Cobham Technical Services
ERA Technology
Cleeve Road, Leatherhead
Surrey, KT22 7SA, England

T: +44 (0) 1372 367000
F: +44 (0) 1372 367099

Business Unit:	Cobham Technical Services ERA Technology RF & EMC Group
Report Title:	Potential Impact of Out-of-Band Emissions from the 2.6 GHz Auction on S-band Maritime Radar
Author(s):	M Ganley and Z Wang
Client:	MCA
Client Reference:	Richard Rees
Report Number:	2009-0258
Project Number:	7G0519501
Report Version:	Final Report

Report Checked and Approved by:

Stephen Munday
Principal Consultant

June 2009

Ref. MG/vs/62/05195/Rep-6448

ERA Technology **is now trading as** ***Cobham Technical Services***

ERA Technology Limited trading as Cobham Technical Services
Cleeve Road
Leatherhead
Surrey KT22 7SA, England
Tel : +44 (0) 1372 367000
Fax: +44 (0) 1372 367099
E-mail: era.info@cobham.com

Read more about Cobham Technical Services on our Internet page at:
www.cobham.com/technicalservices

Executive Summary

Due to the development of new communications systems in the 2500 to 2690 MHz band, there is the possibility of degradation in target detection capability of maritime S-band radars in the 2900 to 3100 MHz band. This is because of the radar receiver's sensitivity to emissions in the 2500 to 2690 MHz band. There may also be relevance to devices operating in the 3400 to 3600 MHz band. For this band, only fixed wireless access services in 3480 MHz to 3500 MHz have been considered for estimating separation distances.

This report details testing of a magnetron maritime radar to determine its sensitivity to out-of-band emissions, which are then used to estimate required separation distances. The methodology used is similar to that for previous testing of interference to maritime radar operation for Ofcom [1].

Testing was performed on a magnetron S-band maritime radar in a laboratory. The radar targets were generated using a radar target generator and the interference using signal generators. The test used the conducted method of injecting the radar target signals and interference into the radar antenna port.

Two interference mechanisms were investigated, the communications system channel power saturating amplifiers in the radar receiver chain and out-of-band (OOB) emissions falling into the radar IF pass band. An additional filter was used to reduce the OOB emission levels to help identify the dominant interference mechanism in each case.

Discussions held with radar manufacturers indicated that the sensitivity of other mobile magnetron radars are likely to be similar. These results may also be indicative of Vessel Traffic Services (VTS) port radars as they are similar in design. Some solid-state radars have started to emerge on the market but there is no measurement data available on the sensitivity of these radars to interference below 2690 MHz and above 3400 MHz. One of the sold-state radar manufacturers has suggested that, as a first-pass assumption, the sensitivity of the Watchman radar is used as there are significant similarities in the design of both.

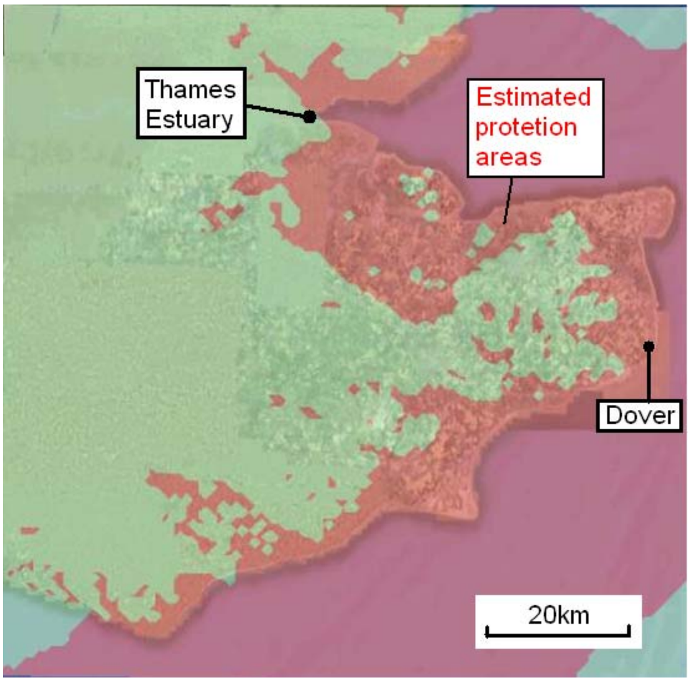
The measured magnetron radar sensitivity data and estimated solid-state radar sensitivity have been used to estimate required protection distances. For mobile ship radar, the two main scenarios considered were mainbeam-to-mainbeam interference and mainbeam-to-sidelobe interference where an antenna coupling loss of 20 dB has been used. In both cases, all of the propagation is considered to be over sea. For VTS radar, mainbeam-to-sidelobe was considered as the main practical scenario.

For proposed communications services in the band 2500 MHz to 2690 MHz, assuming worst-case mainbeam-to-mainbeam antenna coupling, the required separation distances for magnetron radar appear to be below 2 km for both amplifier saturation and OOB emissions falling in the radar IF pass band. For solid-state radar, the required separation distances appear to be below 2 km for OOB emissions falling in the radar IF pass band, but about 15 km for amplifier saturation.

For existing communications services in the band 3480 MHz to 3500 MHz, assuming worst-case mainbeam-to-mainbeam antenna coupling, the required separation distances for magnetron radar are estimated to be about 9 km for amplifier saturation and about 60 km to 70 km for OOB emissions falling in the radar IF pass band. For solid-state radar, the required separation distances appear to be less than 2 km for amplifier saturation, but about 60 km to 70 km for OOB emissions falling in the radar IF pass band.

For VTS radar, only mainbeam-to-sidelobe interference is considered and all of the interference is over land. The only scenario that results in estimated separation distances in excess of 1 km are OOB emissions from existing services in the band 3480 MHz to 3500 MHz (~6 km).

The main protection distance calculations do not include terrain effects, as they are generic and have assumed a flat terrain. Some example simulations including terrain effects were included by considering the location of the main shipping routes in the English Channel. The figure below shows the estimated protection areas from OOB emissions from existing services in the band 3480 MHz to 3500 MHz to ship magnetron radar for example.



In addition to considering terrain effects, a number of other mitigations might reduce the size of the required protection areas. For OOB emissions falling into the radar IF pass band of either magnetron or solid-state radar, there might be more transmitter antenna gain reduction at the radar operating frequencies in addition to the 2 dB assumed. The actual OOB emissions may be below the regulatory limits. The solid-state radar may not be as sensitive to interference as the first-pass assumption advised by the radar manufacturer.

The potential low probability of achieving mainbeam-to-mainbeam interference might also provide some mitigation although this would need further justification. If mainbeam-to-sidelobe interference could be considered the appropriate mechanism then estimated separation distances for all ship radar scenarios would be below about 7 km assuming flat terrain, and less if terrain was taken into account.

If after considering the potential mitigations listed above the protection distances are too large, front-end radar filtering should be able to provide a significant enough reduction in the sensitivity of the radar to amplifier saturation. Although this might prove a practical mitigation in the case of solid-state radar where very small numbers of radars are in operation, the logistics of doing this for magnetron radar would be somewhat more complicated. If required, in order to reduce the effect of OOB emissions in the radar IF pass band, further filtering and better antenna design of communications systems could prove effective.

