IALA

IALA GUIDELINE

G1111-3
PRODUCING REQUIREMENTS FOR RADAR

Edition 1.0

December 2022

urn:mrn:iala:pub:g1111-3:ed1.0

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DOCUMENT REVISION

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

Date	Details	Approval
December 2022	First issue. Major revision of Guideline G1111 sections, divided into sub-guidelines G1111-1 to G1111-9. Edition 1.0 Section structure revised, “Basic”, “Standard” and “Advanced” substituted with guidance on specific areas including Inland VTS, Ports, Ports Approach and Coastal VTS. Guidance on offshore related VTS and Acceptance of VTS Radar Systems added. Measurements in metric terms adopted for Inland Waterways only. (Note - G1111 originated from annex of Recommendation V-128 Ed 3 in May 2015)	Council 76

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1. INTRODUCTION

The intent of this Guideline is:

- to be a common source of information on vessel traffic services (VTS) radar;
- to assist VTS Providers in the understanding of radar performance;
- to support the design of a radar service and its contribution to the VTS traffic image; and
- to assist VTS Providers in establishing appropriate radar functional, performance and associated acceptance requirements.

The Guideline considers radar surveillance in different operational areas (e.g., inland waterways, ports, coastal area and offshore). This includes considerations, related to environmental conditions such as weather and sea state, geographical constraints, and obstructions, which all pose challenges to the detection and coverage of radar sensors.

1.1. THE IALA G1111 GUIDELINE SERIES

This sub- Guideline is one of the *G1111* series of guideline documents. The purpose of the *G1111* series is to assist the VTS provider in preparing the definition, specification, establishment, operation, and upgrades of a VTS system. The documents address the relationship between the operational requirements and VTS system performance (technical) requirements and how these requirements affect system design and sub system requirements.

The *G1111* series of guideline documents present system design, sensors, communications, processing, and acceptance, without inferring priority. The guideline documents are numbered and titled as follows:

- G1111 Establishing Functional & Performance Requirements for VTS Systems and equipment
- G1111-1 Producing Requirements for the Core VTS System
- G1111-2 Producing Requirements for Voice Communications
- G1111-3 Producing Requirements for Radar
- G1111-4 Producing Requirements for AIS
- G1111-5 Producing Requirements for Environment Monitoring Systems
- G1111-6 Producing Requirements for Electro Optical Systems
- G1111-7 Producing Requirements for Radio Direction Finders
- G1111-8 Producing Requirements for Long Range Sensors
- G1111-9 Framework for Acceptance of VTS Systems

1.2. TARGET TYPES

For calculation purposes, the IALA simplified target types are listed in Table 1.

Typical targets of interest are modelled as point targets with conservative estimate of Radar Cross Section (RCS) and height. This is normally sufficient to estimate the detection range for considering VTS radar sensor coverage.

The term fluctuation in the table means that the signal returns will vary in amplitude, from pulse to and from antenna rotation to antenna rotation. This, the hight of the target, the radar cross section and other parameters affects the ability to detect specific targets as further discussed in ANNEX A

Table 1 IALA Target Types

IALA Target Types						
Target Type	Typically Representing	Radar Cross Section			Height (ASL)	Fluctuation
		S-Band	X-Band	Ku-Band		
1	AtoN without radar reflector. Small open boats, fiberglass, wood or rubber	<<1 m^2	1 m^2	1 m^2	1 m	Rapid, depending on sea state and target movement
2	In-shore fishing vessels, sailing boats and speedboats.	1 m^2	3 m^2	4 m^2	2 m	
3	Aids to Navigation with radar reflector.	4 m^2	10 m^2	12 m^2	3 m	
4	Small metal ships, fishing vessels and patrol vessels.	40 m^2	100 m^2	120 m^2	5 m	Moderate
5	Small coasters and large fishing trawlers.	400 m^2	1,000 m^2	1,200 m^2	8 m	
6	Large coasters, bulk carriers, and cargo ships.	4,000 m^2	10,000 m^2	12,000 m^2	12 m	Negligible
7	Container carriers and tankers.	40,000 m^2	100,000 m^2	120,000 m^2	18 m	

Notes:

1 The RCS values assume linear polarized antennas.

a A general reduction of 5 dB can be assumed in the case of circular polarized antennas.

b The reduction of RCS will typically be even larger for non-metallic targets, trihedral reflectors and most Lunenburg reflectors, often omitting detection of such targets in the case of circular polarized antennas.

2 The indicated values include allowance for the RCS-limiting effect of the cell size in the case of radars with high-resolution. See Table 2 for detailed target characteristics.

2. OPERATIONAL AREAS

This guideline considers the application of radar to different operational areas. These areas vary in the types of risks, vessels and their interactions, the required sensor ranges and the types of services. Within the total VTS area, there are generally several different operational areas.

The functional and performance requirements are likely to differ across the VTS area. It is, therefore, recommended to establish the functional and performance requirements for each operational area to make sure the navigational risks are mitigated and VTS Operators can provide services smoothly.

The VTS Provider should identify the operational requirements that may impact the functional and performance requirements of radar sensor(s) within the VTS system.

Operational requirements arise from:

- Risk assessment and needs assessment
- The identified operational areas within the area of interest
- The types and size of vessels operating within the area of interest
- The services intended to be provided by the VTS

From a surveillance perspective, operational areas may be characterized as follows:

- Inland waterways, like rivers and canals
- The port area
- The port approach area incl. anchorages
- Coastal areas and offshore, including shipping lanes, platforms, and windfarms

Identifying the appropriate radar functional and performance requirements should be a careful process, balancing cost and, sometimes opposing, performance requirements (e.g., probability of detection versus false alarm rate).

2.1. INLAND WATERWAY

Inland waterways, like rivers and canals, are confined waters that are used by a large variety of vessels, ranging from sea-going vessels (e.g., a river section as part of the port approach), river-trade, allied services vessels, ferries and even recreational vessels. Traffic separation may be as low as a few metres. This requires a high position accuracy and target separation performance.

Locks, bridges, and waterway intersections may be present that will limit target visibility, affect position accuracy or force reduced target separation.

Although the required sensor range is limited, the sensor may not have a full view of the waterway due to obstructions. Such obstructions may be permanent or temporary e.g., moored large vessels. For that reason, radar location will require proper attention (especially when location options are limited).

Maximum target detection ranges typically vary from 1 km to 10 km. Considering these ranges, radar detection performance is generally not a critical factor.

The addition of short-range gap-filler radars may be an option to cover specific areas, such as locks.

In this operational area, accuracy and separation are the critical performance parameters. At larger ranges, angular separation becomes the limiting factor.

Given the required high accuracy and separation, S-band radar will generally not be able to meet these requirements.

Note: The distances are normally measured in kilometres (km) for inland waterways. Other areas measure distances in nautical miles (NM).

2.2. PORT

The port area consists of confined waters. Traffic includes sea-going vessels, allied services vessels and, possibly, river-trade vessels (trans-shipping). Required position accuracy and target separation performance are comparable to those of inland waterways. The required radar range is usually very limited, but the radar view will be obstructed or mirrored, even if only temporarily, by cranes, moored or passing vessels, cargo, and buildings. For this reason, special attention should be given to radar siting and the possible occurrence of unwanted reflections.

For port areas, required accuracy and separation performances are like those for inland waterways.

Measures to reduce the occurrence and/or impact of false targets may be required in this operational area. This may include:

- Reduction of emitted power in certain directions (blanking or low power emitted)
- Identification of reflection areas
- Short-range gap filler radars to cover specific areas

2.3. PORT APPROACH

The port approach area is usually within the 12 NM zone but may extend beyond. There may be several types of operations within this area:

- Vessels entering and leaving port, possibly crossing coastal traffic lanes
- Pilot (dis-)embarkation
- Anchorages with supply vessel traffic and, possibly, trans-shipping operations
- Fishery
- Maritime traffic exclusion areas including renewable energy harvesting, fish farms, etcetera.
- Recreation

Coverage of this area translates into a medium required sensor range. Traffic of interest may range from small sailing boats up to >20 k TEU container vessels. In dense traffic areas, e.g., pilot boarding areas, radar separation performance is important to be able to separate individual vessels.

2.4. COASTAL AREA AND OFFSHORE

The coastal area may extend well beyond the 12 NM zone, and the number of offshore installations in the coastal areas are increasing world-wide. Ranges to be covered are, in general long, however, radar installation on offshore platforms is typically set up for shorter range than coastal.

Typical operations are traffic monitoring for

- Protection of oil/gas platforms and renewable energy harvesting, like windfarms.
- Protection of the environment
- Regular traffic monitoring and Search and Rescue (SAR)

Coverage of coastal areas usually requires long-range sensors. Traffic of interest may include fishing vessels and larger vessels, but also significantly smaller vessels or even helicopters in case of SAR operations. Monitoring of Marine Aids to Navigation (AtoN) positions including Racons may also be an operational requirement.

Weather, including varying propagation conditions and weather causing clutter, is often challenging.

Separation may be important in busy coastal area, especially with many SOLAS vessels navigating near each other.

Depending on siting and the extent of a windfarm, a short to long sensor range may be needed. Traffic of interest may include fishing vessels and larger vessels in the vicinity, as well as inter-turbine traffic.

Special attention should be given to siting to minimize multipath reflections between wind turbines and larger vessels in the coverage area.

3. PRODUCING FUNCTIONAL AND PERFORMANCE REQUIREMENTS

Producing functional and performance requirements for VTS radar is a challenging task involving iterations, including evaluation of achievable performance versus overall system cost.

The requirements should be based on a business case and a feasibility study (risk assessment, operational feasibility, legality, technical capability, available budget, and time) as described in IALA Guideline *G1150 Establishing, Planning and Implementing a VTS*. The risk assessment should address the specific risks within areas of interest and the way to handle or mitigate the risks.

The use of radar sensors is one of the options to mitigate such risks by providing dynamic maritime situational awareness. When used, the radar sensor's functional and performance requirements, see Figure 1, should be established in consultation with VTS personnel, other stakeholders, and the supplier. The planning or design of the VTS System should specify the requirement or role of the radar sensor(s) to present and track all detectable targets of interest simultaneously in normal and predefined conditions.

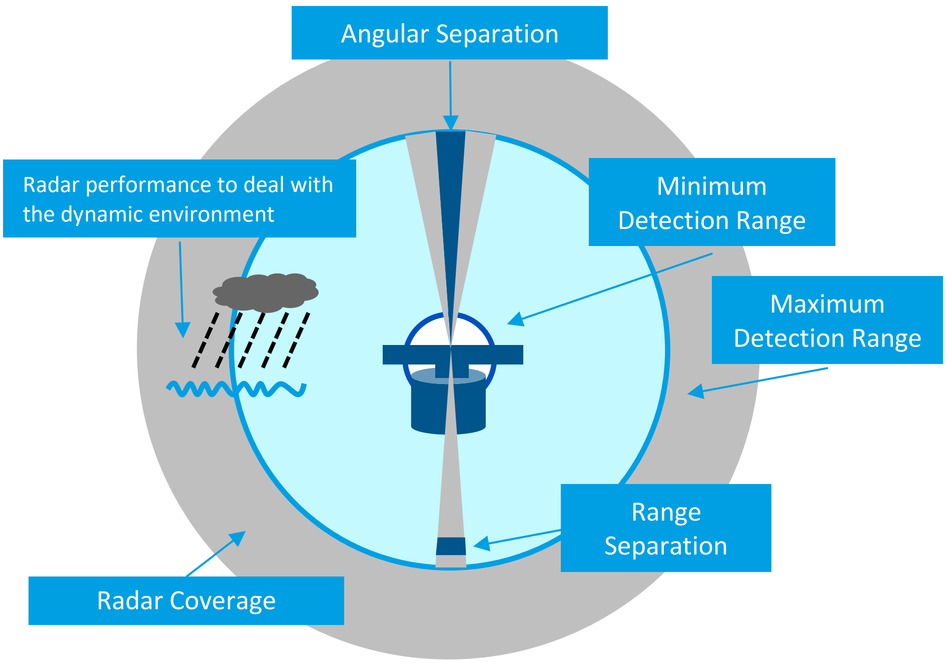

Figure 1 Elements included in producing requirements

The requirements should be established for the identified areas of interest and with characteristics including:

- Core radar performance:
  - Radar coverage, target detection and range performance
  - Target separation
  - Target positional accuracy

- Radar performance versus the dynamic environment:
  - Elimination of false echoes, sidelobes
  - Handling of dynamic characteristics of targets and surrounding
  - Handling of local environmental conditions, including environmental impact on target detection
  - Seasonal impact
  - Handling other influencing factors, e.g., obstructions
- Radar functions and other features:
  - Target positional update rate
  - Operator functions
  - Operational outputs
  - Clutter, noise, and interference reduction/handling
  - Target tracking and false alarm rate
  - Robustness, availability, and serviceability

Different suppliers are likely to have unique solutions to the same functional and performance requirements. Therefore, the VTS Provider should avoid prescribing specific technical solutions. In turn, suppliers should propose solutions that meet the operational and functional requirements, as specified by VTS Provider

3.1. CORE RADAR PERFORMANCE

3.1.1. RADAR COVERAGE

The radar coverage should comprise the area of interest, i.e., the area where a traffic image is required. This, generally, extends well beyond the defined VTS Area. Relevant aspects include minimum and maximum coverage of individual sensors and the possible use of multiple radar sensors. These may be distributed across the VTS Area to optimize system availability and enhance radar data integrity.

Careful consideration should be given to optimize radar location(s) and antenna height(s) to ensure appropriate radar coverage, accuracy, and radar target separation. Refer to ANNEX A for further guidance on determination of radar coverage.

A single radar coverage can be designed by, first, identifying the necessary coverage and then use radar performance modelling software to calculate coverage, taking antenna height, targets to be detected and environmental conditions into account.

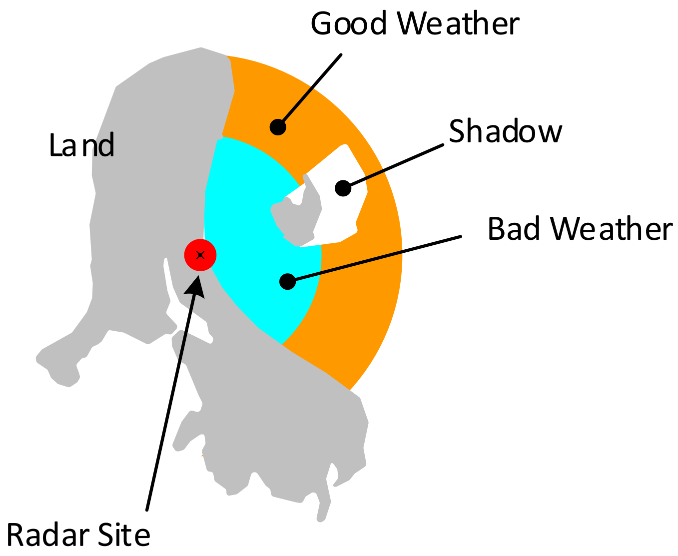

Figure 2 Illustration of radar coverage

Multiple radar sensors may be utilized to provide coverage over large areas and/or to mitigate shadow effects of other vessels. Combined processing of images from two or more radars may be beneficial for the elimination of false (ghost) echoes and may also improve accuracy and target separation.

Limited options for radar siting and the presence of temporary or permanent obstructions are often important factors and such limitations should be considered when determining requirements.

GIS tools will typically be used to provide graphical illustrations, e.g., as illustrated in Figure 2.

3.1.2. TARGET DETECTION AND RANGE PERFORMANCE

Target detection is determined by acquiring of radar plots of the specific targets within the VTS coverage area. The requirements for target detection and range performance can be identified by the target types of interest found within the VTS area, including their minimum and maximum operational range.

The minimum detection range for the radar depends on the antenna height above sea level, the length of the waveguide and the pulse (chirp) length of the transmitted signal. The lookdown angles for the antenna depend on the vertical coverage diagram, e.g., an inverse cosecant beam will typically have look down angles in excess of fan beam antennas.

The Requirements of target detection and range performance can be determined by:

- The target types mentioned in Table 1.
- Minimum and maximum range to be detected
- Antenna height
- Weather (such as fog, sea state and rain) and atmospheric propagation conditions.

3.1.3. TARGET SEPARATION

The required target separation, ref Figure 3, should be based on a business case and feasibility study which is conducted in the planning phase. The Feasibility study on Risk should derive the minimum separation requirement between surface objects or vessels for the areas covered by radar and specified for the target types of interest to the VTS.

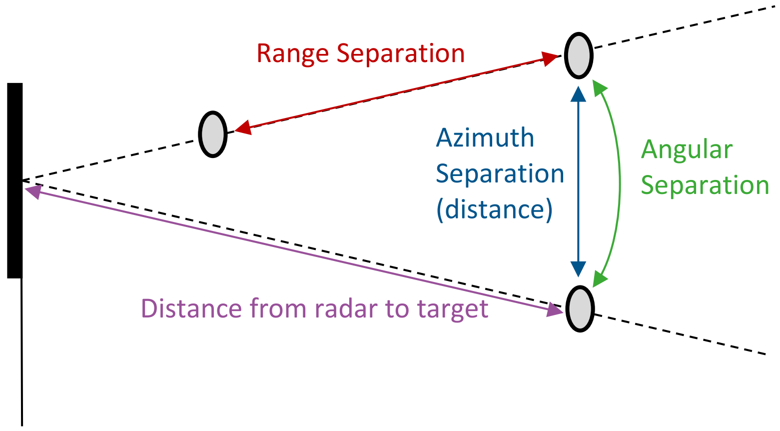

Figure 3 Target separation

Requirements can be determined by:

- The target types mentioned by Table 1.
- Minimum separation of above targets
- Range to require target separation, which should be within detection coverage

3.1.4. TARGET POSITIONAL ACCURACY

Target Positional Accuracy should be based upon the results of the business case and a feasibility study.

The operational requirements in terms of accuracy should consider:

- Limitations of ships in the VTS area that may impose restrictions on the navigation of other ships (e.g., manoeuvrability), or any other potential hindrances
- VTS space allocation
- Route advice
- Navigation assistance
- Responding to unsafe situations

Refer to Annex A for further guidance on the subject

3.2. RADAR PERFORMANCE VERSUS THE DYNAMIC ENVIRONMENT

3.2.1. FALSE ECHOES

False echoes are undesirable radar echoes resulting from various sources, including:

- Multipath caused by large structures and surface reflections
- Radar range (time) sidelobes and antenna azimuth sidelobes

Refer to Annex A for further guidance on the subject.

3.2.2. HANDLING OF DYNAMIC RANGE, TARGETS AND SURROUNDINGS

Received radar returns vary widely in signal strength from quite strong for targets close to the radar to extremely weak for targets far away from the radar. The dynamic range of the radar should be sufficient to maintain detection and processing of the surface objects as specified by the VTS Provider under the weather and propagation conditions typical for the VTS area. This should be achieved without significant side lobes, degradation of target appearance, degradation of detection or degradation of separation capability.

