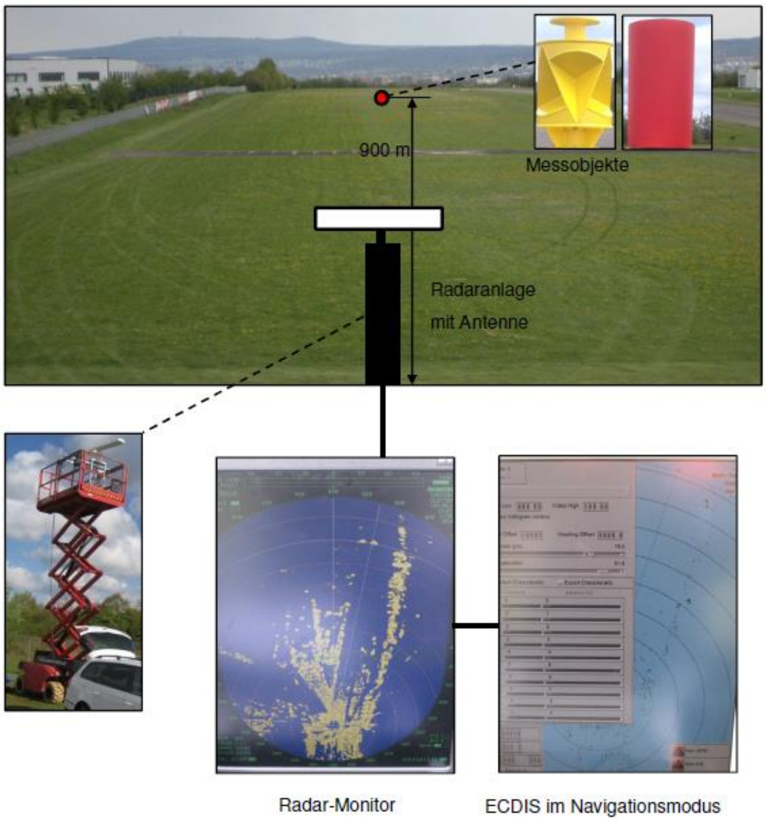


Figure 54 Setup for free field measurements on land

Figure 55 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 at a distance of 900 m. Metal parts of the radar reflector installation were covered with RF absorbers (Figure 55).

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

The test showed that there was nearly no impact of the plastic cover on the radar picture.

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 test to determine the probability of detection between a steel buoy and a plastic buoy with a radar under real conditions in a real life scenario.

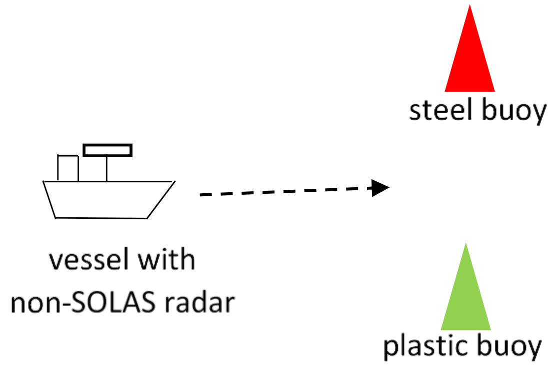


Figure 56 Measurement setup

Figure 57 SZM Bussard (small buoy tender)

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*. Figure 56 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 wave height 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.

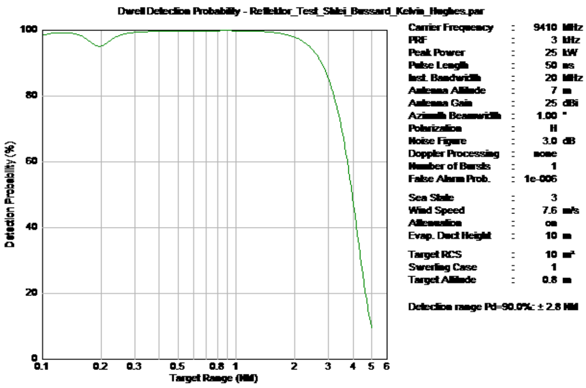


Figure 58 Simulated maximum radar range

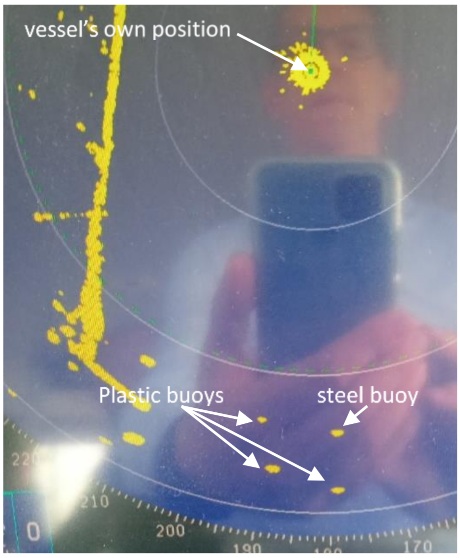


Figure 59 Radar picture, range ring distance 0.1 NM