This page is intentionally left blank

Contents

Tables List

Page No.

Figures List

Page No.

Abbreviations List

AWGN	Additive White Gaussian Noise
TRPC	Theoretical Radar Protection Criteria
FTC	Fast Time Constant
IF	Intermediate Frequency
IR	Interference Rejection
LNA	Low Noise Amplifier
PRF	Pulse Repetition Frequency
PPI	Plan Position Indicator
PRI	Pulse Repetition Interval
PSSTG	Public Spectrum Safety Test Group
RF	Radio Frequency
RPC	Radar Protection Criteria
STC	Sensitivity Time Control
WiMAX	Worldwide Interoperability for Microwave Access
Pd	Probability of Detection
VTS	Vessel Traffic Services
AIS	Automatic Identification System
Pfa	Probability of False Alarms

1. Introduction

Due to the development of new communications systems in the 2500 to 2690 MHz band, there is the possibility of degradation in target detection capability of maritime S-band radars in the 2900 to 3100 MHz band. This is because of the radar receiver's sensitivity to emissions in the 2500 to 2690 MHz band. There may also be relevance to systems operating in the 3400 to 3600 MHz band. These radars cover both mobile ship radars and Vessel Traffic Services (VTS) radars at ports.

This report details testing of a magnetron maritime radar to determine its sensitivity to out-of-band emissions. The methodology used is similar to that for previous testing of interference to maritime radar operation for Ofcom [1]. Conducted measurements were performed on a S-band magnetron maritime radar in the laboratory at Cobham (ERA) by injecting the target signals and interference in the antenna port of the radar with the radar operating at a frequency of 3.05 GHz. The interference covers the frequency bands 2500 to 2690 MHz and 3400 to 3600 MHz, and uses CW, AWGN and WiMAX.

Some commentary is also provided on the likely similarity in performance of the magnetron radar tested to magnetron radar's from other manufacturers. Discussions with a solid-state maritime radar manufacturer have identified a first-pass assumption of radar sensitivity for solid-state S-band maritime radars.

The measured and estimated radar sensitivity data has been used to provide estimated separation distances.

2. Radar Configuration and Test Methodology

2.1 Maritime Radar Parameter Settings

At present the transmitter technology used in the majority of maritime radars is the magnetron although others are types such as solid-state radar are appearing. Through discussions with manufacturers, it has been identified that for existing magnetron maritime radar the antenna, rotating joint, and post-detector processing are very company specific. The vast majority of the RF and IF processing are generally provided by just two companies, either NJRC or E2V. It is thought that the NJRC and E2V designs are very similar.

It has been assumed that VTS radars are very similar to the mobile ship magnetron radars except for more sophisticated video and data post processing, and perhaps slightly higher gain antennas.

There are two possible interference mechanisms, the interferer channel power saturating amplifiers along the radar chain or out-of-band interference falling into the radar IF pass band.

Maritime radars allow the operator significant dynamic control over a number of radar settings. The main parameter's being the gain (threshold), sea clutter and rain clutter controls. These controls allow the relative levels to be set and only qualitative measures of the settings are displayed which differ between radars. The main radar settings used for the testing are shown in Table 1.

Sea clutter and rain clutter controls were set to zero. The gain control was set to determine the probability of false alarms (Pfa). It was intended to set this about 10^{-4} but the actual value was nearer to 10^{-5}. Due to the number of possible variables, not all combinations of parameters could be tested. Previous testing [1] demonstrated that the results for different range settings and night/day settings were very similar and therefore all measurements were made using the 6nm range which allowed both the medium pulse and long pulse modes to be used. The short pulse mode was not used as medium pulse and long pulse allowed the two bandwidth selections to be tested. Short pulse has the same bandwidth selection as medium pulse. Target enhancement was used to make the target detection more objective as discussed in Section 2.4.

Table 1:
Main maritime radar settings

Function	Configuration
Detector	Logarithmic detector
Range scale	6 nm
Pulse widths	Short: 0.05 μs (not used); Medium: 0.25 μs; Long: 0.75 μs
Pulse repetition frequency	Short and Medium: 1750 Hz Long: 750 Hz
IF bandwidth	Short and Medium: 20 MHz Long: 3 MHz
Threshold (Gain)	This will be set at a number of different settings depending on the test
Sea clutter	Set to "off"
Rain clutter	Set to "off"
Sensitivity time control (STC)	Disabled
Fast time constant (FTC)	Disabled (default)
Automatic gain control (AGC)	No automatic gain control, this is done manually
Automatic Frequency Control	Off
Trails	Off
ENH(ance)	On
Image selected	Raw video
Interference Rejection	On (default)
Beamwidth	1.3 degrees (used for gating targets and interference)
Antenna scan rate	30 rpm for medium pulse, 12 rpm for long pulse
Up mast/down mast design	Up mast system
False Alarm Rate	This will vary with the range of threshold settings tested. A light background of 1 to 3 speckles is equivalent to a Pfa of about 10^{-5}. This was reported as 10^{-4} in ref [1].

2.2 Target Generation

In order to generate targets the test configuration in Figure 1 was used, which is the same as the previous maritime proof-of-concept testing [1]. The radar receiver tuning can either be set to "manual" or "automatic frequency control". The latter requires a simulated leakage signal from the expected magnetron transmitter burst (the "main bang leakage"). A modification was made to the radar which improved the stability of the manual tuning. This removed the requirement to generate a "main bang leakage" pulse needed for the automatic tuning. This was done to further improve the configuration as in some cases the main bang leakage created by a signal generator reduced the sensitivity of the radar.