Refer to ANNEX A for further guidance on the subject

3.2.3. HANDLING OF ENVIRONMENTAL CONDITIONS

The environmental conditions of the VTS area should be described, including environmental conditions to be expected as normal over twelve months as well as extreme events. The environmental information can be obtained from meteorological services and be used to set requirements (e.g., temperature ranges, operational/sustainable wind, and sea conditions.

Seasonal impact and restrictions with respect to operation and access to the site(s) in all weather conditions should also be considered.

The VTS provider should define the required radar performance requirements in clear conditions as well as for precipitation conditions typical for the VTS area.

3.2.3.1. Impact from precipitation and sea clutter

Precipitation and sea clutter can significantly affect the radar coverage of the VTS system due to the reduction of radar signal propagation and backscatter from rain as well as backscatter from the sea.

Note that rainfall is rare in dry/hot regions, maybe only once or twice per year, and the VTS provider should consider if performance in the rain should be specified at all.

Also, note that designing a system to perform in tropical rain showers will typically call for lower frequency (typically S-band) radars. However, the worst rain conditions may only be present for a few hours per year, and reduction in performance on other parameters in typical weather conditions should be considered carefully to justify the additional investment.

Refer to ANNEX A for guidance on what is possible and formulas for calculations.

3.3. RADAR FUNCTIONS AND OTHER FEATURES

The radar service in a VTS should, as a minimum, support the operational functions specified by *G1111-1* (target tracking included) as well as the functions listed below.

Note that the tracking functions may be hosted by the radar sensors or other parts of the VTS system.

3.3.1. TARGET TIME-STAMPING AND UPDATE RATE

The VTS operation and, especially, the tracking function depends on accurate time stamping and timely update of the radar information. It is recommended to perform time-stamping at the radar site and to use a time source that is synchronized to the overall system time. Refer to annex 8 for further guidance.

3.3.2. OPERATOR FUNCTIONS

Radar functions should be designed and implemented to optimize performance and minimize VTS operator workload to the level practical. The VTS operator typically need to control basic functions of radar(s) such as start and stop.

It may be necessary to adapt radar settings to the changing weather conditions, etc., automatically, or manually to reduce VTS Operator workload. However, it might be necessary to implement dedicated operational modes (e.g., heavy rain and high sea modes) for adaptation to changing weather.

3.3.3. OPERATIONAL OUTPUTS

The output from a radar service should include radar image data and, when appropriate, track data. In addition, the output from the radar service may include clutter data to enable the identification of squalls, oil spills, ice detection, wave height, etc.

3.3.4. CLUTTER AND NOISE REDUCTION/MANAGEMENT

Appropriate clutter reduction or clutter management should be available to meet the performance requirements.

This will typically include:

- White noise suppression
- Interference rejection
- Sea and rain clutter processing
- Adaptation to varying propagation conditions.

The features should preferably be automatic. These functions may be hosted by the radar sensors or other parts of the VTS system; however, they are normally most efficient and saves bandwidth in the transmission of data if hosted within the radar sensor system or at the individual radar site.

The availability of extra data, such as weather data, may help as well.

3.3.5. TARGET TRACKING

Target tracking is often part of the core VTS system but may also be integrated in the radar sensor processing. Refer to IALA *G1111-1* for guidance on the subject.

3.3.6. INTERFACES

When establishing a VTS system, all internal interfacing between the radars, other VTS equipment and the overall VTS system should be well defined and harmonized.

When updating or expanding an existing VTS system or VTS equipment, it is recommended to include requirements for radar sensor interfaces, including protocols, standards, and bandwidth. This ensures that radar sensors and the updated or expanded VTS system or VTS equipment will interact as intended.

Cybersecurity risks and considerations should be properly reflected in the requirements.

3.3.7. ROBUSTNESS, AVAILABILITY, AND SERVICEABILITY

The radar systems should be designed taking robustness, availability, and serviceability into account.

Special safety precautions for radar should include but not be limited to those applicable to rotating machinery, radiation hazards and electrical shock.

Special precautions should also consider lightning protection, wind load on antennas and access to the systems, including antennas for installation and maintenance. Turbulence, asymmetrical wind and vertical wind components should be considered with reference to the descriptions in ANNEX A

3.3.7.1. Antenna robustness against wind load

The functional requirement of radars should consider potential problems resulting from high winds. In some cases, it may be appropriate to separately specify both the survival wind limits and a lower operational wind limit within which the system should not be degraded due to the normal weather conditions specified for that location. High winds can affect the antenna's physical motor and gearbox design and the instantaneous rotation rate at varying angles to the predominant wind direction. The build-up of ice in some climates should also be a consideration.

High winds can affect plot accuracy, and the overall system azimuth accuracy should consider torsional errors arising from high winds. As a rule of thumb, the maximum torsion of the radar tower should not exceed 25% of the antenna's horizontal beamwidth at the maximum operational wind.

Note that vertical wind components or asymmetrical wind loads may cause stresses to the rotating antennas. This may restrict how antennas are geographically and physically installed, how the tower constructions are made or call for other mitigation methods. Turbulent wind gradients nearby large structures and mountain lee waves may also stress equipment beyond its design limits

In extreme conditions, it may be appropriate to house the rotating radar antenna within a static radome. However, this can increase overall costs, RF losses and maintenance costs.

3.3.7.2. Choice of up-mast versus down-mast transceivers

Careful consideration should be given whether to locate the transceiver up-mast or down-mast. A down-mast transceiver may benefit from an environmentally controlled location that improves equipment reliability at the expense of increased waveguide losses.

Conversely, an up-mast transceiver installation may be more difficult to access for maintenance and service.

Another issue may be the required network bandwidth to transfer the radar video (on copper, fibre or microwave link etc.) which can also influence whether to use an up-mast or down-mast transceiver. Incorporation of transceiver redundancy can also influence the choice of transceiver location.

3.3.7.3. Waveguide considerations

Waveguides should be kept as short as possible. Their length and associated losses need to be included when determining system performance.

Waveguides should always be equipped with dehumidifiers or simple desiccators.

3.3.7.4. Position of the lightning rod

lightning rods are preferably positioned in a blanked sector or a direction of low practical importance.

4. DEFINTIONS

The definitions used in this Guideline can be found in the International Dictionary of Marine Aids to Navigation (IALA Dictionary) and were checked as correct at the time of going to print.

Azimuth (Antenna) Side Lobes - antenna responses (in azimuth) outside the intended radiation beam. Weighting of the illumination function allows a significant reduction of these lobes, but some response outside the intended direction is unavoidable, normally presenting an irregular pattern with “peaks” and “nulls”. The side lobes may produce responses from targets in unwanted directions, allowing disturbing signals (intentional or not) to enter the receiver, and in addition makes the radar detectable by receivers, which are not illuminated by the main beam.

Availability - is the probability that a system will perform its specified function without failure when required.

Blind Spots – typically resulting from either blind range (the range corresponding to an echo delay of one or more pulse repetition intervals: the echo then arrives at the receiver while the radar is transmitting a new pulse and the receiver is blanked) or Blind speed (target speeds which produce Doppler shift which are integer multiples of the radar pulse repetition frequency (PRF), which are therefore aliased to zero Doppler and cancelled by the clutter rejection filtering). Blind spots can also arise behind significant obstructions in the field of view (buildings, land masses, oil tankers).

*BITE***:** Built in Test Equipment

Chirp - frequency modulation of the carrier frequency applied within the radar pulse to increase its bandwidth and therefore the range resolution (see also pulse compression).

Coherence - capability of a system to keep a stable phase reference during the target illumination time in order to properly exploit the received phase information for moving target indication (MTI), pulse Doppler processing or other purposes.

Doppler Shift - shift in frequency of a wave due to the relative motion between the transmitter and the receiver. Frequency shift is relative target velocity/wavelength. Radar echoes are shifted twice this value because this shift must be accounted for in both the forward and the return path.

Doppler Side Lobes - when using Doppler processing (or MTI) the integrated ideal pulse always presents a response outside the integration peak (across all Doppler filters) known as Doppler side lobes. Their main effect is to limit the capability to discriminate weak returns in the proximity of strong returns (with side lobes of the same order of magnitude as the primary response of the weak return).

FMCW - Frequency Modulation - Continuous Wave - a type of radar where a continuous wave instead of pulse is transmitted. The range information is derived by frequency modulating the carrier with a saw tooth waveform and comparing the echo FM modulation envelope with the reference.

Gap Filler **-** a radar used to supplement the coverage of a principal radar in areas where coverage is inadequate.

Ghost Targets (Ghost Echoes) – undesirable radar echoes resulting from a number of sources. For example, multipath related wave reflections caused by large structures or surface reflections, time sidelobes, antenna azimuth sidelobes, and Doppler sidelobes.

Interference Rejection - this function reduce or eliminate interference received from transmitters utilising the same or nearby frequencies. One common technique is to compare adjacent range cells in the present "live" video signal with the video signal from the previous sweep. The output video signal to the display device is inhibited should the comparison indicate the presence of interference.

Normal Weather and Propagation Conditions - are normal conditions as defined by the individual VTS Provider. The rest of the time is considered having adverse weather and propagation conditions.

Plot Extraction – the process of determining the likely target related radar returns from the radar video signal. This typically consists of comparing the video level with a threshold which can be (dynamically) adapted to local background noise and clutter conditions.

Polarization – of a radar signal is determined by the orientation of the electrical field. In the case of *circular polarization***,** the field rotates left or right.

Pulse – typically a pulse (which is modulated in the case of pulse compression radar) of RF energy transmitted from the radar.

Pulse Compression – a technique used to achieve a wide pulse bandwidth (and, therefore, enhanced range resolution) using long pulse (for high pulse energy with limited peak power) by introducing an intra-pulse modulation (e.g., chirp frequency modulation or Barker discrete phase modulation) and performing a correlation on the received echo.

Radar Cross Section (RCS) – an assessment of the cross-sectional area presented by a reflector (typically a target or unwanted "clutter") to the transmitted radar energy. The RCS can vary with frequency and target attitude.

Radar Information – a generic term potentially referring to the radar picture/video, target data, clutter data, topographical data, aids to navigation SARTs etc.

Radar P_D – is the probability of target detection at the output of a radar, after plot extraction, but prior to tracking, and presentation. Note, in some systems the boundary of the radar and its achieved P_D complicate this definition – clarification may be required to avoid misunderstanding arising from, for example, data compression or video processing.

Radar P_{FA} – is the probability of false alarm at the output of a radar, subsequent to plot extraction, but prior to tracking, and presentation. In this context, the P_{FA} is defined as relating to the number of false target declarations per radar cell (range cell x azimuth cells), arising from a noise plus clutter environment (only). Note, in some systems the boundary of the radar and its achieved P_{FA} complicate this definition – clarification may be required to avoid misunderstanding arising from, for example, noise related threshold crossings vs. unwanted radar energy reflections (unwanted targets, ghost targets etc.).

Radar Plot – is the generic term to describe the report resulting from a radar sensor observation. Each report contains positional information, possibly *supplemented by other data.*

Useful definitions used in this document:

Radar Target – an object about which information is sought with radar equipment.

Radar Video – a time-varying signal, proportional to the sum of the radio frequency (RF) signals being received and the RF noise inherent in the receiver itself. Traditionally, radar video is an analogue signal with associated azimuth reference information. Recently, radar systems have become available which provide equivalent data in digital format.

Radar Sensor – the transmitting, receiving and signal handling apparatus, delivering radar information to the tracking and presentation features of VTS.

Radar Service – a service that delivers all radar-derived data, such as radar image, radar plots and radar tracks.

Radar Track – an estimate of a target's position and speed vector, resulting from the correlation, by a special algorithm (tracking), of present and past radar-reported positions (radar plots). The report normally contains an identification (e.g., a track number), a timestamp, the estimated position, and a speed vector. Additional information may include e.g., estimated errors, the last associated radar plot and perceived track quality

Range Ambiguous Returns – the measured range of a target typically assumes that the target true range is less than the first range ambiguity (the Range corresponding to an echo delay of one pulse repetition interval) whereas large targets beyond this range can be detected but typically with (incorrect) ambiguous range measurement. Techniques exist for the resolution of range ambiguity if required. See also blind spots above.

Range Side Lobes – see Time Side Lobes (below).

Receiver Dynamic Range – essentially the range of signal levels over which a receiver can operate. The low end of the range is governed by its sensitivity whilst, at the high end, it is governed by its overload or strong signal handling performance.

Reliability – the probability that a system, when it is available performs a specified function without failure under given conditions for a given period of time.

Sea Characteristics – often described by sea state but additional parameters can also be of interest. Sea characteristics include wave/swell height, direction and speed of waves/swell, distance between waves/swell, salinity etc.

Standard Atmospheric Condition – the International Commission of Air Navigation uses a definition for a standard atmosphere, defining temperature and pressure relative to the height. In the troposphere (0 metres to 11,000 metres), the temperature is defined to be 15 °C at the surface and changing -6.5 °C/km.

Squint – the potential angular difference between antenna boresight and the antenna beam pointing direction. This angular difference may change with transmission frequency. The effect can be fully compensated.

Swerling Cases – a series of mathematical models representing RCS fluctuations to characterize the statistical behaviour of reflected radar signals from a target (see also target fluctuations).

Target Fluctuations (also known as Glint or Swerling characteristic) - Fluctuation of a target radar cross section (RCS) (and, therefore, of the received echo amplitude) due to changes in the target attitude and illuminating frequency. For complex targets (consisting of a number of reflecting surfaces), RCS is normally strongly dependent on the angle of observation.

Target Separation (also known as Target resolution) – the ability to successfully identify two discrete detectable, similarly sized targets when closely spaced in either range or azimuth.

Track Swapping – the (usually unwanted) transfer of a track identity (track label) to another track. This can break the intended association between a track and a physical object.

Time Side Lobes – when using pulse compression, the correlated pulse always presents responses outside the correlation peak (before and after it) known as time (or range) side lobes. Their main effect is to limit the capability to discriminate weak returns in proximity of strong returns (with side lobes of the same order of magnitude as the primary response of the weak return).

For general terms used throughout this section refer to IEEE Std *686-2017 [1]IEEE Standard Radar Definitions.*

5. ABBREVIATIONS

Please refer to IALA *G1111 Establishing Functional and Performance Requirements for VTS Systems* for an extensive list of abbreviations and acronyms covering the entire *G1111* series.

6. REFERENCES

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[4] Ingo Harre – RCS in Radar Range Calculations for Maritime Targets.

[5] International Maritime Organization (IMO) Performance Standards for radar reflectors.

[6] ITU-R SM.1541, Unwanted emissions in the out-of-band domain.

[7] ITU-R SM.329-9, Spurious emissions.

[8] ISO 8729 Ships and marine technology – Marine radar reflectors.

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[13] Influence of evaporation ducts on radar sea return, J. P. Reilly and G. D. Dockery, IEE Proceedings Vol. 137, Part F, No. 2, p.80 – 88, April 1990.

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ANNEX A VTS RADAR CONSIDERATIONS

This annex is descriptive and intended to supplement previous sections in this document and introduce the reader to common radar topics and knowledge specific to VTS radar as well as guidance on what is possible to achieve from radar configurations typical for VTS.

Calculation methods for the determination of performance are described and examples of that possible with various technologies and simplified configurations are provided.

A.1. RADAR TECHNOLOGIES

VTS radars could be based on the following technologies:

- Pulse radar (usually Magnetron based)
- Pulse compression radar (usually Solid State)
- Frequency Modulated Continuous Wave, FMCW (usually Solid State)

A.1.1. PULSE RADAR

A Magnetron based pulse radar typically transmits high peak power RF pulses (10 to 50 kilowatt (kW)) of very short duration (50 to 1000 nanoseconds). The transmission is made with a pulse repetition frequency (PRF) of typically 1000 to 4000 pulses per second. Upon reception, the returned signal is amplified, demodulated, and processed.

Main characteristics include:

- It is a well-known and proven technology
- It has fixed pulse lengths
- Increased pulse duration translates into longer-range detection, but reduced range separation and reduced ability to penetrate precipitation due to increased backscatter
- Normally with a fixed transmission frequency (given by the magnetron characteristics)
- The need to reduce out-of-band transmissions

Note: ITU requirements for land-based radar are more stringent than for shipborne radar in respect to out of band emissions.

A.1.2. PULSE COMPRESSION RADAR

A pulse compression radar transmits low peak power modulated chirps (typically up to 200-300 Watt (W), in some cases higher) with a typical pulse duration of up to 100 microseconds (μs). The transmission is made with a chirp repetition frequency of typically 1000 to 20000 chirps per second. The longer chirps are converted into short pulses upon reception by the process of pulse compression; therefore, improved range separation can be achieved at all ranges within a single radar mode.

The average transmitted energy of a pulse compression radar is comparable to that emitted by a magnetron radar.

Main characteristics include:

- It is based on well-known and proven principles
- No need for magnetron replacement, reducing the need for periodic maintenance
- Increased ability to penetrate adverse weather conditions facilitating smaller target detection
- Transmission frequencies can be programmed
- Cleaner spectrum than magnetron radars, with reduced emissions outside the allocated frequency band(s)

Additional challenges compared to magnetron radars include:

- The need for sophisticated interference rejection due to the longer chirps transmitted
- The need for simultaneous short- and long-range detection increases complexity
- High-power solid-state amplifiers operate with large currents therefore requiring careful design to obtain high reliability.
- By nature, the pulse compression radar creates so-called time (or range) side lobes. Avoiding such side lobes, requires sophisticated techniques, alternatively side lobes suppression may imply a reduced detection of small targets in the vicinity of larger targets.
- Additional focus on dynamic range to avoid saturation which will create very distinct sidelobes in range and reduce sensitivity in front of and behind large objects.
- Inability or less sensitivity in the detection to trigger RACONS and SART transponders

Note: There may be legal restrictions (dual use, catch-all etc.) limiting the pulse compression ratio and other parameters when exporting radars to certain countries. This may limit the availability of this technology to some VTS authorities.

A.1.3. FREQUENCY MODULATED CONTINUOUS WAVE RADAR

Frequency modulated continuous wave radar transmits low peak power continuous wave forms (typically up to 50 W). The waveforms are repeated with a typical rate of 500 to 2000 per second. The waveforms are converted into pulses upon reception, therefore high range resolution can be maintained at all ranges.

The energy in a frequency modulated continuous wave radar is comparable to the energy emitted in a pulse from a magnetron radar.

Main characteristics include:

- Well-known and proven principles
- No need for magnetron replacement, reducing the need for periodic maintenance
- The ability to detect at very short range
- Transmission frequencies can be programmed
- Cleaner spectrum than magnetron radars, with reduced emissions outside the allocated frequency band(s)

Additional challenges compared to other types of radar include:

- Dynamic limitations restrict the ability to handle small and large targets simultaneously and also affects long range detection
- Target revisit rate may be low compared to other technologies
- The need for sophisticated interference rejection, even more than for pulse compression radars
- By nature, FMCW creates so-called time side lobes and suppressing the side lobes may reduce detection of small targets in the vicinity of larger targets
- More complicated antenna system, 2 antennas or complicated antenna feed
- The inability to detect RACONS and SART transponders

A.2. FREQUENCY BANDS

The choice between available frequency bands will always be a compromise depending on the operational area, weather and balancing several parameters. Typical capabilities are provided later in this Annex. Frequency bands allocated for radar and suitable for VTS lie in the following range:

- *S-band, 2.0 – 4.0 GHz*: Frequency band occasionally used for VTS Coastal radar to minimize the effect of rain on longer ranges but is for modern radars a less dominating argument as X-band radars improve in capabilities. Frequency allocation (predefined by ITU) is challenged by other users, e.g., Cellular phone operators aiming at expanding band allocation. By nature, S-band radars provide less separation in azimuth (limited antenna size).
- *C-band, 4.0 – 8.0 GHz*: Not used for VTS
- *X-band, 8.0 – 12.0 GHz:* The commonly used frequency band across VTS operational areas – Frequency allocation (sub-bands for radiolocation and radionavigation services) predefined by ITU. X-band is often a good compromise for balance between separation, weather penetration and cost across application areas.
- *Ku-band, 12.0 – 18.0 GHz*: Frequency band occasionally used to improve separation and minimize antenna size. Ku-band radar is generally more sensitive to weather (rain) than S- and X-band radar.

  Note: There is no Ku-band Frequency allocation for VTS predefined by ITU, meaning that frequencies shall be allocated by individual countries.

A.3. ANTENNAS

The selection of antenna parameters (height, gain, side lobes, rotation rate, polarization etc.) for a given installation is key to the resulting radar performance. VTS authorities are, however, advised to avoid specifying detailed antenna characteristics and should preferably specify operational area and performance requirement.

The identified requirements will allow the radar vendor some flexibility to achieve the best solution within the given constraints and considering cost and location options.

A.3.1. ANTENNA PRINCIPLES

Typically, the VTS radar design includes an antenna, which provides a narrow beam in azimuth and a wide beam in elevation. Thus, the VTS antenna is not designed to measure the target elevation (from which target height might be determined) and to separate targets based on elevation angle difference.

The installed antenna height is determined based on avoidance of physical obstructions, and the compromise between the need for close range coverage vs. long-range performance.

The radar designer, in his selection of antenna characteristics, needs to optimize the compromise between antenna size (and cost), track update rate, integration time on target (related to rotation rate and azimuth beamwidth and contributing to target detection range) and azimuth target separation and accuracy. In addition, the choice of transmission frequency influences the size vs. beamwidth compromise.

Flat panel electronic scanning antennas (phased array) may provide advantages in terms of no rotating parts, however, adding to technical complexity.

A.3.2. ANTENNA POLARIZATION

Radio waves are polarized, and objects (target and clutter) will often reflect differently depending on the polarization used. This can be utilized by radar system designers, where rules of thumb are that:

- Target returns from linear polarization, (horizontal or vertical) in general will be stronger than returns from circular polarization.

- Non-metallic and natural objects, such as human beings will return linear polarized radio waves much better than circular polarized radio waves.
- Most radar reflectors will be poor reflectors for circular polarized radio waves.
- Distant ships with vertical masts tend to give the strongest return for vertical polarization, whereas the opposite tends to be the case for modern ship designs without tall masts.
- In addition, target detection in clutter can be affected by the polarization. For instance:
  - linear polarization (horizontal or vertical) will result in higher rain clutter returns than circular polarization; and
  - vertical or circular polarization will result in higher sea clutter returns than horizontal polarization, especially for lower sea states.

Complex designs are possible in which operators may select the polarization. However, this adds to equipment costs and adds to the VTS operator workload.

In general, the best cost/performance combined with ease of operation is achieved by horizontal polarization.

Note: In case of a radar station also being used for oil spill detection, the preferred polarization is vertical.

A.4. TARGET CHARACTERISTICS

VTS radar targets can be defined by their height above sea level, speed and manoeuvrability, polarization characteristics, radar cross section (RCS) and the RCS fluctuations.

A.4.1. RADAR CROSS-SECTION

The amount of radar energy reflected by a target is proportional to its effective area, called the radar cross section (RCS). The RCS is defined as the ratio between the power (in W) scattered by the target back towards the radar receiver and the power density (in W/m^2) hitting the target. Thus, the RCS has the dimension of an area, being measured in m^2. In practical terms, the RCS can be interpreted as the cross-sectional area of a perfectly reflecting metal sphere that would give rise to the same reflected energy as the target in question.

Being an effective area, the RCS of a target is not necessarily related to the physical cross-sectional area of the target, but rather depends strongly on the nature and shape of the surfaces exposed to the radar beam. Consequently, targets of similar physical sizes may exhibit vastly different RCS, and additionally, their RCS may vary drastically with aspect angle (see [2]) as the exposed surfaces change with orientation. Finally, the apparent RCS of a target is subject to fluctuate over time, for instance, due to minor changes in orientation between exposures to the radar beam.

To obtain quantitative and reproducible results during performance testing, it is necessary to use physically small simple targets and calibrate their RCS against that of a well-known reference target. During these measurements, the dependence of the RCS on the aspect angle can additionally be mapped out. A method to perform such a measurement is described in ANNEX C

A.4.2. TARGET MODELS VERSUS DETAILED CHARACTERISTICS

The point target characteristics, see Table 1, may be sufficient for the range calculation of specific targets of interest in VTS.

However, the design of a radar system should consider the overall characteristics of all objects within the coverage range of the individual radar. Table 2 provides an overview of such characterizes for targets, typically of interest to VTS radar.

Table 2 Detailed target characteristics

Target	Typical characteristics at X-band		
	RCS	Height	Fluctuations etc.
Aids to Navigation without radar reflector.	Up to 1 m^2	1 to 4 m ASL	Rapidly fluctuating, highly dependent on sea characteristics. Polarization characteristics will often vary depending on wind.
Aids to Navigation with radar reflector.	10 – 100 m^2		Rapidly fluctuating, wind and currents may tilt to blind angles and lobing may cause reflectors to be in blind spots. Most radar reflectors will be poor radar targets in case of circular polarization
Small open boat, fibreglass, wood or rubber with outboard motor and at least 2 persons on board, small speedboat, small fishing vessels or small sailing boats.	0.5 – 5 m^2	0.5 to 1 m ASL	Rapidly fluctuating may be hidden behind waves up to 50% of the time. Slow moving targets tend to lie lower in the water than fast moving ones and therefore RCS visible to the radar tends to increase with speed. Humans and non-metallic targets will give poor radar return in case of circular polarization
Inshore fishing vessels, sailing boats and speedboats, equipped with radar reflector of good quality.	3 – 10 m^2	1 to 2 m ASL	Rapidly fluctuating.
Small metal ships, fishing vessels, patrol vessels and other similar vessels.	10 – 100 m^2	2 to 4 m ASL	Moderately fluctuating.
Coasters and other similar vessels.	100 – 1000 m^2	6 to 10 m ASL	RCS is highly dependent on aspect angle of the individual vessel. Rate of fluctuations is typically moderate.
Large coasters, Bulk carriers, cargo ships and other similar vessels.	1000 – 10,000 m^2	10 to 25 m ASL	
Container carriers, tankers and other similar vessels.	10,000 – 2,000,000 m^2	15 to 40 m ASL	
Buildings, cranes. Stacks of containers and other large structures.	Up to 1,000,000 m^2	Depends on site	Insignificant.
Floating items, oil drums and other similar items.	Up to 1 m^2	0 to 0.5 m ASL	Rapidly fluctuating, highly dependent on sea characteristics and target movements.
Birds, floating or flying.		Sea level and up	
Flocks of birds.	Up to 3 m^2	Sea level and up	Rapidly fluctuating, flight paths tend to be characteristic of given species in given areas of interest.
Jet Skis and other personal watercraft	Up to 0.5 m^2	0 to 1 m ASL	Rapidly fluctuating but virtually independent of aspect angle

Target	Typical characteristics at X-band		
	RCS	Height	Fluctuations etc.
Wind turbines (onshore and offshore)	Up to 10,000,000 m^2	Up to 300 m ASL	Fluctuations for towers are insignificant. Rotating parts give a wide spectrum of Doppler shifts with RCS up to hundreds of m^2

Data is primarily based on references [3] + [4], supplemented by data obtained from the experiences of IALA VTS committee members.

Note: Modern warship design seeks to minimize RCS, and, as a result, the above figures cannot be related to such vessels.

In case the physical size of the target exceeds the size of the resolution cell of the radar, the target gets extended into other resolution cells. In such a case, the RCS values, as mentioned above, may be incorrect (as the target reflection is now distributed across more than one resolution cell). Additionally, the extension of the target poses extra challenges on detection and tracking performance. Extension of targets and the consequences thereof should especially be considered in situations where the radar is positioned close to the targets to be detected and tracked and/or in case of high-resolution radars.

RCS on targets using S-band is typically 40% and Ku-band is typically 120% of the RCS in X-band except for small non-metallic targets where the RCS difference between the 3 bands can be much higher.

A.4.2.1. Target RCS fluctuations

For VTS target types, statistical RCS fluctuations can adversely affect target detection. To predict range performance more realistically, such fluctuations can be mathematically modelled using the different Swerling cases. The radar design and the location of radars can compensate for the consequences of target RCS fluctuations.

A.4.3. MULTIPATH EFFECTS

Avoidance or reduction of effects from reflections requires in depth analysis, often combined with site surveys and calculations by the experienced radar engineer to determine acceptable radar positioning.

A.4.3.1. Reflections from large objects

Multipath conditions resulting from reflections from large buildings and large vessels can still impact on VTS radar performance resulting in the possibility of target signal cancellation or enhancement. This effect is hard to predict, and it is unreasonable to expect to model multipath affected performance unless a (potentially expensive) site-specific radar model is developed.

Mechanisms in Port areas will often include reflection from large surfaces, e.g., large buildings, piers etc and it can result in very challenging situations, even calling for more than one radar to cover certain areas.

A.4.3.2. Probability of detection and false alarm rate

The probability of detection and the false alarm rates, used for calculations, should comply with those required to meet the operational performance. Please note the definitions of radar P_D and radar P_{FA}, refer to section 4.

It should also be noted that improved system performance may be obtained by allowing a higher radar P_{FA} in combination with subsequent, enhanced plot extraction and tracking.

At specified maximum coverage ranges, the single-scan probability of detection values for VTS will typically lie in the range from 70% to 90%.

It is normally not desirable to have noise and clutter spikes presented to the VTS operator in each scan. Classically, optimal false alarm rates for VTS applications normally lie in the range from 10^{-4} to 10^{-5} for the radar video display. Different values may apply to the specific tracking system to obtain optimal, tracking.

With modern high-resolution technology there is a tendency to allow higher false alarm rates and let the extraction and tracking discriminate between noise and targets of interest.

False alarms considered in the calculations, include unwanted information from noise and clutter, as presented to the VTS operator to the tracker (after signal processing), but not signals from other unwanted objects or other targets.

A.5. RADAR COVERAGE

A.5.1. RADAR CONFIGURATION EXAMPLES

The following imaginary radars with simplified system characteristics and key parameters was used for the example calculations and illustrations made for this document.

Table 3 Imaginary, simplified VTS Radar System configurations and associated key parameters

System type	S1	S2	X1	X2	X3	Ku1	Ku2
Frequency Band	S	S	X	X	X	Ku	Ku
Radar signal processing	Simple	Medium	Simple	Medium	Advanced	Medium	Advanced
- Corresponding Pfa prior to processing	1.00E-06	1.00E-05	1.00E-06	1.00E-05	1.00E-04	1.00E-05	1.00E-04
- Corresponding Pd for good tracking	90%	80%	90%	80%	70%	80%	70%
Antenna Gain [dB]	25	29	32	35	38	32	36
- Antenna Horizontal Beamwidth [degrees]	2	1.25	0.6	0.45	0.36	0.5	0.3
- Antenna Verical Beamwidth [degrees]	30	20	20	15	10	20	12
Pulse radar specific							
Peak power [KW]	30	30	10	25	50		
Pulse length [ns]	Optimised to the individual operational area						
Pulse compression radar specific							
Peak power [W]	50	200	10	50	200	20	200
Equivalent peak pulse power [KW]	50	250	10	50	250	25	250
Compressed pulse length [ns]	50						
All assumed to have 3 dB one way transmission losses and an overall noise figure of 3 dB							

Antenna Heights (metres ASL)	Sea States (Douglas scale)	Precipitation (mm/hour)
20	1	clear
40	3	4
80	5	10
200		20

The example calculation provides a good idea of the baseline coverage, but it does not cover all VTS and individual manufacturers' characteristics, site specifics and settings for various operational areas. The calculation examples can only be used as a guideline, and they need to be supplemented by specific calculations made for the individual VTS radar site. Performance could be optimised to operational needs by configuration of systems with different parameters, i.e., power levels and/or different antenna characteristics.

A.5.2. MINIMUM DETECTION RANGE

Radars used for VTS typically have a blind range close to the radar station depending on the pulse characteristics, the waveguide length and processing. In addition, the minimum detection range depends on antenna height and antenna vertical beam "look down angle" as illustrated in Figure 4, and with corresponding figures per Table 4.

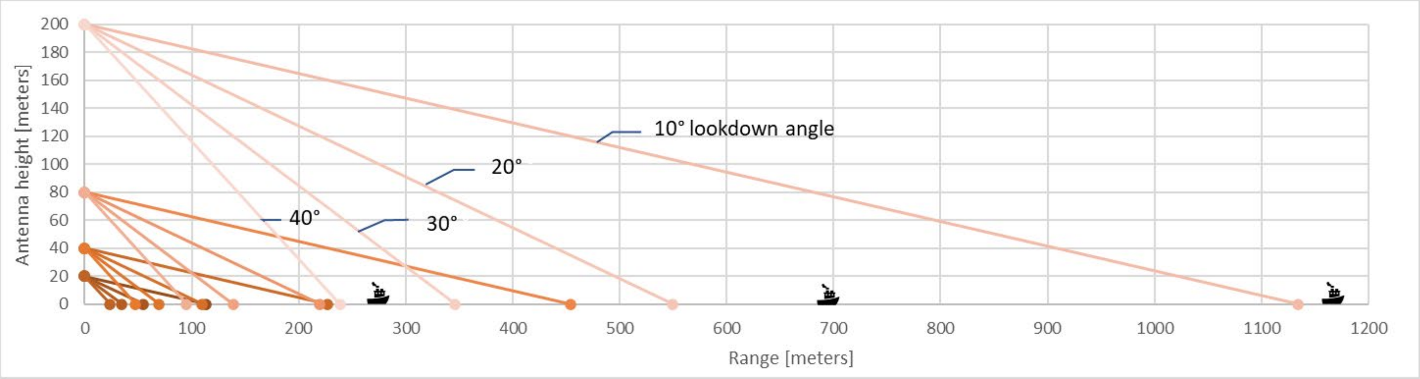

Figure 4 Minimum detection range as a function of antenna height and lookdown angle.

As a rule of thumb, the lookdown angle can be determined as the -20 dB point on the vertical antenna patten. Inverse cosecant beam techniques are used to improve the minimum detection range.

Aa antenna tilt mechanism may only have a marginal influence on the minimum range, and it may have the negative effect of increasing sea clutter returns.

Table 4 Calculated minimum range as a function of antenna characteristics and antenna hight

Ranges at sea level [metres]		Antenna height [m]			
		20	40	80	200
look down angle [°]	10	113	227	454	1134
	20	55	110	220	549
	30	35	69	139	346
	40	24	48	95	238

A.5.3. RADAR HORIZON

Figure 5 illustrates the basic geometry in target detection associated with antenna height above sea level (ASL) and the effect of the earth curvature, determined by the following formula:

$$Target\ Horizon = 2.2 \times \left(h_{target}{}^{0.5} + h_{antenna}{}^{0.5}\right)[NM].$$

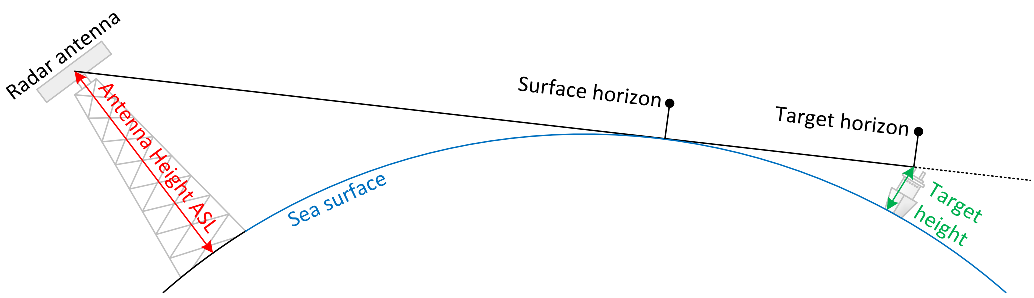

Figure 5 Geometry, antenna height and target height

Table 5 provides the radar Horizon for specific antenna heights and target heights corresponding to IALA targets type 1-7.

Table 5 Calculation of radar horizon.

Target range [Nautical Miles]		Target Height [metres]						
		1	2	3	5	8	12	18
Antenna Height [m]	20	12.0	12.9	13.6	14.8	16.1	17.5	19.2
	40	16.1	17.0	17.7	18.8	20.1	21.5	23.2
	80	21.9	22.8	23.5	24.6	25.9	27.3	29.0
	200	33.3	34.2	34.9	36.0	37.3	38.7	40.4

In addition to the minimum range and radar horizon, the target detection range is highly dependent on several other factors, including target characteristics, weather (such as fog, sea state and rain) and atmospheric propagation conditions, calculated and expressed in statistical terms.

These factors may be used to calculate range coverage, taking several radar parameters, installation, and the environment into account. Formulas and calculations are provided as follows.

A.5.4. ANALYSIS OF RADAR DETECTION PERFORMANCE

The requirements for radar coverage and range detection performance can be determined by a combination of site inspections and radar system performance predictions, including:

- evaluation of the effects from propagation conditions and obstructions in the on-site environment.
- calculation of range detection performance focused on the smallest targets of interest in poor weather conditions (all applicable losses (atmospheric and system related) should be included in the calculations); and
- evaluation of dynamic range requirements.

It will typically not be possible to cover all combinations of variables. Therefore, calculations are calculations are typically based on simplified models of the targets and the environment, based on statistical information with associated limitations and tolerances.

Furthermore, in the design of radar systems it is very important not only to focus on maximum detection range but also on perceived radar image quality and target separation at all ranges, the ability to handle clutter, the ability to suppress interferences and the ability to simultaneously handle of small and large targets in the VTS area covered by radar.

Notes: The radar prediction models require full understanding of their applicability and limitations. The calculations should be performed by radar specialists using a suitable tool and radar formulas given in this document.

It should also be noted that radar performance predictions are indications and not guarantees of real-world performance. There are many variables and explicit or implicit assumptions within most known prediction tools and the results obtained can only cover approximations of target, radar, and environment behaviour.

Live testing during site acceptance may be included to evaluate the actual performance against expectations.

Warning: Cumulative Detection seen in some modelling tools can be very misleading for determination of VTS related radar detection performance.

A.5.4.1. Symbols

The following symbols are used in the document to represent mathematical quantities. SI units are used throughout.