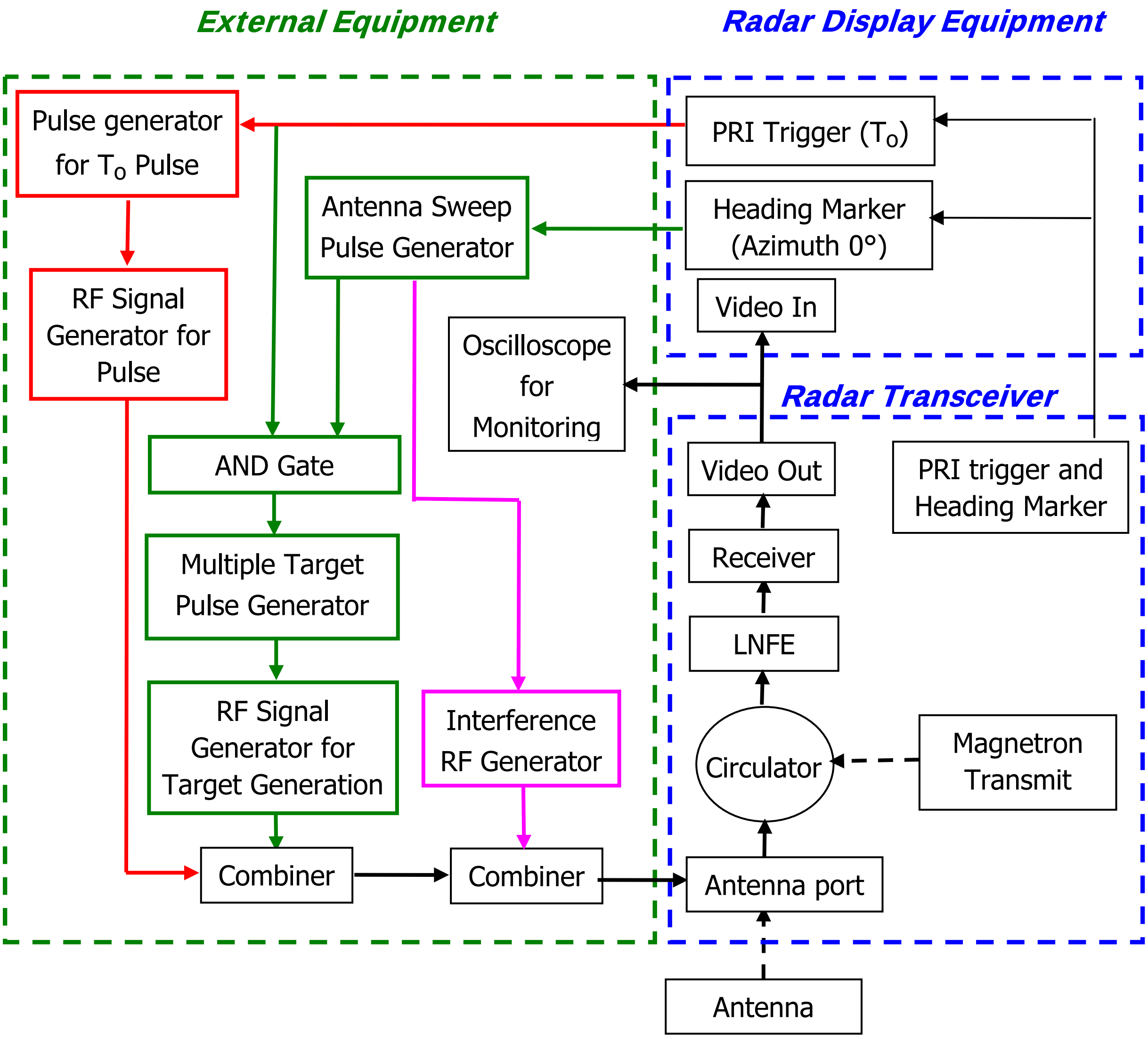


Figure 1: Injection of interference and targets

The method for injecting the targets has been developed in coordination with the radar manufacturers. In order to inject targets from a target generator the following tasks were performed:

- Disable the transmission and rotation of the radar
- Generate pseudo rotational information
- Trigger output from the radar to start the external target generation process
- Generation process
    - Main bang leakage (T_0 Pulse) – for automatic tuning only
    - Target generation

The radar transmission has to be disabled in order to allow the safe injection of targets and interference signals. The rotating joint is also prevented from rotating to make the RF connections from the signal generators simpler, and allowing the injection to occur as close to the base of the radar antenna as possible. The radar target signals and interference were injected directly into the radar antenna port.

The timing and generation of the radar target pulses were created using external pulse generators, as highlighted in green in Figure 1. The radar heading marker was used to synchronise the targets so that they are in the same azimuth direction for every rotation. This heading marker is used to trigger a pulse generator to create a rectangular pulse, equivalent to the time taken for the antenna beamwidth to sweep past a fixed target. This method gates the targets to simulate the affect of an antenna sweeping past the targets.

Due to the time constraints only a simple antenna gating method based on a rectangular window was used. For example, for a medium pulse of 250 ns and a sweep time of 2.4 s a 10 ms gating window was used to create a rectangular antenna pattern with an equivalent beam width of 1.5°. An example of the antenna sweep timing and gating is shown in Figure 2. This shows the on time of the gating for each antenna rotation and the individual target triggers within the antenna gating for medium pulse mode.

Ten equally spaced targets were created and placed outside of the Sensitivity Time Control (STC) region. These targets were synchronised using the output trigger of the 'AND' gate. An initial delay of 13.7 μs followed by ten targets equally spaced by 6.7 μs was generated (see Figure 2). The output of the pulse generator was then used as an input to an RF signal generator to create the up-converted signals at the radar operating frequency of 3.05 GHz. This process is demonstrated in Figure 3.