Symbol		Symbol	
P_t	Transmitter peak power	ϕ	Incidence angle
τ	Chirp duration	A_i	Interference term
L_t	Transmitter loss	A_u	Upwind term
L_r	Receiver loss	A_w	Wind term
L_p	Processing loss	σ_{HH}^0	Surface clutter cross-section
λ	Wavelength	η	Volume clutter cross-section
G	Antenna gain	P_n	Received noise power
k_B	Boltzmann constant	P_{sc}	Received power from surface clutter
T	Receiver temperature	P_{vc}	Received power from volume clutter
N	Receiver noise figure	x	Signal to (noise + clutter) ratio
σ	Radar cross section	N_b	Number of incoherently integrated pulses
r	Slant range	Y	Normalized detection threshold
F_p	Propagation factor	P_d	Probability of detection
α	Attenuation factor	P_r	Received power from target
B	Chirp Bandwidth	r_r	Rain rate [mm/h]

A.5.4.2. Received powers

A.5.4.2.1. Received power from the target

The power received from a given target, for a pulse compression radar, is computed from the following

$$P_r = \frac{P_t B \tau L_t L_r L_p \lambda^2 G^2}{4\pi} \frac{\sigma}{(4\pi)^2 r^4} |F_p^4| e^{-2\alpha r}$$

And for a pulse radar, such as a magnetron-based radar, the power received is

$$P_r = \frac{P_t L_t L_r L_p \lambda^2 G^2}{4\pi} \frac{\sigma}{(4\pi)^2 r^4} |F_p^4| e^{-2\alpha r}$$

The antenna gain depends on the angle, considering that both a direct path and an indirect, reflected path exists between the transmitter antenna and target. The propagation factor (F_p) is a coherent addition of the phase terms in the direct path between target and antenna. The reflected path includes the reflectivity of the Earth surface.

For observations of targets over the sea, the reflection coefficient depends on the water salinity and sea state.

For target ranges exceeding the radar horizon, a linear transition is used from the optical to the diffraction region. The target return power will be a function of target altitude and slant range. The radar cross section is a function of the radar wavelength as described elsewhere in this document, refer to Table 1 and Table 2.

Figure 6 gives an example of received power versus range, X2 system, 20-metre antenna height, IALA type 4 target, Sea State 3 and 4 mm/hour uniform rain

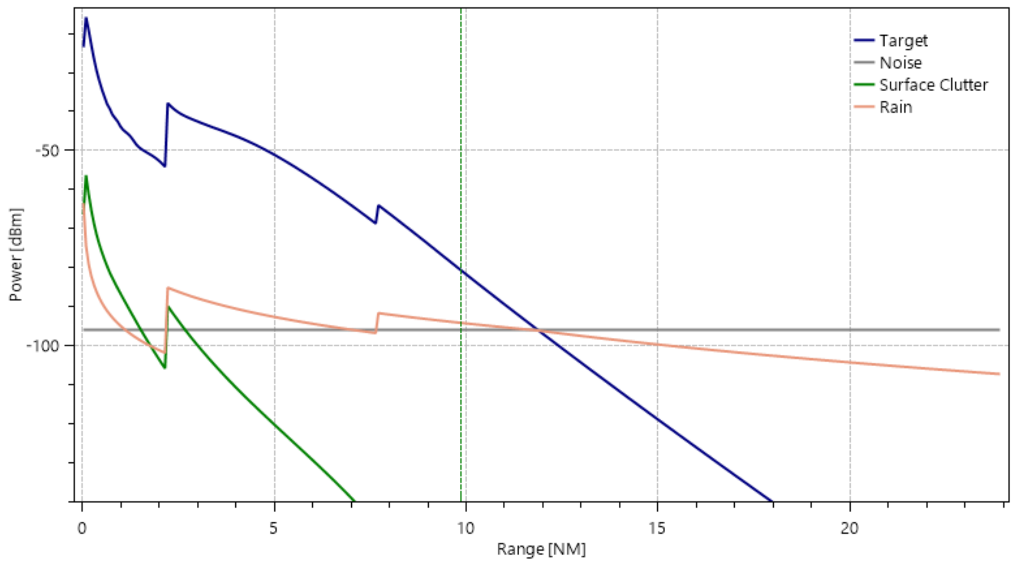

Figure 6 Example of received power versus range

A.5.4.2.2. Received power from sea clutter

The power received from surface clutter is computed using the de-facto industry standard model of sea clutter from Georgia Institute of Technology (GIT) [13]. Based on the size of the illuminated area and wind speeds, the total received power from sea clutter is calculated using a radar equation similar to that of the target. The model uses a surface clutter cross section (in m^2 / m^2) of

$$\sigma_{HH}^{0} = 10\log[3.9 \cdot 10^{-6}\lambda\,\phi^{0.4}\,A_i A_u A_w] \text{ [1-10 GHz] (S and X-band)}$$

$$\sigma_{HH}^{0} = 10\log[5.78 \cdot 10^{-6}\lambda\,\phi^{0.547}\,A_i A_u A_w] \text{ [10-100 GHz] (Ku-band)}$$

The illuminated area depends on the antenna beam width and the duration of the pulse (for pulse compression radars it is the duration of the compressed pulse). The exact shape of the Interference term, Upwind term and Wind terms are different in the two frequency ranges.

Note: The models described here have been derived for pulse radars and may be less representative for modern pulse compression radars with the ability to resolve individual sea clutter spikes.

A.5.4.2.3. Received power from land clutter

The power received from land clutter is computed using the constant-gamma model of [16] and the illuminated area. The total received power from land clutter is calculated using a radar equation similar to that of the target and a surface clutter cross section (in m^2 / m^2) of

$$\sigma_{HH}^{0} = \gamma \sin(\phi)$$

A.5.4.2.4. Received power from volume clutter

The power received from volume clutter (rain) is computed from the radar equation and the illuminated volume based on the antenna beam width in azimuthal and elevation plane. The radar cross section of rain is taken from [12], Chapter 19. The clutter is modelled as stratiform rain resulting in a volume clutter cross section (in m^2 / m^3) of

$$\eta = \frac{\pi^5}{\lambda^4} 1.86 \cdot 10^{-14} \cdot r_r^{1.6}$$

Valid from S-band to Ku-band. The power received depends on the clutter cross section and the illuminated column of rain, the size of which is given by the antenna beam width and height of the rain cloud ceiling.

A.5.4.2.5. Thermal noise

The thermal noise contribution in the received power is given by the simple thermal noise term:

$$P_n = k_B \, TBN$$

A.5.4.3. Attenuation

The radar signals are attenuated by the atmospheric air and any potential water in the shape of droplets.

Many highly detailed studies of attenuation exist, and the exact values of attenuation for both atmosphere and rain must be read of from a curve or table such as those given in [12]. In particular, the atmospheric attenuation does not have a simple dependence on wavelength due to molecular absorption bands in the Ku band.

Approximate 2-way values for VTS-radar relevant frequencies are given in Table 6 below.

Table 6 Atmospheric attenuation for various radar frequencies.

Frequency [GHz]	Atmospheric loss [dB/km]	Dense Fog loss, 50m visibility [dB/km]	Rain rate 1 mm/h, loss [dB/km]	Rain rate 2 mm/h, loss [dB/km]	Rain rate 4 mm/h, loss [dB/km]	Rain rate 10 mm/h, loss [dB/km]	Rain rate 20 mm/h, loss [dB/km]
3 (S)	0.016	0.007	0.001	0.001	0.003	0.007	0.015
9.5 (X)	0.032	0.080	0.013	0.031	0.045	0.248	0.606
14 (Ku)	0.038	0.181	0,056	0.124	0.276	0.793	1.762
17 (Ku)	0.120	0.240	0.095	0.205	0.440	1.210	2.598

A.5.4.4. Evaporation ducting

Ducting can severely affect radar range in clear conditions as described in annex A, Section A.10. The effect of evaporation ducting is to reduce the loss in the diffraction region. A very simplified ducting model consists of the Naval Research and Development evaporation duct model where a fit to a waveguide solution is used to model the diffraction loss. All ranges and heights are scaled to an X-band solution. The dimensionless range scale factor is

$$R = \sqrt[3]{f/9600}$$

And the dimensionless height scale factor is

$$Z = \sqrt[3]{(f/9600)^2}$$

The fitted solution allows the modelling of ducts up to a scaled height of 23.3 metres. For scaled duct heights less than 10.25 metres, the height gain function in the diffraction region is

$$F(z) = C_1 z^{C_2} + C_3 z^{C_4} + C_5$$

Where z is the scaled transmitter / target height. The coefficients C1 to C5 have a complicated form dependent on the scaled duct height. For well trapped modes with scaled heights between 10.25 and 23.3 metres, the height gain function is

$$F(z) = \begin{cases} C_1 \ln(\sin(C_1 z^{C_2})) + C_4 & 1 < z < z_{max} \\ C_5 z^{C_6} + C_7 & z > z_{max} \end{cases}$$

The maximum scaled altitude of the first solution is dependent on the duct height. The various numeric constants in the waveguide fit model have complicated forms and require specialized simulation tools.

The effects of other than evaporation ducting phenomena will also require specialized simulation tools.

A.5.4.5. Detection probability

From the computed power terms, the final ratio of signal to noise and clutter at a given target position (slant range and altitude) is

$$x = \frac{P_r}{P_n + P_{sc} + P_{vc}}$$

This is converted to a probability of detection using the statistical models first developed by Swerling [14]. The choice of Swerling case depends on the target geometry as well as the decorrelation from sweep to sweep.

Large complex targets such as ships are classically modelled as Swerling case 1 targets with a large number of reflectors and small variation from sweep to sweep, with only variation from scan to scan. A complex target with fast variation is represented by Swerling case 2. Small point targets (missiles etc) are modelled as Swerling case 3 targets, with a single dominant reflector and little variation from sweep to sweep.

However, using modern radars with multiple frequencies, each frequency hitting the target more than once, leads to a partial decorrelation over the sweeps hitting the target. Swerling case 3 can be used as an approximation for complex surface targets when multiple carrier frequencies are used by the radar, since the curve for Pd versus signal-to-noise for Swerling case 3 lies between Swerling cases 1 (perfect correlation, many roughly identical scatterers) and 2 (perfect decorrelation, many roughly identical scatterers) For single frequency radars, complex surface targets are represented by Swerling case 1.

Table 7 Swerling Cases

Target type	Single carrier frequency radar (magnetron or similar)	Multiple carrier frequency radar
Large complex targets (larger ships, aircraft etc)	Swerling case 1	Average between Swerling case 1 and 2 (represented by Swerling case 3)
Small point targets (buoy)	Swerling case 3	Swerling case 3

A false alarm rate is specified, and the false alarm rate and number of incoherently integrated pulses determine the detection threshold from

$$P_{fa} = 1 - \Gamma(N_B, Y)$$

After determining the detection threshold, an intermediate term, c, is first defined as

$$c = \frac{1}{1 + (N_B x)/2}$$

The probability of detection can subsequently be calculated as

$$P_d = 1 - \Gamma(N_B - 1, Y) + c\frac{Y^{N_B - 1}}{(N_B - 2)!}e^{-Y} + \frac{e^{-cY}}{(1-c)^{N_B-2}}\left(1 - \frac{c(N_B - 2)}{1 - c} + cY\right)\Gamma(N_B - 1, Y(1-c))$$

This is the final output of the model, providing a probability of detection for given target, antenna, and weather conditions.

HThe example given in Figure 7 illustrates calculated range for an IALA type 4 target in Sea State 3 and clear conditions assuming 20, 40, 80 and 200-metre antenna height, respectively.

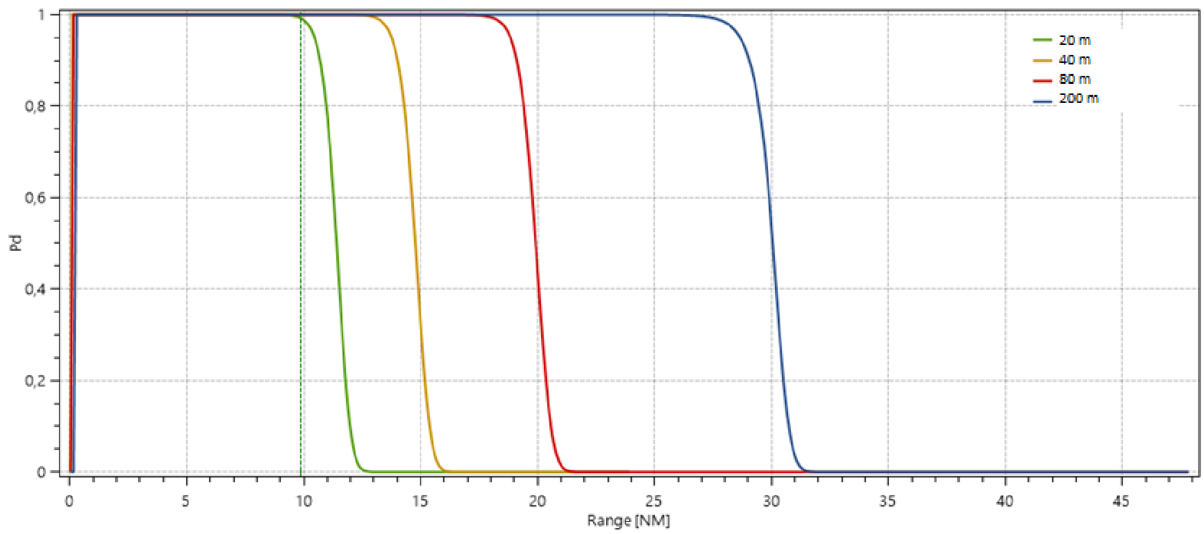

Figure 7 Probability of detection

A.5.4.6. Calculation examples, comparison of technologies

A.5.4.6.1. Range performance

The radar technologies available for VTS have all their strength and weaknesses, especially depending on weather, range and antenna height. The examples are intended as a simplified guideline to what is possible and what should be avoided in specific situations.

Table 8 reflects simplified coverage calculations for the system types defined per Table 3, all set up for 24 nautical mile coverage and various weather conditions. Targets are modelled as a vertical line to minimize the effect from lobing on the calculations.

Table 8 Example of performance across various radar types and weather situations

Radar Performance Calculation per IALA G111-3																					
<u>Radar type:</u> Pulse Compression Compressed <u>Pulse length</u>: 50nS <u>Antenna Hight ASL:</u> 40 m <u>Instrumented Range</u>: 24 NM																					
Target detection range in SS3		IALA1 target: AtoN without radar reflector. Small open boats, fiberglass, wood or rubber					IALA 2 target: In-shore fishing vessels etc					IALA 3: AtoN with radar reflector					IALA 4 target: Small metal ships etc.				
		Clear + 7m duct	Clear	4 mm/h rain	10 mm/h rain	20 mm/ rain	Clear + 7m duct	Clear	4 mm/h rain	10 mm/h rain	20 mm/ rain	Clear + 7m duct	Clear	4 mm/h rain	10 mm/h rain	20 mm/ rain	Clear + 7m duct	Clear	4 mm/h rain	10 mm/h rain	20 mm/ rain
Radar Type	S1	Target RCS <<1 m2 at this frequency may not allow for reliable detection					4.3 NM	4.2 NM	4.2 NM	4.2 NM	4.1 NM	5.9 NM	5.9 NM	5.9 NM	5.9 NM	5.8 NM	9.0 NM	8.9 NM	8.9 NM	8.9 NM	8.8 NM
	S2						6.7 NM	6.4 NM	6.3 NM	6.2 NM	5.8 NM	8.7 NM	8.5 NM	8.4 NM	8.3 NM	8.1 NM	12.1 NM	12 NM	11. 7 NM	11. 7 NM	11.5 NM
	X1	4.1 NM	4.1 NM	3.9 NM	2.9 NM	< 1 NM	6.1 NM	6.2 Nm	5.9 NM	5.4 NM	2 NM	8.2 NM	8.1 NM	7.8 NM	7.2 NM	3 NM	11.9 NM	11.4 NM	11 NM	10.4 NM	8.8 NM
	X2	6.8 NM	6.3 NM	5,6 NM	4,5 NM	3,5 NM	9.5 NM	8.9 NM	8.5 NM	7.7 NM	6.6 NM	12.1 NM	10.8 NM	10.5 NM	9.8 NM	8.7 NM	14.9 NM	13.7 NM	14.4 NM	12,8 NM	11,6 NM
	X3	10.0 NM	8.6 NM	6.7 NM	5.3 NM	4.3 NM	13.5 NM	11.2 NM	10.0 NM	8.8 NM	7.7 NM	16.5 NM	13.0 NM	12.2 NM	11.2 NM	10.2 NM	21.9 NM	15.8 NM	15.2 NM	14.3 NM	13.3 NM
	Ku1	5.0 NM	5.0 NM	4.1 NM	< 1 NM	< 1 NM	7.8 NM	7.7 NM	6.6 NM	2.9 NM	< 1 NM	10.0 NM	9.6 NM	8.3 NM	4.3 NM	3.9 NM	15.3 NM	12.8 NM	11.6 NM	6.6 NM	5.9 NM
	Ku2	9.9 NM	8.3 NM	6.3 NM	4.4 NM	< 1 NM	14.9 NM	11.0 NM	9.8 NM	8.2 NM	2.9 NM	18.8 NM	12.7 NM	11.6 NM	10.1 NM	4.4 NM	24.0 NM	15.3 NM	14.3 NM	12.7 NM	6.8 NM

The calculations are simplified and indicative of typical achievable performance. Targets are modelled as point targets and calculations use equivalent pulse power and compressed pulse width as specified per Table 9.