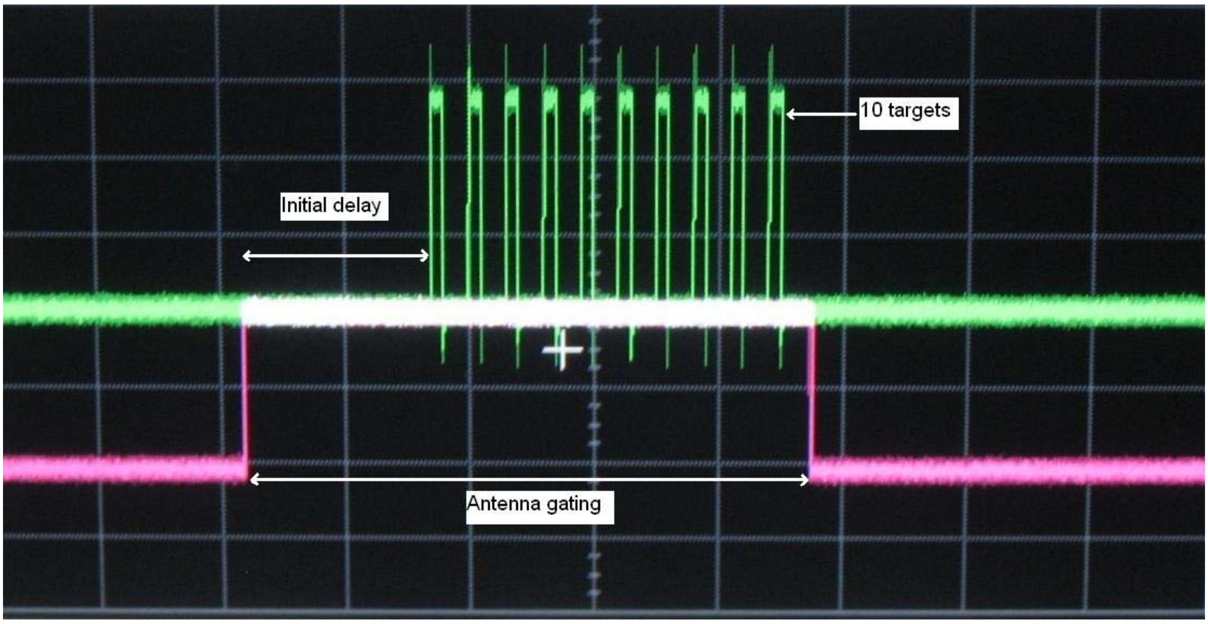


Figure 2: Antenna sweep timing and gating with 10 individual targets

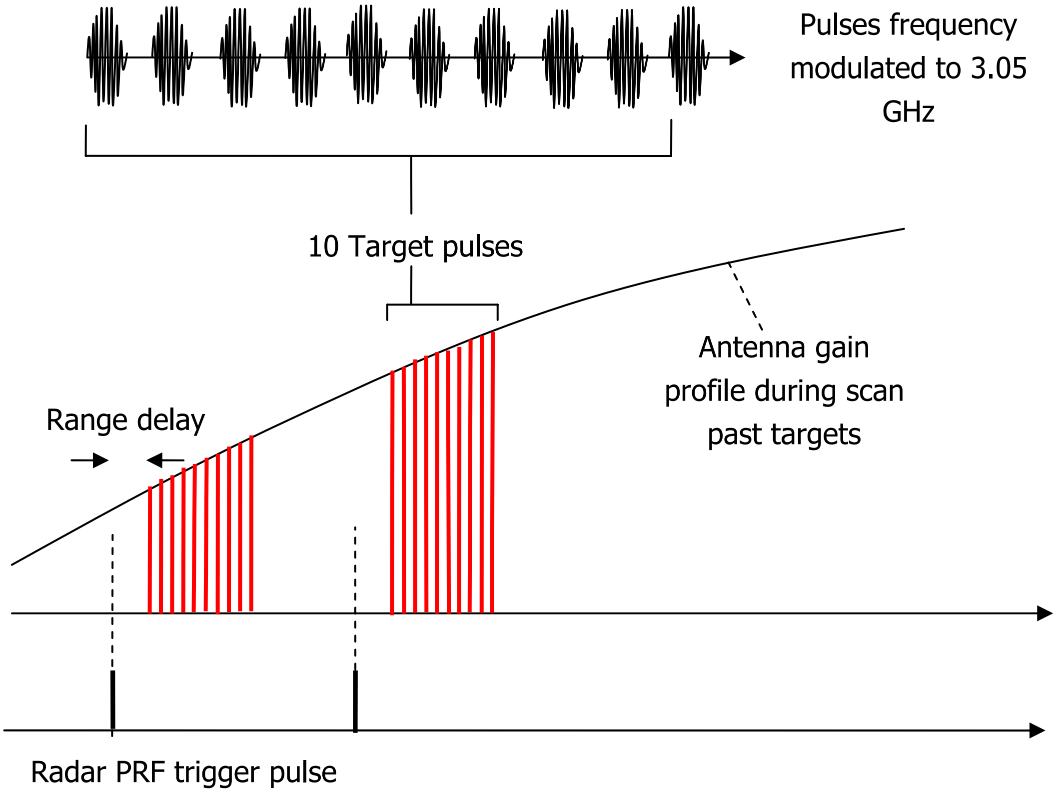
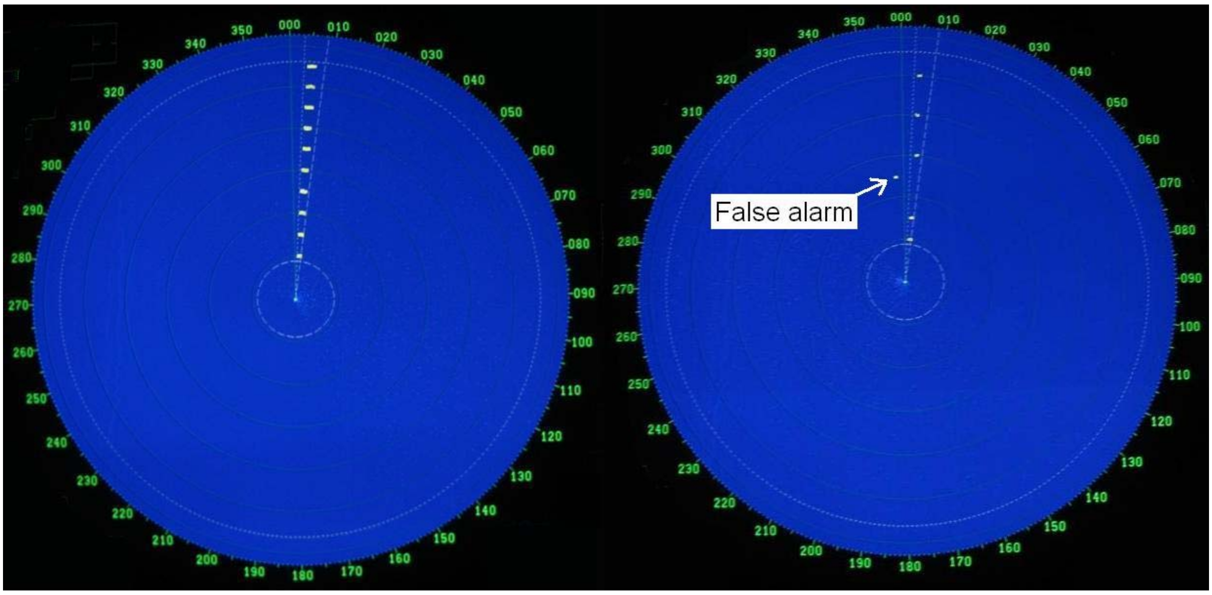


Figure 3: Synchronising the targets with reference to the radar trigger pulse

The resulting targets appearing on the radar PPI display are shown in Figure 4 for a Pd of 100 % and 50 %.



Pd 100%

Pd 50%

Figure 4: Example of a Pd of 100% and 50% for 10 targets on 6nm range with medium pulse and the enhance threshold on

2.3 Target Placement

As proposed by in the Parameter Study [3] the target placement for the main testing was done outside of the clutter region, and therefore outside of the region where any attenuation is applied, e.g. Fast Time Constant (FTC).

Multiple targets can be placed in a number of ways as shown in Figure 5. The targets can be placed along a constant azimuth radial, with each target progressively located at a further range. The targets can be placed at a constant range with a number of targets appearing at different azimuth directions. Alternatively, targets can be placed on a number of radials. However, as noted in an NTIA report [2], it was found to be easier to count a number of radially distributed targets rather than a number of targets at the same range, but with different azimuth directions. Therefore, a number of targets on one radial were used for the testing.