Table 9 Example of performance across various radar types, longer range

Radar Performance Calculation per IALA G111-3																					
<u>Radar type:</u> Pulse Compression Compressed <u>Pulse length</u>: 50nS <u>Antenna Hight ASL:</u> 200 m <u>Instrumented Range</u>: 48 NM																					
Target detection range in SS3		IALA1 target: AtoN without radar reflector. Small open boats, fiberglass, wood or rubber					IALA 2 target: In-shore fishing vessels etc					IALA 3: AtoN with radar reflector					IALA 4 target: Small metal ships etc.				
		Clear + 7m duct	Clear	4 mm/h rain	10 mm/h rain	20 mm/ rain	Clear + 7m duct	Clear	4 mm/h rain	10 mm/h rain	20 mm/ rain	Clear + 7m duct	Clear	4 mm/h rain	10 mm/h rain	20 mm/ rain	Clear + 7m duct	Clear	4 mm/h rain	10 mm/h rain	20 mm/ rain
Radar Type	S1	Target RCS <<1 m2 at this frequency may not allow for reliable detection at any sea state					4.9 NM	4.9 NM	4.8 NM	4.7 NM	4.3 NM	7.7 NM	7.7 NM	7.7 NM	7.6 NM	7.5 NM	14.1 NM	14.1 NM	14.1 NM	14 NM	13.9 NM
	S2						10.9 NM	10.9 NM	10.8 NM	10.7 NM	10.5 NM	15 NM	15 NM	15 NM	14.9 NM	14.7 NM	21.7 NM	21.7 NM	21.6 NM	21.5 NM	21.5 NM
	X1	Poor detection at all ranges at sea state 3 or higher					2.6 NM	2.6 NM	2 NM	NIL	< 1 NM	4.1 NM	4.1 NM	3.7 NM	2.6 NM	1.3 NM	8.9 NM	8.9 NM	8.1 NM	6.8 NM	5.1 NM
	X2	3.6 NM	**3.6 NM**	**1.7 NM**	**< 1 NM**	< 1 NM	8 NM	8 NM	5.3 NM	2.1 NM	< 1 NM	12.5 NM	12.5 NM	11.3 NM	7.3 NM	2.6 NM	24.8 NM	24.8 NM	21.4 NM	16,6 NM	8.5 NM
	X3	13,6 NM	**11.5 NM**	**10.8 NM**	**< 1 NM**	< 1 NM	20.6 NM	20.6 NM	18.7 NM	4 NM	< 1 NM	23.9 NM	23.9 NM	22.7 NM	19.1 NM	7.3 NM	28.1 NM	28.1 NM	26.3 NM	25.7 NM	17.3 NM
	Ku1	< 1 NM	**< 1 NM**	**< 1 NM**	**< 1 NM**	< 1 NM	1.7 NM	1.7 NM	1.4 NM	< 1 NM	< 1 NM	6.9 NM	6.9 NM	1.6 NM	1.4 NM	**< 1 NM**	3.5 NM	3.5 NM	3 NM	2.6 NM	2.1 NM
	Ku2	8.3 NM	**8.3 NM**	**< 1 NM**	**< 1 NM**	< 1 NM	13.2 NM	13.2 NM	5.3 NM	< 1 NM	< 1 NM	21.9 NM	21.9 NM	10.8 NM	3.7 NM	**< 1 NM**	28.6 NM	28.6 NM	20 NM	11.3 NM	6.6 NM

Note that 20 MM/h uniform rain is rare over such long distances (48 NM) and evaporation ducting has lite influence when the antenna is high elevated. The values in those fields are therefore greyed.

A.5.4.6.2. Circular versus linear polarization

The utilization of Circular polarizations has traditionally been done to improve performance in rain; however, it also reduces the ability to detect small non-metallic targets and some types of reflectors. Furthermore, modern pulse compression radars and narrow beamwidth antennas reduces the sensitivity to rain

Table 10 reflects calculations of various combinations. The Pulse radar is set up with a pulse length of 0,5 uS in the examples. 10 mm/h uniform distributed rain was assumed as more dense widespread rain is rare.

Table 10 Comparison between Horizontal and Circular polarization

Radar Performance Calculation per IALA G111-3				
Radar type: X2 Antenna Hight ASL: 40 m				
Radar type / Polarization	Detection probability for combinations of precipitation and polarization Instrumented Range: 24 Nautical miles Propagation: 10 mm/h rain Sea State: 3			
	X2 pulse comp / Horizontal	X2 pulse comp / Circular	X2 pulse (magnetron) / Horizontal	X2 pulse (magnetron) / Circular
IALA1: AtoN without radar reflector. Small open boats, fiberglass, wood or rubber	4,5 NM	This type of target may not give returns from circular polarized radar	< 1 NM	This type of target may not give returns from circular polarized radar
IALA 2: In-shore fishing vessels etc.	7.7 NM	7.4 NM	4.7 NM	8.0 NM
IALA 3: AtoN with radar reflector	9.8 NM	9.1 NM	8.5 NM	10.1 NM
IALA 4: Small metal ships etc.	12.8 NM	12.0 NM	12.5 NM	13.0 NM
IALA 5: Small coasters etc	15.4 NM	12.8 NM	15.7 NM	15.7 NM
IALA 6: Large coasters etc.	18.1 NM	17.4 NM	18.6 NM	19.0 NM
IALA 7: Large coasters, bulk carriers, and cargo ships.	20.9 NM	20.2 NM	21.7 NM	21.2 NM

A.6. TARGET SEPARATION

The ability to separate two small point targets in range and angle (azimuth) is illustrated by Figure 3, where the range separation is, for traditional magnetron radars, linked to the transmitted pulse length and linked to the compressed pulse length for the pulse compression (solid-state) radars.

The angular separation is given by the antenna characteristics and the angular separation performance is generally broader over distance

The range separation performance is given by the transmitter and receiver characteristics and is generally equal over distance.

An increase in frequency will improve the angular target separation and increase gain for antennas with the same physical size and thereby increase range detection performance, but it also increases susceptibility to rain. However, pulse compression radars are less sensitive to this than pulse radars.

A.6.1. ANGULAR SEPARATION

Figure 8 shows an example of returns from two identical targets using an antenna with 0.45° -3dB beamwidth and separated by 0.8 °. The echoes of T1 and T2 are added, which in average, is illustrated by the red. However, the separation will also be dependent on integration processes and the phase of the signals received, and the resulting separation can vary between the dotted and the dashed lines in the figure.

To calculate the resulting angular separation, the antenna beamwidth and sampling interval must also be considered where the sample interval as a rule of thumb can be added, i.e., 0.08° should be added if the azimuth is sampled every 360°/4096.

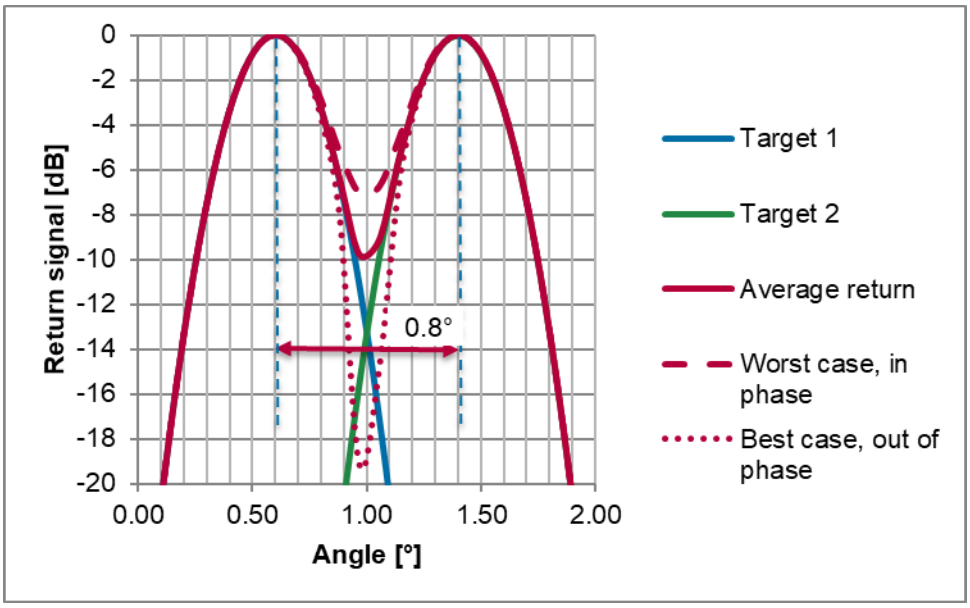

Figure 8 Example of Return from two identical targets placed at the 0.6° and 1.4° angles

In the worst-case angular separation for point targets are:

- Approximately 1.75 times the – 3 dB antenna beam width + 1 resolution cell to achieve 6 dB separation.
- Approximately 2.5 times the – 3 dB antenna beam width + 1 resolution cell to achieve 20 dB separation.

The first will typically be sufficient for visual discrimination of targets and the later should be sufficient for visual separation of targets.

Table 11 Typical azimuth separation as a function of system type and range.

System type		S1		S2		X1		X2		X3		Ku1		Ku2	
Antenna Horizontal Beamwidth [°] @ -3 dB		2.00		1.25		0.60		0.45		0.36		0.50		0.30	
Angular Separation [°], excl sampling inaccuracies		@-6dB	@-20dB	@-6dB	@-20dB	@-6dB	@-20dB	@-6dB	@-20dB	@-6dB	@-20dB	@-6dB	@-20dB	@-6dB	@-20dB
		3.50	5.00	2.19	3.13	1.05	1.50	0.79	1.13	0.63	0.90	0.88	1.25	0.53	0.75
Azimuth Separation [m] versus range, incl sampling inaccuracies	1 NM	116	164	74	104	37	51	28	39	23	32	31	43	20	27
	6 NM	695	985	441	623	221	308	170	235	139	192	187	259	119	162
	12 NM	1391	1971	882	1246	441	616	340	470	278	383	373	519	238	325
	24 NM	2782	3942	1765	2491	883	1232	679	941	557	766	747	1038	475	650
	48 NM	5563	7884	3529	4982	1765	2463	1358	1882	1114	1533	1494	2076	951	1300
				# of Azimuth encoder samples per 360°:				4096							

A.6.2. RANGE SEPARATION

Figure 9 illustrates an example of returns from two targets separated in range and the sum (power) of the two. The range separation is determined by the frequency of range samples and the bandwidth. The echoes of T1 and T2 are added, which in average, is illustrated by the red. However, the separation will also be dependent on integration processes, and the phase of the signals received, and the resulting separation can vary between the dotted and the dashed lines in the figure.

To calculate the range separation, the effective bandwidth and sampling interval must be considered, where the worst-case range separation for point targets are:

- Approximately 2 times the – 3dB pulse width + 1 resolution sample to achieve 6 dB displayed separation.
- Approximately 3 times the – 3dB pulse beam width + 1 resolution sample to achieve 20 dB displayed separation.

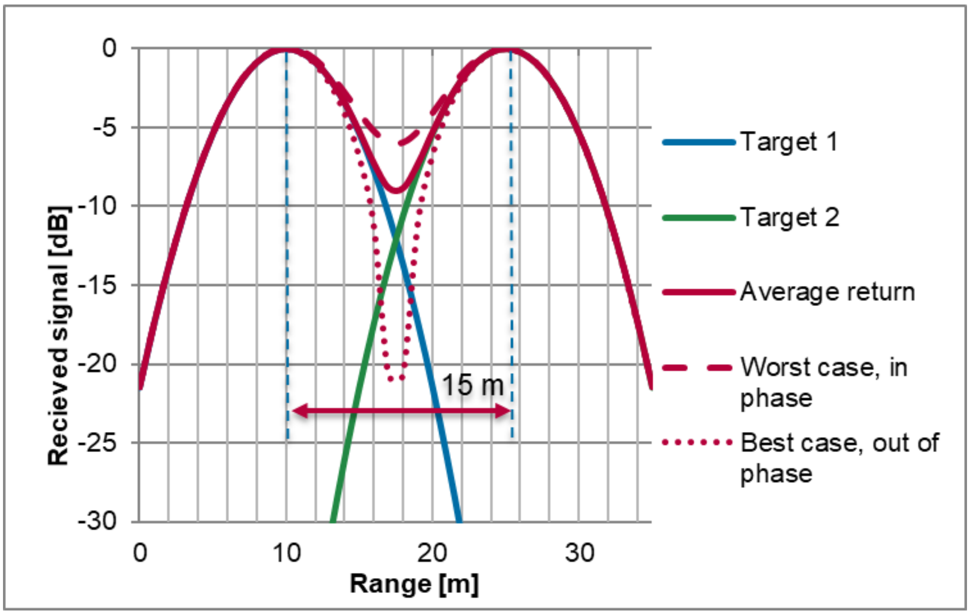

Figure 9 Range discrimination

The sampling resolution cell size should be added to obtain a figure for the achieved range separation, i.e., 3 metres in the case of 50 MHz sampling rate.

I.e., this will, for a 50 nS effective pulse width (7,5 m) and 50 MHz sampling rate, result in range separation of:

- 18 m at the -6 dB points
- 24 m, at -20 dB points

Note that for larger targets and for separation of dissimilar sized targets, the definition of separation is highly dependent on physical size, aspect angles, and other radar characteristics.

A.7. TARGET POSITIONAL ACCURACY

The “accuracy” is characterized in accordance with *ISO 5725-1* by two parameters; trueness (systematic error) and precision (random error), which are illustrated in Figure 10.

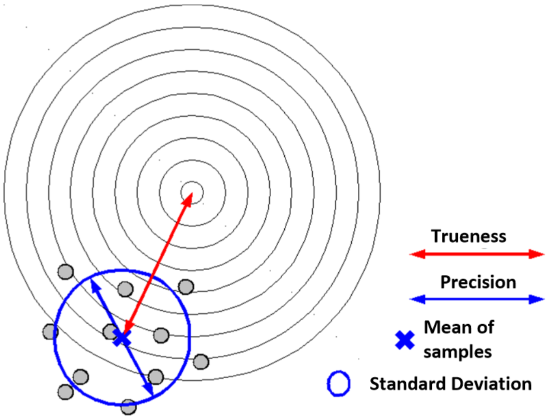

Figure 10 Definition of trueness and precision

The “overall accuracy” is the average deviation between sets of single measurements and the corresponding set of reference values. Overall accuracy thus equals the definition of trueness provided that enough measurements are averaged.

The overall RMS accuracy is calculated by:

$$Accuracy_{RMS} = \sqrt{Trueness^2 + Precision^2}$$

The impact of the antenna height on the measuring accuracy (slant range vs plan range) is additional.

Typical requirements for VTS are listed in Table 12. Values are valid for stable tracks on uniformly moving, small point targets.

Table 12 Typical target positional accuracies for pulse compression radars

Operational area	Typical obtainable Slant Range and Azimuth Target Positional Accuracies, RMS		
	Systems designed for areas without dense traffic	Intermediate	Systems designed for areas with dense traffic
Inland waterways, like rivers and canals Port with berths and anchorages	20 metres/ 0,5 degree	15 metres/ 0,35 degree	10 metres/ 0,25 degree
Port approach	30 metres/ 0,5 degree	20 metres/ 0,35 degree	15 metres/ 0,25 degree
Coastal areas and offshore	100 metres/ 0,5 degree (S-band: 1 degree)	50 metres/ 0,35 degree (S-band: 1 degree)	25 metres/ 0,25 degree (S-band: 0,5 degree)

As a rule of thumb, the range inaccuracy will be increased by 20 % of the pulse length for pulsed magnetron radars.

A.8. TARGET POSITIONAL UPDATE RATE

The VTS operation and especially the tracking function is dependent of timely update rates of the radar information and the required radar update rate is determined by the behaviour of the expected target types. Typical update rates (antenna rotation rates) are listed in Table 13:

Table 13 Update rate

Operational area	Typical Positional Update Rate
Inland waterways, like rivers and canals	1.5 – 3 seconds
Port with berths and anchorages	1.5 – 3 seconds
Port approach	1.5 – 3 seconds
Coastal areas and offshore	2-6 seconds

A.9. DYNAMIC CHARACTERISTICS

A.9.1. DYNAMIC RANGE

The required dynamic range is determined by:

- The ratio between the largest nearby objects expected and the smallest distant objects to be detected.
- Target return signal fluctuations, including multipath.

Requirements for the radar(s) can be determined from the characteristics of the objects in the coverage area of the individual radar. This is shown as a function of RCS and detection range in Figure 11.

The figure represents targets in free space, which is normally sufficient for VTS radar requirements when combined with 10 dB allowance for target fluctuations.

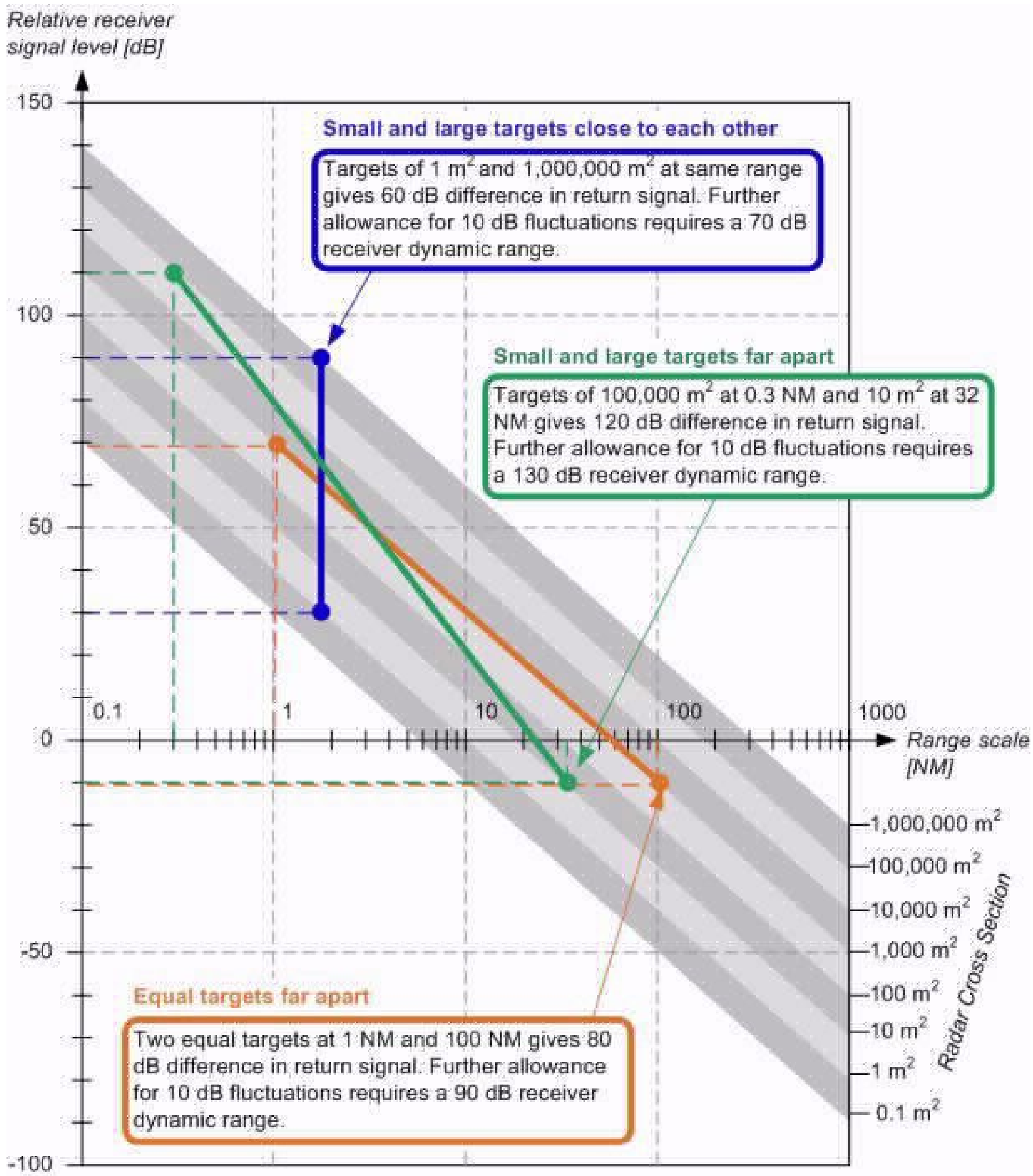

Figure 11 Dynamic characteristics of the signal received versus target RCS and target range

It should also be noted that the vide span of signals makes it very difficult to measure the dynamic range of a given radar, and it is recommended to use analytical methods i.e., considering the following for a pulse compression radar:

3 The effective dynamic range of the ADC where each bit corresponds to 6 dB, i.e.,:

- The max dynamic range for a 14-bit ADC 84 dB.
- However, inaccuracies in the ADC limit the dynamic range down to the so called effective dynamic bit that may be 13bit, equal to 78 dB.