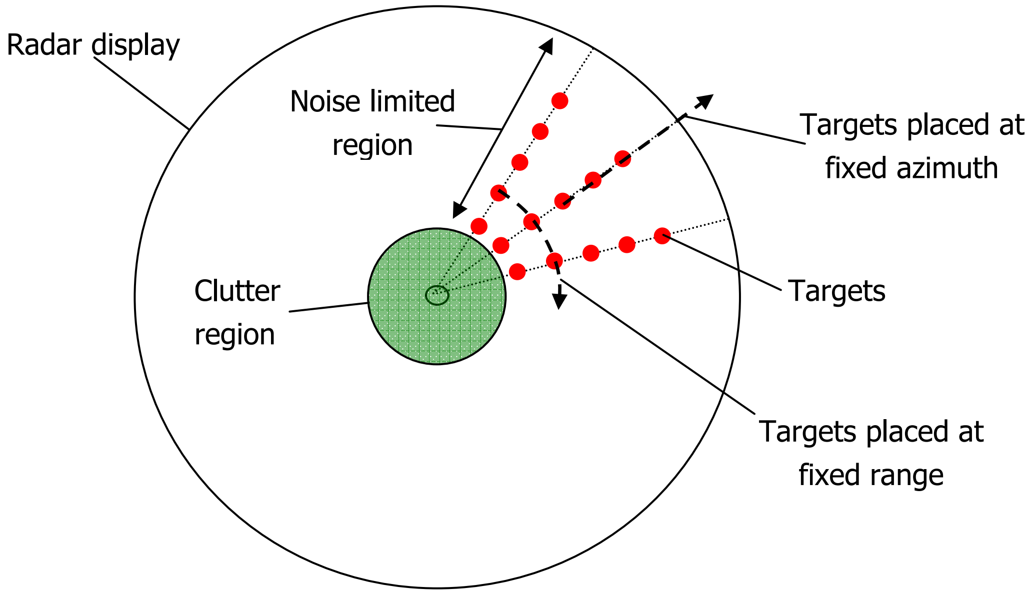


Figure 5: Target placement

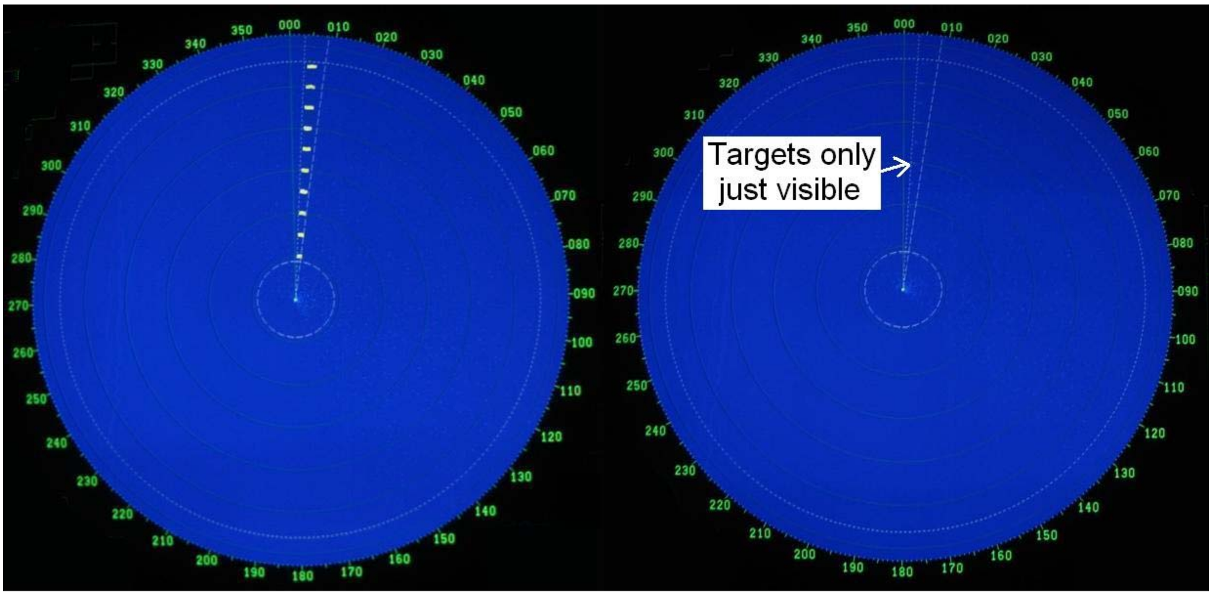
Ten targets were configured to appear along a radial at the following ranges: 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5 nm. As with previous testing [2] it was found that 10 targets was a sensible balance between maximising the number of targets on each sweep, and hence reducing the test time, and the maximum number of targets that can accurately be counted on each sweep.

The majority of the tests were performed for a base-line target Probability of Detection (Pd) of 90%, irrespective of the target location. However, some additional tests were also made for a baseline Pd of 60 %. The Pd of all of the targets was the same and was not reduced with range. This also allows a more efficient method of assessing the probability of detection as a number of identical targets can be counted with each scan and included in the same statistical calculation of Pd.

2.4 Target Detection

The parameter used for the assessment of the radar performance was the target probability of detection (Pd). This was achieved by counting the number of targets visible over a period of time, compared to the total number of targets used. The number of targets generated for each rotation was 10, and with for example 50 antenna rotations, a total of 500 targets were present over this period. If the total number of target detections counted over this period were to be 250 for example, then the resulting probability of detection would be 250 divided by 500 equalling a Pd of 50 %.

Target detection can be a very subjective matter and could require very large amounts of testing with a number of different operators to properly consider the issue of human factors [1]. However, the previous maritime proof-of-concept testing [1] developed a more objective and repeatable method. This was achieved by modifying one of the radar circuit boards and using an automatic detection threshold which enhances any signals above this threshold level. This made the transition from no target to a clear target a much more cliff-edge effect, making the target detection more objective. Figure 6 shows the same level of input target signal with and without the enhance processing.



Modified enhance threshold ON Modified enhance threshold OFF

Figure 6: With and without the enhance threshold for the same target signal strength

The number of antenna rotations required has been discussed in the previous work [1] and for this testing, 50 target rotations were used for each assessment. The radar target properties used are the same as for the previous maritime testing [1]:

- Non-interference Pd of 90 % and 60 %
- Swerling 0 targets
- Targets in noise-limited region

Additional radar settings for the purpose of these conductive OOB interference tests include:

- Sea clutter set to off[1]
- Enhanced target detection set to be on (see Figure 6)

The target non-interference Pd level was set by controlling the target generator output level. The position of the targets was set by the timing of the target bursts. The radar target generator specification used for the testing is shown Table 2.

Table 2:
Specification for the radar target generator

Requirement	Specification for these tests
Target fluctuation	Swerling 0 (no fluctuation)
Non-interference Pd	90 % and 60 % (limited tests)
Radar range	6 nm
Target placement (in noise limited region)	1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5 nm
Multiple targets	10 targets along a single radial
Target movement (to avoid being removed by clutter algorithms)	Not required

2.5 Pd Degradation and Run Times

The Parameter Study [3] proposed a practical degradation in the probability of detection (Pd) which can be measured of 5 %. The accuracy of the measurement is dependent upon the reliability of the target generation method, and possibly variations in the radar receiver. The accuracy also depends on the sample size of the data.

The Parameter Study based the 5 % degradation on the collection of 90 samples. This appeared to concentrate more on what is achievable for field trials as opposed to conducted

---

[1] As these tests use conducted targets, and do not use any form of recorded or generated clutter, then no clutter will be present in the radar. Therefore, due to the limited scope of these tests clutter was not included.

laboratory testing. If 10 targets are used per scan, then 90 samples will be collected in 9 scans which equates to 36 seconds.

The NTIA testing on short-range ATC radars was based on sample sizes of typically 200 targets, with 10 targets per scan, so 20 scans which would be about 1 minute and 20 seconds. This testing used 500 samples to further improve accuracy as discussed in detail in the previous maritime testing report [1].

2.6 Measurement Procedure

The following test procedure was used to perform the conductive OOB interference measurements on a maritime radar:

1. The radar was set up for either long pulse or medium pulse using the parameters described in Table 1.
2. Ten targets were generated using external radar trigger outputs as described in Section 2.2 and with the additional parameter described in Table 2.
3. The gain control on the radar was set to produce a light background of 1 to 3 speckles is equivalent to a Pfa of about 10^{-5}
4. The radar was set to a range of 6 nm and was manually tuned to provide the highest sensitivity with respect to the RF level of the generated targets at a frequency of 3.05 GHz.
5. The RF level of generated targets was then adjusted give a probability of detection of 90 % or 60% without any interference.
6. Interference was applied to the radar via the antenna port at a range of frequencies, levels and types (CW, AWGN, WiMAX).
7. The probability of detection was counted over a period of 50 antenna rotations (500 targets) for each combination of frequency, level and interference type.

3. Interference Sources

Potential interference from systems operating in the bands 2500 MHz to 2690 MHz and 3400 MHz to 3600 MHz was considered. For the band 2500 MHz to 2690 MHz, the transmitter characteristics are defined in the auction documents which specifies a maximum channel EIRP of 61 dBm and a maximum out-of-band emission limit of -45 dBm/MHz. The auction is technology and application neutral. However, a practical representative set of interference sources were considered to be CW, AWGN and WiMAX.

The usage of the band 3400 MHz to 3600 MHz is shown in Table 3. For the purpose of this study only the fixed wireless access systems in the band 3480 MHz to 3500 MHz have been considered. This band uses the WiMAX technology. The assumptions used for this study are a maximum channel EIRP of 44 dBm/MHz, 20 MHz channels, and a maximum out-of-band emission limit of -14 dBm/MHz.

Table 3:
Usage of 3400 MHz to 3600 MHz band

Frequency	Use
1 kHz to 60 GHz	Technology Development
150 MHz to 4000 MHz	Ground Probing Radar
3400 MHz to 3420 MHz	PMSE (fixed site, Link, Low Power)
3400 MHz to 3475 MHz	Amateur Radio
3480 MHz to 3500 MHz	Fixed Wireless Access *P-MP EN 302 326-2* *P-P EN 302 217-2-2* *Fixed Wireless Access IR2015* *Tx power 14 dBW/MHz* *50 dB attenuation for OOB*

For AWGN, bandwidths of 5 MHz and 20 MHz were used. The WiMAX (IEEE 802.16d/e) source used a 10 MHz bandwidth and an activity rate of 80%. The interference was gated for the antenna rotation. The interference emissions masks are discussed in Section 4.1.1.

4. Measurement Results

4.1 Amplifier Saturation versus In-Band Noise

Interference to S-band maritime radar from communications services that are in the band 2.5 GHz to 2.69 GHz or above 3.4 GHz, could be the result of either out-of-band interference (OOB) in radar IF pass band or the communications channel power saturating various amplifiers in the radar chain. This is shown in Figure 1.

Which mechanism dominates will depend upon the characteristics of the radar receiver and the interference source emissions mask. In order to clarify this, testing was performed with and without the use of an additional filter.

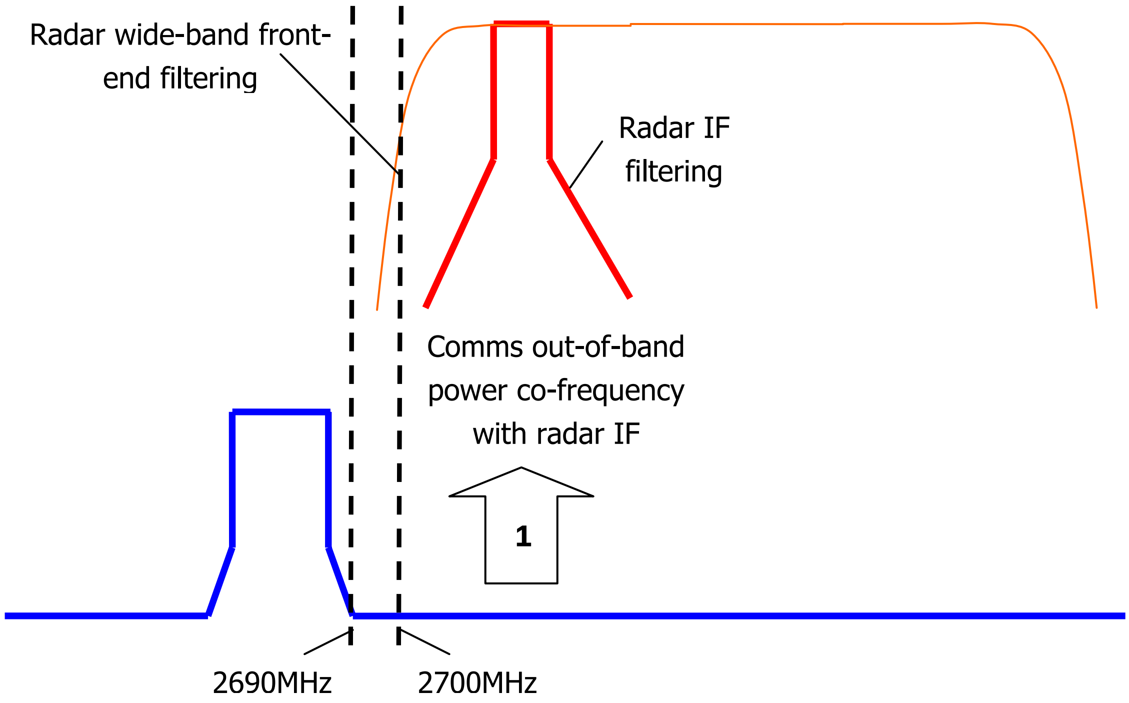


Figure 7: Interference mechanisms for 2500 to 2690 MHz

4.1.1 Interference Source OOB Emissions

The level of OOB interference present in the radar IF pass band expected to cause degradation of the radar performance is about -112 dBm for medium pulse mode which has a receiver bandwidth of 20 MHz[1] and about -120 dBm for long pulse mode which has a receiver bandwidth of 3 MHz.

The emission mask of the CW interference is shown in Figure 8, which was measured using a 100 kHz resolution bandwidth. The emission mask of the AWGN interference is shown in Figure 9 and Figure 10, for different frequency spans, which was measured using a 100 kHz resolution bandwidth.

The level of channel power that would result in OOB emission levels which exceed an interference-to-noise (I/N) ratio of -15 dB, assumed for a 5% Pd degradation, are calculated in Table 4 for CW, and AWGN with a bandwidth of 20 MHz. The results are the same for other AWGN bandwidths.