4 The required minimum bit-level of sampled noise in ADC (full sampling bandwidth), i.e.,:

- To make the ADC sampling noise small compared to the thermic noise in the RF receiver, the received thermic noise is gained up to be 10 dB above the quantization noise of the ADC. This uses 10 dB of the effective dynamic range of the ADC

5 Noise power reduced by the ratio of processing bandwidth relative to sampling bandwidth i.e.,:

- The noise power level sampled by the ADC is received in a full Nyquist bandwidth of 50 MHz. As the digital match filter reduces the bandwidth defined by the range resolution, the noise power level is equally reduced. The bandwidth ratio is up to 50 to 8, giving a reduction factor of 6 times or 8 dB. This is referred to as over-sampling.

6 Range, azimuth or area dependent sensitivity (swept gain) prior to ADC

- Typically, a feature of advanced radars adding to the effective dynamic range
- May be used to attenuate specific areas based on previously scans.

7 Range dependent sensitivity of different pulse compression gain of short and long chirps.

- Typically, a feature of advanced radars adding substantially to the effective dynamic range

8 Reduction of the effective RCS of large structures when they are in close range

- When the RCS of an object is defined, it is normally to assume that the object is in far field of the radar. However, the phase difference to all parts of a distributed target is significant at X-band when the object is in close range to the radar.
- Likewise, the radar beam may not illuminate all of a nearby target, e.g., a large ship.
- As an example, the RCS of a 100 m high, 6 to 4 m tapered cylinder (the tubular tower of wind turbines) is 66 dBsqm in the far field, but in 20km, it is reduced by 13 dB to 53 dBsqm. In 2 km it is reduced by 23 dB to 43 dBsqm.
- The effect depends on the object type, but it will not be an exaggeration to include 10 dB in the dynamic range on this account.

9 Transmitter power variations

- Depending on geographical conditions it may be possible to reduce power towards areas with the largest targets. (Sector power transmission)

10 Reduction of the antenna gain when operating in the antenna near field.

- The effect will only be significant on very close object, typically less than 100 m.

11 Acceptable saturation handled without violation of specified range side lobe level.

- Minor saturation i.e., 5 dB can for advanced radars be accepted and handled by the CFAR, especially in the case of short chirps.

Actual values will be dependent on the individual manufacturer solution. It is furthermore unlikely that all elements can be considered simultaneously.

Table 14 gives a calculation example and Table 15 state values typical for VTS applications.

Table 14 Example of a dynamic range evaluation for an imaginary pulse compression radar

1	The effective dynamic range of the ADC	78 dB
2	The required minimum signal level of the sampled noise	-10
3	Bandwidth reduction factor, oversampling	+8
4	Swept gain prior to ADC	+0
5	Difference in pulse compression gain of near range and long-range chirps	+26
6	Sector power transmission	+0
7	Near range RCS reduction	+10
8	Near range antenna gain reduction	+0
	Unsaturated dynamic range	**112 dB**
9	Saturation giving acceptable range side lobe levels	+5
	Dynamic range, including acceptable saturation	**117 dB**

Table 15 Dynamic range typical for VTS applications

Operational area	Typical Dynamic Range		
	By systems designed for areas without large structures, or very large ships	Intermediate	By systems designed for areas with large structures and/or very large ships
Inland waterways, like rivers and canals	90 dB	100 dB	110 dB
Port with berths and anchorages	100 dB	100 dB	100 dB
Port approach	90 dB	100 dB	110 dB
Coastal areas and offshore	80 dB	100 dB	120 dB

A.9.2. SIDELOBES

Side lobes, see Figure 12, are unwanted, as they will limit the size of a small radar cross section (RCS) target that can be detected when located next to a large RCS target.

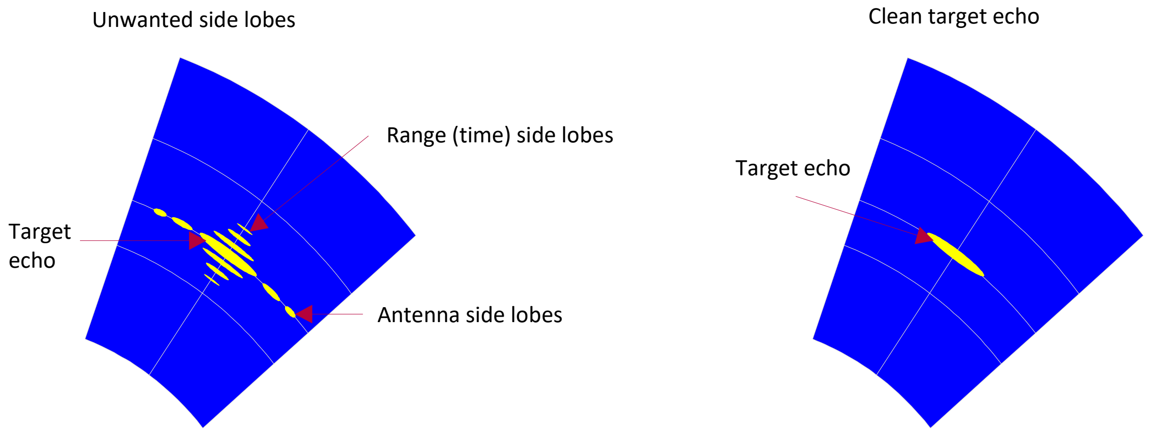

Figure 12 Range and antenna (azimuth) side lobe effects

The ratio between the peak level of the target and the highest side lobe is called the peak side lobe ratio (PSLR).

Typically, azimuth (antenna) side lobes are the only contributor in traditional magnetron pulse radars. FMCW and pulse compression radars are subject to range as well as azimuth side lobes.

Side lobes need to be sufficiently low to avoid masking of smaller targets in the proximity of large returns from targets or clutter. In addition, low side lobes minimize the probability of false targets arising from other large returns. However, it is normally not possible to eliminate false echoes from range and time sidelobes completely.

Table 16 recommends the typical allowed signal presented to the display and plot extractors.

The figures account for two-way propagation, therefore the antenna side lobe requirements (one way) equal half the values indicated (dBs divided by 2).

Table 16 Typical requirements to maximum side lobe level relative to non-saturating target signals

All Operational Areas	Typical side lobe Level requirements		
	Areas without large structures, or very large ships	Intermediate	Areas with large structures and/or very large ships
Maximum near side lobe level (within +/- 10° in azimuth and +/- 250 m in range from any target)	- 52 dB (-26 dB one way)	- 54 dB (-27 dB one way)	- 56 dB (-28 dB one way)
Maximum far side lobe level (outside +/- 10° in azimuth and +/- 250 m in range from any target)	- 66 dB (-33 dB one way)	- 68 dB (-34 dB one way)	- 70 dB (-35 dB one way)

Note that objects within the near field of the antenna may increase azimuth side lobe levels. This should also be carefully considered when defining locations or radars.

A.9.2.1.1. Antenna side lobes

The antenna designer uses an amplitude weighting function to control the azimuth side lobe levels to a level which recognizes the requirements for close in (< 10° from the main lobe peak) azimuth side lobes and the requirements for side lobes beyond this region. Side lobes are specified as a ratio (in dB) relative to the antenna beam peak.

The antenna gain defined from a specific point in the radar system is specified as a ratio above "isotropic" (dBi) and can be increased by increasing the physical size of the antenna. This will also reduce the beamwidth (azimuth, elevation, or both).

Sidelobes exist in Azimuth and elevation, however, elevation side lobes are unlikely to be a major contributor to the performance of the VTS radar system. So called grating lobes are of special concern for array antennas and these should be included in consideration and measurement of side lobe levels.

Also note that structures near antennas (in some cases up to 100 metres) tend to distort wave propagation and, thereby, increase the azimuth side lobe level in the direction of such structures.

A.9.2.1.2. Range side lobes

Pulse compression and FMCW uses an amplitude weighting function alike that used for antennas to control the range side lobe levels to a level which recognizes the requirements.

Note: Suppression values for range side lobes should in principle, be the same as for the antenna sidelobes. However, it might not be economically feasible to obtain more than 55-60 dB suppression by such weighting, and follow-on suppression/cancellation of range sidelobes by signal processing may be required in order to avoid false tracks and poor video quality. The drawback from such measures is reduced dynamic range locally, which my limit the ability to detect small targets near to larger ones.

A.10. ENVIRONMENTAL INFLUENCE

There is a strong and complicated relationship between radar performance, geographical constraints and environmental conditions and it is highly recommended that individual assessments involving radar and meteorological experts are made for each VTS site separately. The sections below discuss typical conditions covering the majority of VTS installations.

A.10.1. PRECIPITATION AND SEA

Rain will attenuate signals and backscatter from sea, and rain will "compete" with the signals received from targets and thereby reduce detection ranges.

A.10.2. REDUCED VISIBILITY - FOG, SAND AND DUST

Reduced visibility due to fog, sand and dust will in general, have small influence on radar coverage, compared to that of clear conditions. However, sand and dust storms are often associated with abnormal propagation conditions, as discussed below

A.10.3. AIR MASS (PROPAGATION)

The performance of surface-based radar systems is strongly influenced by the electromagnetic properties of the atmosphere and the surface of the Earth. In free space, electromagnetic waves propagate in straight lines from the antenna toward the targets and back. However, radars located near the Earth's surface should deal with and adjust to the diffraction and refraction of the propagating wave.

Performance should, in all cases, be evaluated assuming standard atmospheric conditions, combined with precipitation and sea state information for the individual location. Evaluation of the effects from adverse propagation should in addition, be considered for hot, dry areas of the world, e.g., the Arabian Gulf.

A.10.3.1. Propagation in the standard atmosphere

An electromagnetic wave observed at a target consists of a summation of an infinite number of contributions from different paths to the target leading to constructive and destructive contributions at the target. The return path suffers from similar effects. For small low targets, this results in shorter detection ranges than the distance calculated by a simple line of sight calculations.

In addition, the barometric pressure and water vapour content of the standard atmosphere decreases rapidly with height, and the temperature decreases slowly with height. This causes the electromagnetic waves to bend a little towards the Earth's curvature.

Radar parameters, losses in transmission lines (not only waveguide), processing losses, clutter and precipitation add to the complexity and, even for the Standard Atmosphere, it is necessary to combine this with propagation factors by radar calculation tools in order to determine the predicted performance for a VTS radar sensor. This is typically modelled by increasing the radius of the Earth by a multiplier (typically 1.33) and assuming straight-line propagation.

A.10.3.2. Sub-refraction and super-refraction

Sub-refraction, bending the electromagnetic waves up, and super-refraction, bending the electromagnetic waves down, exists when the atmosphere deviates from the standard.

Sub-refraction can be caused by fast reduction of temperature and slower reduction of water vapour content with height, bending the electromagnetic waves towards space. However, this phenomenon occurs rarely in nature.

Super-refraction can be caused by temperature increase with height (generally by temperature inversion) and/or rapid decrease of water vapour with height, decreasing the refractivity index (N). Decreasing the refractivity gradient will eventually cause it to reach the critical gradient, at which point an electromagnetic wave will travel parallel to the Earth's curvature.

A.10.3.3. Ducts and trapping layers

Super-refraction will develop into trapping layers, if the refractivity gradient decreases beyond the critical gradient, at which point the electromagnetic wave will be trapped and follow the Earth's curvature.

Ducts act like waveguides for propagating waves bordered by trapping layers or the Earth's surface. To couple into a duct and remain in a duct, the angle of incidence must be small, typically less than 1°.

Ducting can be categorized into three main types:

- Evaporation duct:
  - Weak, caused by evaporation from the sea surface, and only at low levels (maximum of 40 metres ASL).
  - Generally increasing the radar horizon, especially for low mounted antennas.
- Surface-based duct:
  - Surface ducts caused by low level inversion (increase of temperature /decrease of humidity with height), up to 500 metres ASL.
  - Increase of radar range, depending on duct and antenna height.
- Elevated duct:
  - 0.2-2 km above the surface.
  - Typical no effect on surface-based antennas.

The effects are typically increased range but also increased amounts of noise and 2nd / multiple time around returns which may appear as false radar returns.

Notice that the electromagnetic waves are refracted (bent) and not reflected by the trapping layers.

A.10.3.4. Evaporation ducts

Evaporation ducts exist over the ocean to some degree, almost all the time. A change in the moisture distribution without an accompanying temperature change will lead to a trapping refractivity gradient. The air in contact with the ocean surface is saturated with water vapour, creating a pressure that is decreasing to some value above the surface. This results in bending down of the electromagnetic waves as illustrated by Figure 13.

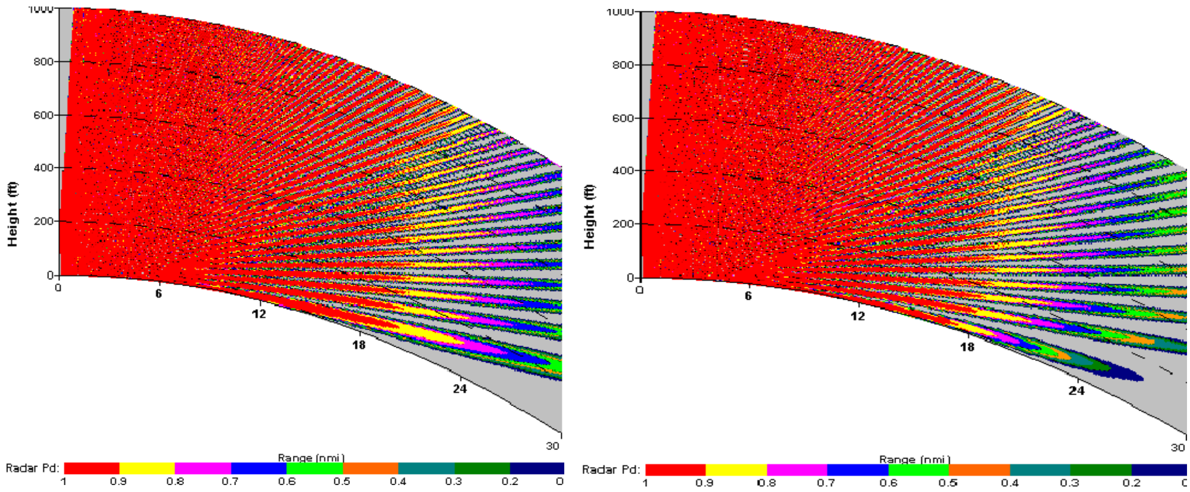

Figure 13 Coverage diagram, in standard atmosphere (left) and including an evaporation duct (right).

This will cause a steep refractivity gradient (trapping) near the surface but will gradually equalize towards normal refractivity gradient at a certain height, which is defined as the evaporation duct height.

Evaporation ducts are generally increasing the radar detection range and the antenna can be located above the duct and still have extended propagation strength. The effect of evaporation ducts is usually more noticeable for higher frequency radars. This means that the radar range extension caused by an evaporation duct will in general, be more noticeable for a X-band radar than for a S-band radar.

For typical coastal radar installations, evaporation duct heights of 6 – 15 metres lead to the longest detection ranges. Evaporation duct heights of more than 10 metres will also introduce an increased amount of clutter, setting additional demands to clutter processing and noise reduction capabilities.

For example, investigations of weather data from the Persian Gulf area shows that evaporation ducts exist all the time with typical duct heights of 5 to 25 metres, resulting in increased radar range in 80% of the time and increased clutter in 50% of the time.

A.10.3.5. Surface-based duct

Surface based ducts can be much stronger than evaporation ducts. They occur when the air aloft is hot (and dry) compared to the air at the Earth's surface. Over the ocean and near land masses, dry continental air may be advected over the cooler water surface; either directly from leeward side of continental land masses or by circulation associated with sea-breeze.

In addition to the temperature inversion, moisture is added to the cool marine air by evaporation, increasing the trapping gradient. In coastal areas, this leads to surface trapping ducts. However, away from land, this trapping layer may well rise from the surface thereby creating an elevated duct.

The electromagnetic wave will be refracted towards the surface of the Earth and be trapped in the duct like in a waveguide. This kind of trapping condition greatly increases the surface detection range – and the amount of noise received. Note that surface detection may occur far beyond the radar horizon with a "dead zone" in between.

Surface based ducts are often combined with evaporation ducts and examples of radar performance in such conditions, as illustrated by Figure 14:

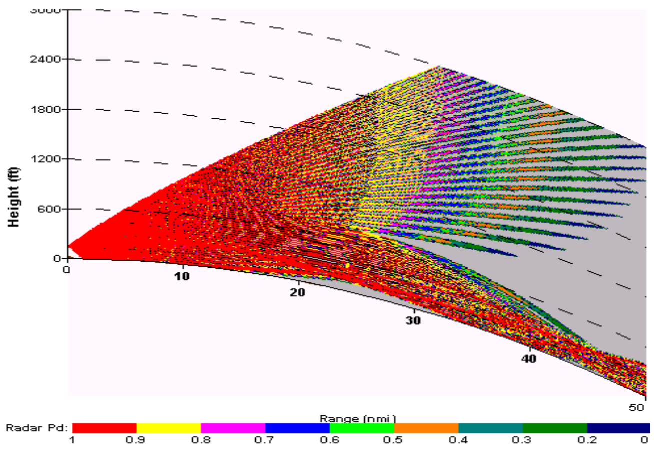

Figure 14 Example of simulated radar coverage in surface based + evaporation ducting conditions

A.10.3.6. Elevated duct

Generally, elevated ducts occur from descending, compressed and thereby heated air, from anticyclones, approaching the marine boundary layer and causing ducts like that simulated in Figure 15. Elevated ducts may also occur from elevating surface-based ducts.

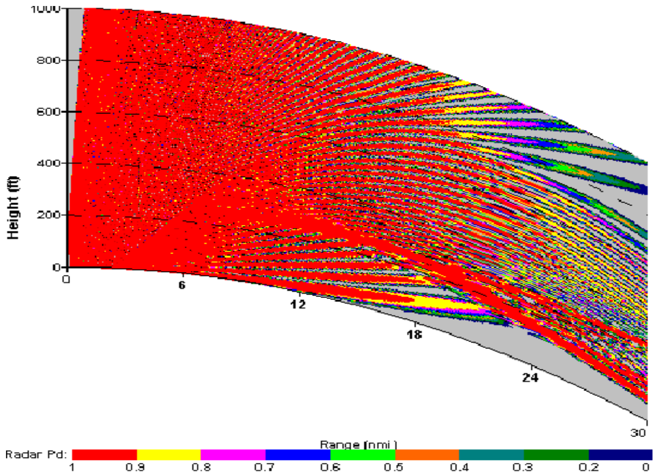

Figure 15 Coverage diagram, elevated duct

Surface detection might also occur in this case, far beyond the radar horizon with a "dead zone" in between, adding noise to the radar image.