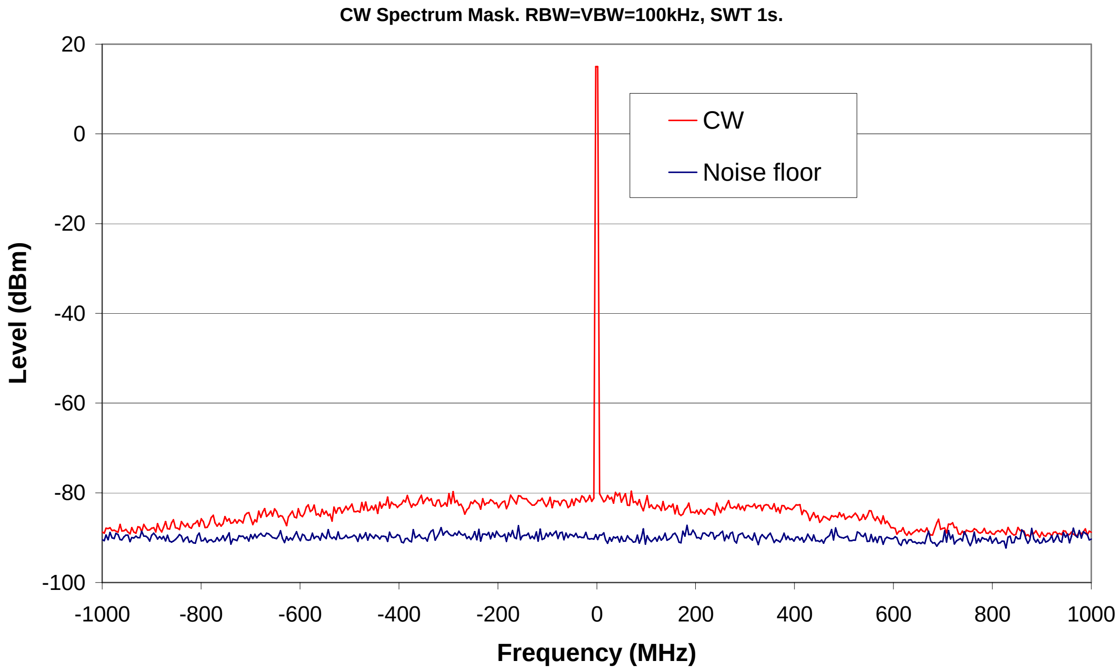


Figure 8: Spectrum Mask for CW interference

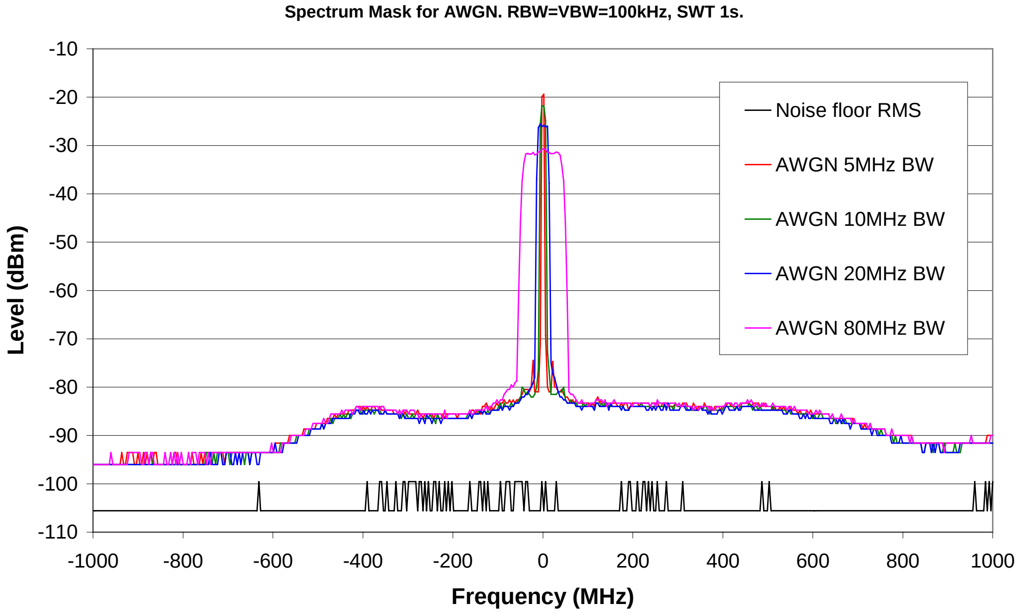


Figure 9: Spectrum Mask for AWGN interference of different bandwidths

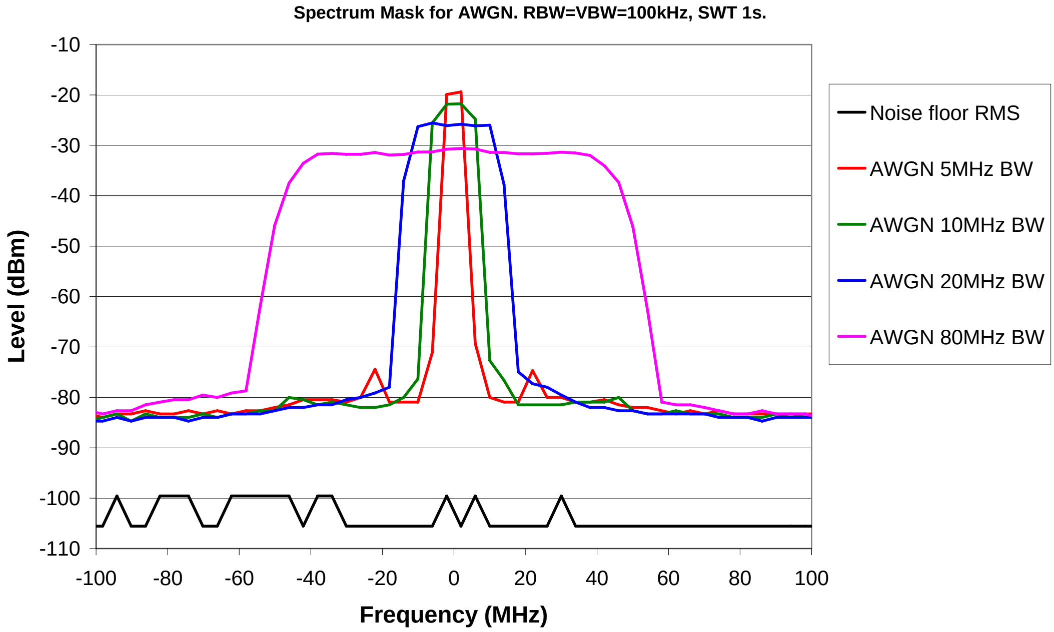


Figure 10: Spectrum Mask for AWGN interference of different bandwidths, reduced X-scale