A.10.3.7. Severe ducting at coastlines adjacent to hot flat deserts

The large temperature variation between night and day in desert areas and the associated pressure differences between land and sea tend to cause very strong temperature inversion during night-time and result in strong sea breeze in the afternoons. This can result in very severe ducts. This type of duct can be very low, as little as 15 metres has been experienced

Range performance is very different for an antenna positioned inside or above these ducts, and radar systems with an antenna positioned within such a duct will have substantial increase in the detection range for surface targets. If the antenna is positioned above the trapping layer (outside the duct), the electromagnetic wave will be refracted and the detection range for surface targets will be substantially reduced.

Figure 16 shows a coverage diagram based on a measured condition at a coastline adjacent to hot flat deserts - 15 m antenna height (left) and 55 m antenna height (right).

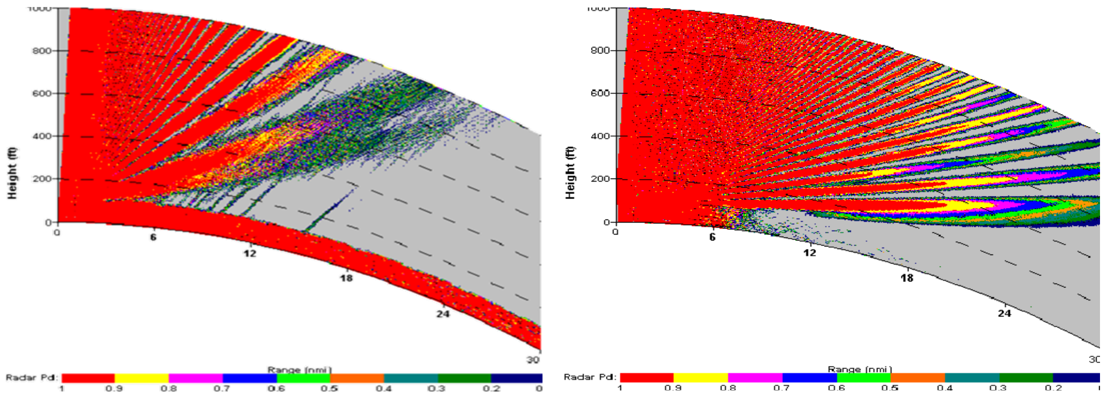

Figure 16 Coverage diagram based on a measured condition

Note. The radar detection using antennas positioned inside the duct (left) and above the duct (right) corresponded to the simulated coverage diagram.

The sea breeze also causes eddies over the sea, forming distinctive sea clutter patterns. The eddy results in a “snake” like pattern moving forth and back for a few hours in the afternoon on hot days with strong sea breezes (see Figure 17). Of course, this may disturb display and tracking.

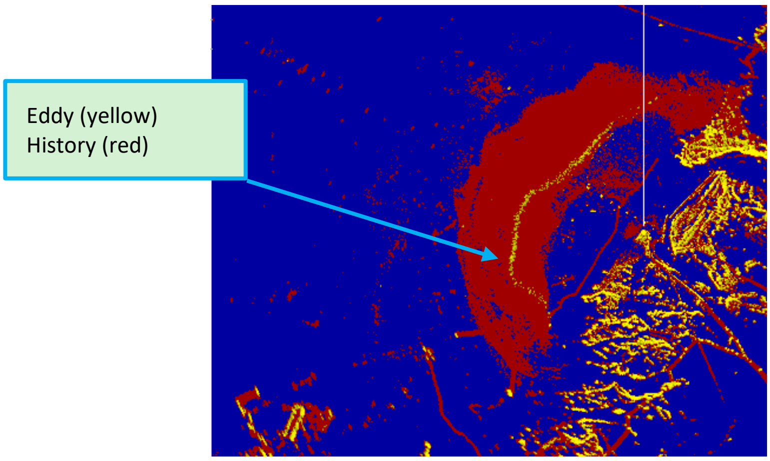

Figure 17 One hour of recordings with trials (snail tracks) shown in red.

Note: The yellow “snake” at sea is an eddy moving back and forth with a speed of approximately 4 knots.

A.11. OTHER INFLUENCING FACTORS

Obstructions, e.g., topography, buildings and other man-made structures may block or reflect radar signals. Other radars and sources of electromagnetic radiation may cause interference.

Depending on the operational area, VTS will often require special considerations as the number of structures, their density and their close ranges can create very complex distortions. Additional care should be taken to assess and mitigate effects caused by natural and man-made structures such as bridges, buildings, riverbanks, sheet metal pilings, and steep bends.

A.11.1. SHADOWING EFFECTS

Radar detection may be blocked by shadowing effects that, to the extent possible, should be avoided. Such effects include:

- Targets being hidden by larger targets or other obstructions.
- Masking of small targets by the effects of range and time side lobes.

These effects can be minimized by the appropriate siting of radars and selection of equipment with low side lobes.

A.11.2. INTERFERENCE

Interference can be split into susceptibility (received interference) and compatibility (transmitted interference).

To minimize interference, separation between wanted and unwanted transmissions has to be optimized – this can be achieved by a combination of frequency separation, physical separation of transmission sites, antenna directionality, sector blanking, separation by time and also by ensuring that all the systems competing for the same or adjacent spectrum do not transmit excessive and unnecessary transmit power levels or transmit time periods. The radar receiver design will typically be very sensitive (to achieve the required performance), although gain control techniques (swept gain or sensitivity-time control (STC)) offers further resistance. Waveform designs incorporating staggered PRFs, and processing schemes designed to reject known interference patterns can also aid the radar receiver to suppress unwanted returns.

A.11.3. RADAR SUSCEPTIBILITY

In the case of any radar installation, (e.g., a permanent VTS installation of a radar or of each radar in a VTS network), the performance of that radar can be detrimentally affected by received emissions from other radiating sources (e.g., physically adjacent VTS radars, maritime shipborne radars, and other users (legitimate or otherwise)) of the electromagnetic spectrum. Typically, local legislative regulations and restrictions will control and minimize unwanted received signals, but elimination of such signals is likely to be impossible. National spectrum allocation authorities should always be approached by a VTS integrator when considering any changes to a VTS network (radar, microwave link, communications etc.) to enable a holistic view of the changes and how they might affect all users.

The radar design can assist in minimising the susceptibility to unwanted received interference, e.g., by utilising low antenna side lobes, avoiding large reflecting surfaces, minimising receiver front end bandwidth etc.

Note that FMCW and pulse compression radars may typically require larger front-end receiver bandwidths than conventional magnetron systems. The multi-pulse waveforms transmitted (and consequently received) by pulse compression radars have to achieve a compromise between pulse chirp bandwidth (related to range cell size and hence range resolution), use of frequency diversity (to optimize performance in clutter), unwanted pulse to pulse interaction and so on versus spectrum usage and hence unwanted susceptibility with other transmitting spectrum users. FMCW radars transmit and receive (at low levels) 100% of the time across a swept bandwidth.

A.11.4. RADAR COMPATIBILITY WITH OTHER USERS

In the case of any radar installation (e.g., a permanent VTS installation of a radar or of each radar in a VTS network), the performance of adjacent systems can be detrimentally affected by transmitted emissions from the radar in question (physically adjacent VTS radars, maritime shipborne radars, and other users (legitimate or otherwise) of the electromagnetic spectrum). Typically, local legislative regulations and restrictions will control and minimize unwanted transmitted signals but elimination of the influence of such signals is likely to be impossible. As with the susceptibility above, National spectrum allocation authorities should always be approached by a VTS integrator when considering any changes to the RF sub- systems within a VTS network.

The radar design can assist in minimising the impact of transmitted signals, for example, by utilising low antenna side lobes, avoiding large reflecting surfaces, minimising transmit power, consideration of peak and mean power levels, sector blanking, physical location of the radar etc.

Note that conventional magnetron radars require larger peak power levels than pulse compression and FMCW radar systems. The magnetron technology can result in unnecessary wideband spectral emissions unless steps are taken to include frequency band pass filtering (which has an inherent loss to the wanted signal). However, pulse compression radars and FMCW radars, although utilising lower peak powers, use techniques which may include frequency modulation, pulse-to-pulse frequency variation, frequency diversity etc., all of which increase the use of the spectrum and increase the chances of unwanted degradation of adjacent systems.

A.11.5. INFLUENCE OF WIND FARMS

Wind turbines produce large static target-like returns which, from a VTS operator's perspective, normally are easy to distinguish from vessel traffic.

Multipath propagation where signals are reflected by objects within the radar coverage, can generate so called ghost echoes as illustrated by Figure 18

To calculate the estimated amount of ghost targets, as well as the ghost targets size in RCS, there are basically three scenarios to consider, which for a wind turbine situation is shown in Figure 19.

The complex return from a wind turbine is made up of two key elements:

- the tower and generator housing offering a large static zero-Doppler RCS, in some cases up to 1 million m^2; and
- the rotating blades of the turbine offering a complex spread of non-zero-Doppler RCS, typically up to 100 m^2, which will vary with wind direction and speed.

This composite return will be seen as a large static target by a conventional pulse radar, whereas FMCW and coherent radars using Doppler processing will see a complex target spread across the Doppler domain.

The influence, independent of the applied radar technology, will be reflections causing unwanted ghost echoes and suppression of nearby targets. The large RCS may also result in antenna side lobe returns, resulting in reduced detectability. The symmetrical layout of wind farms may add further to the disturbance.

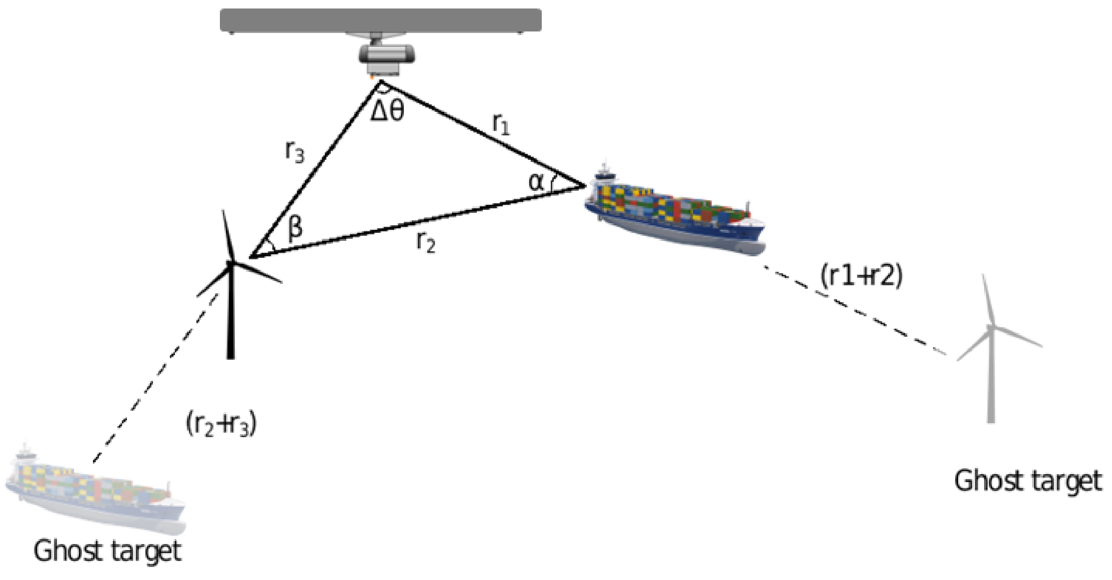

Figure 18 Multipath propagation resulting in Ghost images

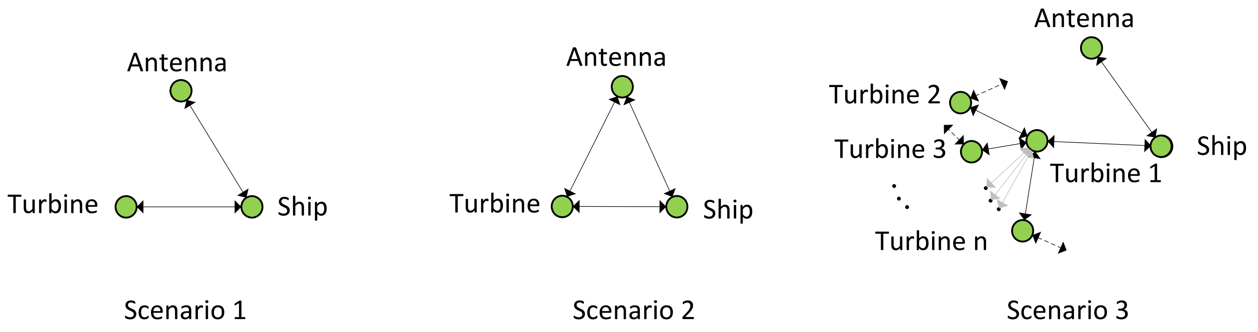

Figure 19 Possible scenarios for ghost target analysis

A.12. SIGNAL PROCESSING AND TRACKING

Modern radars use a variety of signal processing techniques to discriminate targets of interest from noise and clutter, often based on the statistical properties of the signal. This will increase the sensitivity of the radar by allowing for more noise in the incoming signal. In reverse, it will also result in higher dynamic range of the incoming signals setting additional requirements to the receiver. The techniques will often include pulse compression, correlation, and automatic adaptation to the environment.

The tracking functions in VTS will often offer fully automatic target acquisition and functions to correlate with information from other sources i.e., AIS.

Tracking stationary objects or slowly moving surface objects like boats is normal done without Doppler based processing, whereas Doppler based processed video provides enhanced discrimination between moving targets and background clutter for surface targets with radial speeds significantly different from the radial speed of nearby clutter.

The tracker function may be part of the individual radar sensors, hosted as part of the overall VTS system or a combination. Please refer to *G1111-1* for further discussion on the subject.

ANNEX B ACCEPTANCE OF VTS RADAR SYSTEMS

IALA Guideline *G1111-9 Acceptance Framework of VTS System* provide general acceptance steps and key area of consideration related to the acceptance of a VTS system and VTS equipment.

The radar systems could be tested to evaluate the fulfilment of the specific requirement in the agreed requirement in accordance with a test plan and test procedure.

The radar system should be set up in normal operational mode, and its receiver gain may be adjusted to meet the specified false alarm probability requirements.

The meteorological and hydrological conditions significantly impact radar performance. These testing conditions should resemble the agreed requirements for the specific target type and be recorded during the test.

It might also be desirable to verify the availability and include (part off) an annual cycle in the acceptance process and perform fine tuning underway to ensure good long-term operation.

B.1. TEST TARGETS

A qualitative site acceptance performance test for radar systems could be conducted using any of the following three targets:

- Target of opportunity
- Controlled target
- Controlled and calibrated target

The selection of test target(s) depends on the agreed, test requirements, test method, budget, time span and other resources.

B.1.1. TARGET OF OPPORTUNITY

A target of opportunity means a random target navigating at the operational area and maritime constructions (such as buoys, meteorological and hydrological constructions and wind farms). Radar systems cannot identify the target of opportunity; however, AIS information, charts and other resources are typically used to identify the target of opportunity during testing.

The selecting target of opportunity for test target enables to:

- Use real targets for VTS operation
- Use various types of targets
- Test for an extensive period
- Test under different meteorological and hydrological conditions of opportunity

B.1.2. CONTROLLED TARGET

A controlled target means target which is under control to accomplish specific testing. A controlled target should be selected to reflect the RCS specified in the agreed requirements. It is an almost impossible task to judge the RCS of a target by inspection and quantitative measurements. The determination of selected targets can be carried out using IALA target types, see Table 1.

The selecting controlled target for test target enables to:

- Use specific targets of interest which is compatible with the requirements
- Control target to navigate a specified route and move
- Repeat the same test

It is preferable to secure communication between ship to shore to conduct acceptance test smoothly.

B.1.3. CONTROLLED AND CALIBRATED TARGET

A controlled and calibrated target means the controlled target with the required ability to reflect electromagnetic waves, such as a target with RCS of 1 m^2 to 10 m^2 is typically used. The calibration improves the accuracy of the used target RCS.

B.2. LOBING

One of the most common pitfalls during the verification of radar systems is that the echo intensity from a point target can vary drastically with height. As illustrated in Figure 20, the radar signal will reach the target by travelling along different paths of which the most important ones are the direct path and the path where the radar signal has been reflected by the sea surface. The radar signals travelling along the two paths are added to form a resultant signal, a phenomenon known as multipath reflections. At some target heights, the two waves interference constructively, leading to increased signal levels, whereas the waves interference destructively leading to decreased or even vanishing signal levels at other target heights.

As a result, the coverage area exhibits a “lobed” structure where the detection probability alternates between high and low as a function of target height. Hence, if two point-targets of equal RCS are placed at the same distance from the radar, their echoes can differ significantly if their heights happen to be picked such that one is situated in a multipath peak (top left pane) while the other is at a multipath minimum (top right pane). Thus, the appearance of multipath reflections must be accounted for when selecting target heights and positioning the targets.

Multipath reflections are severe at low sea states, elevated heights, and at long ranges. Furthermore, the lobing will depend on atmospheric conditions making range detection tests with point targets, e.g., traditional radar reflectors, very difficult and in practice, impossible to reproduce. The practical solution is to use targets distributed in height, such as small vessels with measured RCS.

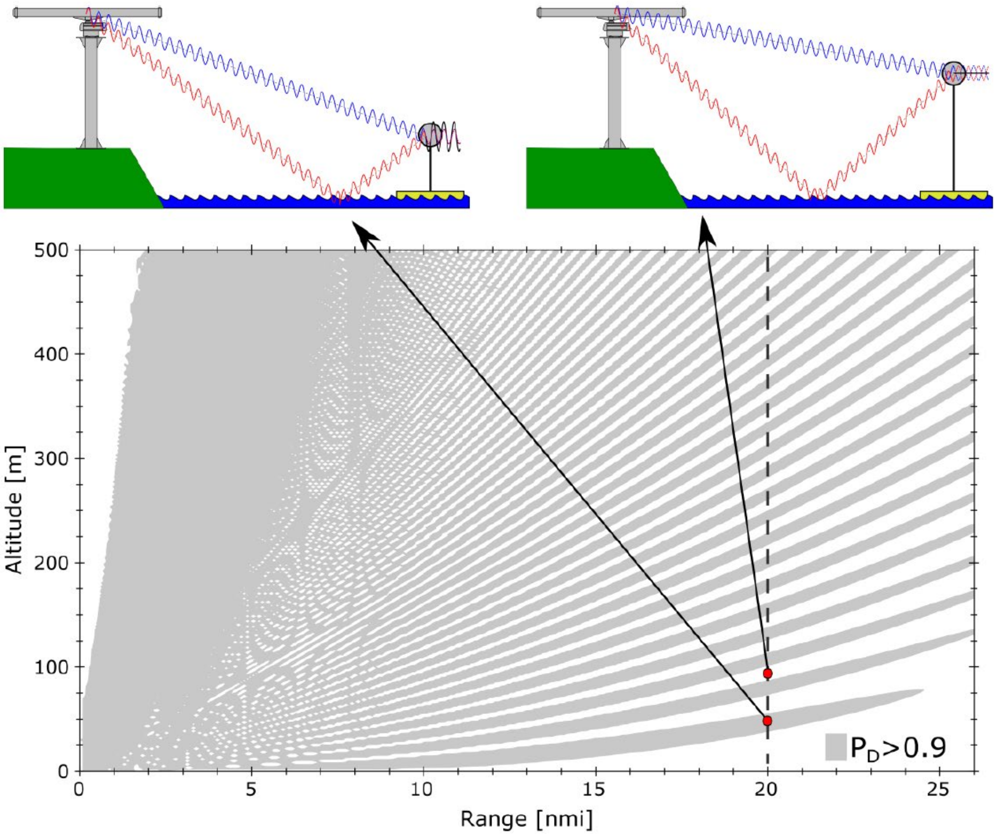

Figure 20 Multi-path reflections (lobing)

B.3. TEST METHODOLOGY

This chapter gives the functional and performance test methodology for VTS radars. However, these methodologies are examples, not a complete list of testing and do not limit the other test methodology. The VTS provider should be select a suitable test methodology considering aspects such as the purpose, importance and budget.

B.3.1. RADAR FUNCTIONS AND OTHER FEATURES

The verification of operator functions, operational outputs and update rate can normally be made as functional tests, whereas verification of clutter and noise reduction functions can be part of the performance testing as outlined below.

B.3.2. CORE RADAR PERFORMANCE

B.3.2.1. Radar coverage

The continuous coverage of the VTS radar can be checked by utilising targets of opportunity which align with the requirement, as illustrated in Figure 21, giving an example of video capture with “snail tracks” lasting several hours and showing uninterrupted vessel traffic within the coverage of a radar sensor.

This test may be complemented using small, controlled targets to determine the maximum range of a target with specific RCS, and also the ability small targets to monitor small targets continuously.

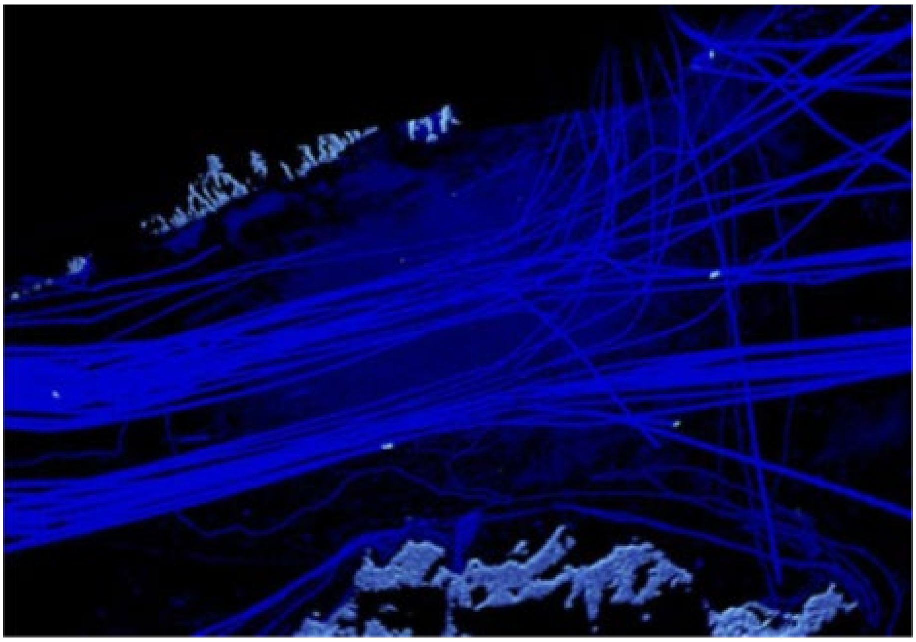

Figure 21 Example of video capture with "snail tracks"

B.3.2.1.1. Testing Minimum detection range

A test target could be selected from:

- A controlled target, which is compatible with the requirement using the IALA target ref. Table 1 or
  - A controlled and calibrated target having as small RCS as possible (<5 m^2) and a low profile.

Test sequence: Observe the radar detection performance on the radar display. The following steps are carried out:

1) Test target should be positioned at least two times beyond the expected minimum detection range
2) Ask the test target to move towards radar site,
3) For each antenna scan, observe whether radar video is detected on the radar screen, and
4) Record the horizontal distance from the boat to the radar station when the radar echo is lost.
5) Repeat the same test several times to find the average value, the minimum detection range.

B.3.2.1.2. Testing Maximum detection range

A test target could be selected from:

- a controlled target, which is compatible with the requirement using the IALA target ref. Table 1; or
- a controlled and calibrated target.

The test trajectory can be in a radial direction along the free line of sight and extending from close to the radar to at least 10% beyond the expected detection range. An example of such a trajectory is shown in Figure 22. This includes that the test target can be asked to perform a manoeuvre, like sailing along a large circle, after traversing a certain distance. The manoeuvre shown enables identifying the controlled target in the radar video, and it shows the radar echo as a function of aspect angles.

Test sequence: Observe the radar performance from the radar display and establish tracking of the test target. The following steps are then carried out:

1) Ask the controlled target to move along the predetermined test trajectory, including the manoeuvres repeated every 1-2 NM

2) For each antenna scan, observe whether the target is visible and/or tracked in the radar video. Record the result

3) Re-establish tracking if target tracking is lost, e.g., as a result of increased clutter levels, shadowing effects due to large ship, or similar

4) Continue the test until target tracking is permanently lost, and until video plots of the test targets are seen in less than 3 out of 10 antenna scans

5) Repeat the test with the target sailing inbound

Maximum detection range is normally determined by the range the target is seen in, e.g., 8 out of 10 scans.

The maximum detection range can be determined by the test target proceeding to the radar station. When the echo of this target is almost disappeared on the radar screen, the horizontal distance from the boat to the radar station should be measured by the radar.

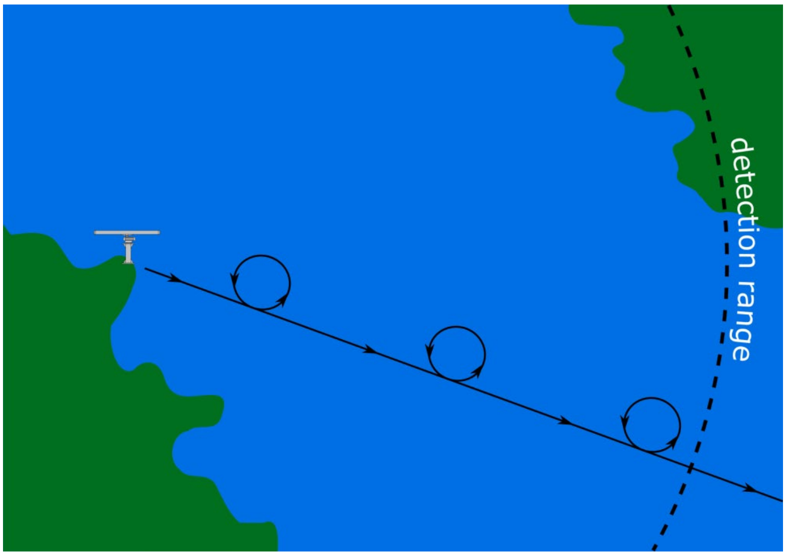

Figure 22 Example of a test trajectory for range detection testing

B.3.2.1.3. Test during given weather situations

Naturally, the weather plays a significant role in target detection, and conditions during testing should preferably resemble those described for the specific target type in requirements. However, tests are often determined and planned for a certain period (of the year), implying that the test is forced to be carried out under the actual weather conditions at the given time. In this situation, the test results can be used to benchmark simulation tools which then can be used to predict range detection performance under the specified weather conditions using the calculation formulas in ANNEX A

Before any testing, ensure that the targets used meets the requirements and that the radar is in normal operational mode with the receiver gain adjusted to meet the specified false alarm probability requirements.

Weather information should be recorded at the beginning and during the test activities.

B.3.2.2. Target separation

Verification of target separation aims to determine the minimum distance, in range and bearing, where a clear separation between the returns from two small, close targets is obtained.

As the distance between the two targets must be changed during testing, at least one of the targets must be moveable. It can be cumbersome to perform the test at sea, as it requires floating, non-reflecting supports for the test targets, which must be moved relative to each other on the sea surface. Furthermore, the test should not be performed in higher sea states than two (2).

If geographical conditions allow, a much easier and valid approach is to perform the test on land, e.g., at a beach or flat paved area, thus providing much better control of the positioning of the reflectors.

Note: One of the controlled targets can in some cases, be substituted for the target of opportunity, which may be a well-known resilient maritime construction.

B.3.2.2.1. Range separation

B.3.2.2.1.1. Test using controlled targets

Two controlled targets specified in the agreed requirement or test procedure could be selected for the test target to test range separation.

Test sequence: Observe the range separation performance on the radar display as illustrated by Figure 23. The following steps could be carried out:

1) One controlled target is placed to keep the same position. The other controlled target approaches towards the other target at the same bearing and with clear separation. (Speed is preferably less than 10 knots). The distance between the two targets along the range direction should give a clear separation of the targets.

2) Record the minimum distance where the two targets can be seen as two separate targets on the radar display.

3) As an option, the distance can be measured using measurement equipment on-site (e.g., laser range finder).

B.3.2.2.1.2. Test using a controlled and calibrated target

Test sequence: Observe the range separation performance on the radar display. The following steps are carried out:

1) The two reflectors are placed in the test area at the same bearing and with clear separation. One reflector is kept fixed throughout the test.

2) Record the minimum distance where the two reflectors can be seen as two separate targets.

The test is passed if the recorded distance is less than the range separation required.

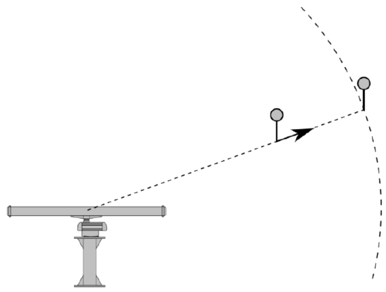

Figure 23 Measurement of range separation

B.3.2.2.2. Angular separation

B.3.2.2.2.1. Test using controlled targets

Two controlled targets specified in the agreed requirement or test procedure could be selected for the test target to test angular separation.

Test sequence: Observe the angular separation performance on the radar display. The following steps could be carried out:

1) One controlled target is placed to keep the same position. The other controlled target approaches towards the other target at the same radial and with clear separation. (Speed is preferably less than 10

knots). The distance between the two targets along the azimuthal direction should give a clear separation of the targets.

2) Record the minimum distance where the two targets can be seen as two separate targets on the radar display.

3) As an option, the distance can be measured using measurement equipment on-site (e.g., laser range finder).

B.3.2.2.2.2. Test using a controlled and calibrated target

Test sequence:

1) The two reflectors are placed in the test area at the same radial distance beyond 1 NM from the radar (to ensure the reflectors are placed in the far field region of the antenna). The distance between the two reflectors along the azimuthal direction should give a clear separation of the targets. One reflector is kept fixed throughout the test.

3) Record the angle in the bearing where the two reflectors can be seen as two separate targets.

The test is passed if the recorded distance is less than the azimuth separation stated in the requirements.

B.3.2.3. Target positional accuracy

Measurement of the target positional error is a combination of the trueness (systematic error) as well as the precision (random error), ref annex A.7

If possible, the measurement should be done with fixed targets of opportunity. The optimum is to use the centre/leading edge of physically small structures with known positions.

It is recommended to verify the maximum target position errors utilising at least two reference targets at known positions. It is normally sufficient to measure at one or two points in the distance.

The determination of errors can be precisely determined by making a high number of observations and calculating as follows.

B.3.2.3.1. Range accuracy

Testing method: Stationary targets should be selected. The distance of the target measured by high-precision locator (Its accuracy is at least one order of magnitude higher than radar’s accuracy) is taken as the true value. Compared that with the distance measured by radar. The range error of stationary and moving targets can be determined separately according to the following formula

（1）The range trueness (systematic error) is:

$$A_r = \frac{1}{n}\sum_{1}^{n}(R_i - R_t)$$

R_i—radar range observation value.

R_t—range observation value of high precision locator (true value).

n—number of observations, $n \geq 20$.

（2）The range precision error (random error) is:

$$\sigma_r = [\frac{1}{n-1}\sum_{1}^{n}(R_i - R_t - A_r)^2]^{\frac{1}{2}}$$

（3）The root mean square error of range is

$$m_R = [\frac{1}{n}\sum_{1}^{n}(R_i - R_t)^2]^{\frac{1}{2}}$$

（4）The Maximum (sigma 3) range error is

$$E_{Rmax} = |A_r| + 3\sigma_r$$

B.3.2.3.2. Bearing accuracy

Testing method: Stationary targets should be selected. The bearing of the target measured by high-precision locator (Its accuracy is at least one order of magnitude higher than radar's accuracy) is taken as the true value. Compared that with the bearing measured by radar. The bearing error of stationary and moving targets can be determined separately according to the following formula.

（1）The bearing trueness (systematic error) is:

$$A_a = \frac{1}{n}\sum_{1}^{n}(a_i - a_t)$$

a_i—radar bearing observation value.

a_t—bearing observation value of high precision locator (true value).

n—number of observations, n≥20.

（2）The bearing precision error (random error) is:

$$\sigma_a = [\frac{1}{n-1}\sum_{1}^{n}(a_i - a_t - a_r)^2]^{\frac{1}{2}}$$

（3）The root mean square error of bearing is

$$m_a = [\frac{1}{n}\sum_{1}^{n}(a_i - a_t)^2]^{\frac{1}{2}}$$

（4）The Maximum (sigma 3) bearing error is

$$E_{amax} = |A_a| + 3\sigma_a$$

B.3.3. RADAR PERFORMANCE VERSUS THE DYNAMIC ENVIRONMENT

The verification of performance versus the dynamic environment may be based on observations of the radar screen by experienced operators.

The magnitude of false echoes due to multipath or sidelobes can often be measured in the video and it is thereby possible to evaluate if specifications are met.

Evaluation of noise and clutter behaviour, including rain suppression and sea clutter suppression, is normally indirect by checking if targets of known size can be detected in clutter as specified.

B.3.3.1. Dynamic range

It may only be possible to measure the dynamic range of radar in a laboratory environment. On-site calculation using targets of opportunity and evaluating the display of returns from the largest nearby objects and the smallest distant objects may be used, but this method tends to be subjective.

A qualitative on-site evaluation can be carried out utilizing traffic of opportunity, possibly combined with the verification of continuous coverage, ref B.3.2.1.

Test sequence: Ensue that set up of the radar is correct and observe the radar performance from the radar display. The following steps are then carried out:

1. Check that small distant targets are detected as specified.
2. Evaluate the appearance of large objects within the area and check for malfunctions. The typical malfunctions in case of insufficient dynamic range includes the loss of small targets near larger ones, time sidelobes due to saturation of receivers and/or longitudinal stretch of large targets due to saturation.
3. Repeat same test in different angle and distance.

B.3.4. TARGET TRACKING

Refer to IALA *G1111-1* for guidance on the subject.

ANNEX C TEST TARGETS AND THEIR CALIBRATION

Test targets also referred to as controlled target, is assumed to be small vessel which are typical for a test of VTS systems.

The RCS of the test targets are needed to obtain quantitative and reproducible results during testing of range performance, and it is necessary to calibrate the RCS of the test targets against a known reference reflector.

A prerequisite for performing RCS calibration is, furthermore, that the radar receiver characteristics is known, or more specifically, that the relationship between the received power and the output video level is known. If not, the characteristics must first be mapped out.

The calibration procedure must be performed in calm weather with a low sea state, and a well-known reference reflector must be at hand. An example of a reliable reference reflector is a calibrated Luneberg reflector mounted on a floating support as shown in Figure 24. It is important that the height of the reference reflector resembles that of the test target to be calibrated. If not, the measurements can be influenced by lobing as discussed in section 0, which leads to erroneous RCS estimates for the test targets.

Figure 24 Luneberg reflectors

Note that the RCS of the individual target is dependent on the radar frequency in use.

Calibration sequence:

The controlled target and the reference reflector should be placed within 2 NM from the radar sensor and preferably within 0.5 to 1 NM. Moreover, the targets should be positioned within free line of sight of the radar sensor and away from objects yielding intense radar echoes.

With the reference target on board, the controlled target is positioned in the test area where the following steps are carried out:

1) The reference reflector is placed in the water on its floating support.

2) The controlled target moves away from the reflector until the two targets are clearly separated on the radar display.

3) The radar gain is adjusted to obtain a clear picture of the test area with the test and reference targets clearly visible and stable in the water, both in azimuth and range. Make sure that any automatic gain adjustment is disabled such that the gain will remain constant throughout the calibration procedure.

4) Record the intensity of the reference target echo during at least 30 consecutive scans. Convert all recorded intensities to received power levels using the receiver characteristics. Calculate the average value and variance of the received echo power.

5) The controlled target is then positioned with its stern pointing in the direction of the radar, see Figure 25.

6) Record the intensity of the controlled target echo during at least 30 consecutive scans. Convert all recorded intensities to received power levels using the receiver characteristics. Convert the received power, to an RCS value. Calculate the average value and variance of the measured RCS.

7) The controlled target changes its orientation in steps of 45 degrees, and after each orientation change, the measurement in 6) is repeated. The last measurement is performed with the controlled target seen from the astern.

8) Let the controlled target move in a circle centred at the reference target and with a radius of approximately 100 metres. In each scan, record the intensity of the controlled target echo. Convert all recorded intensities to received power levels using the receiver characteristics and further to RCS values. Calculate the average value and variance of the measured RCS.

The RCS of the target has now been measured for several different orientations (step 6 and 7), and in addition, a value for the overall RCS (the RCS averaged over all orientations) has been obtained in step 8.

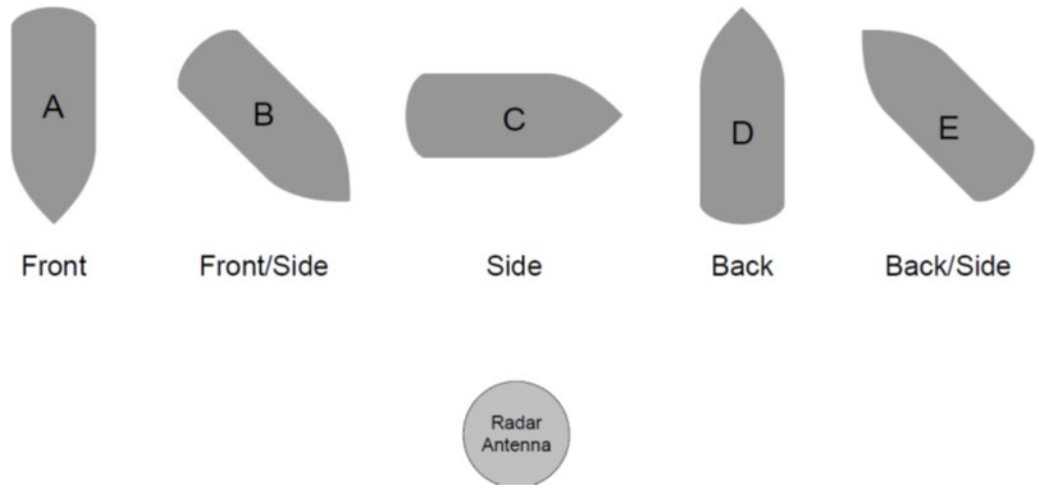

Figure 25 Target aspect angle relative to the radar antenna