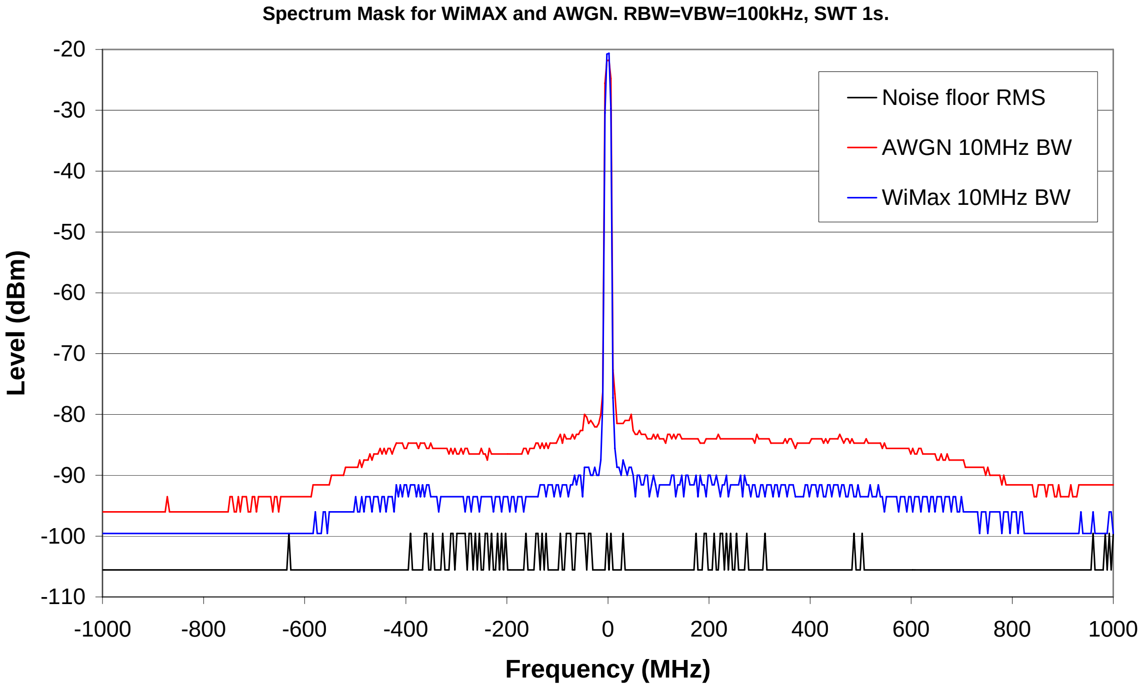


Figure 11: Spectrum Mask for WiMAX and AWGN, both with a 10MHz channel bandwidth

Table 4:
Calculation of CW channel power required for OOB emissions to exceed an I/N of -15 dB

Radar pulse mode	**Total Channel power**	**OOB in 100kHz**	**OOB in radar bandwidth**	**OOB relative to carrier**	**Interference in IF pass band for I/N = -15dB**	**Peak power for I/N = -15 due to OOB**
CW Interference						
Long pulse, 3MHz	15dBm	-82dBm	= -82dBm + 15dB = -67dBm	= 15dBm – (-67dBm) = 82dBc	-120dBm	= -120dBm + 82dBc = -38dBm
Medium pulse, 20MHz	15dBm	-82dBm	= -82dBm + 23dB = -59dBm	=15dBm – (-59dBm) = 74dBc	-112dBm	= -112dBm + 74dBc = -38dBm
AWGN (20MHz) Interference						
Long pulse, 3MHz	-2dBm	-84dBm	= -84dBm + 15dB = -69dBm	= -2dBm – (-69dBm) = 67dBc	-120dBm	= -120dBm + 67dBc = -53dBm
Medium pulse, 20MHz	15dBm	-84dBm	= -84dBm + 23dB = -61dBm	=-2dBm – (-61dBm) = 59dBc	-112dBm	= -112dBm + 59dBc = -53dBm

4.1.2 Amplifier Saturation from Interference Channel Power

In order to determine if OOB emissions in the radar IF pass band or interference channel power saturating the receiver amplifiers were the dominant mechanism, a filter was used to reduce the OOB emissions. The response of the filter used for the testing is shown in Figure 12, for a number of different centre frequency tunings.

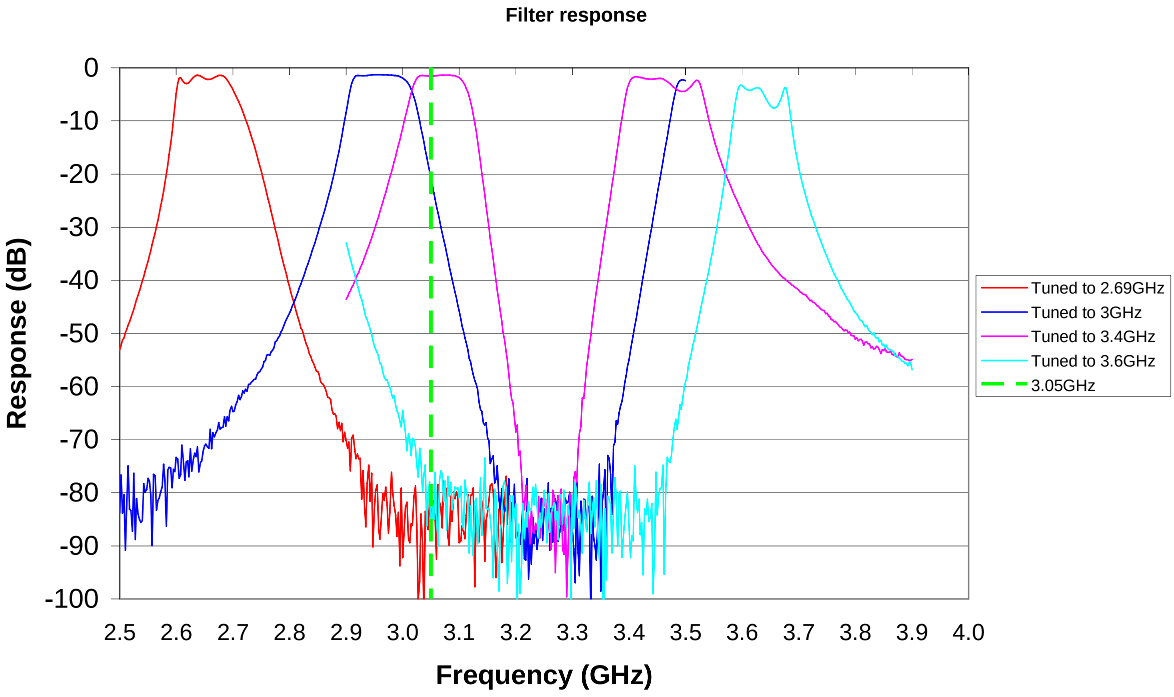


Figure 12: Filter response used for the testing

The effect of the filter on the emissions mask for CW is shown in Figure 13, for a measurement bandwidth of 100 kHz. The filter was tuned for interference at 2690 MHz such that the filter began to roll-off at frequencies just above 2690 MHz. The OOB emissions start to degrade the radar performance when the level is equal to the noise floor (N) plus the interference-to-noise (-15 dB). Without the filter, the radar performance is degraded when the CW peak power at 2.69 GHz is about -38 dBm. With the filter, the CW peak power can be increased up to about +46 dBm before the radar performance is degraded due to OOB emissions. Therefore the filter is effective in removing the effect of OOB interference into the radar IF pass band such that amplifier saturation levels can be investigated independently. For AWGN with the filter, the channel power would need to be about 31 dBm before OOB emissions in the radar IF pass band started to dominate.

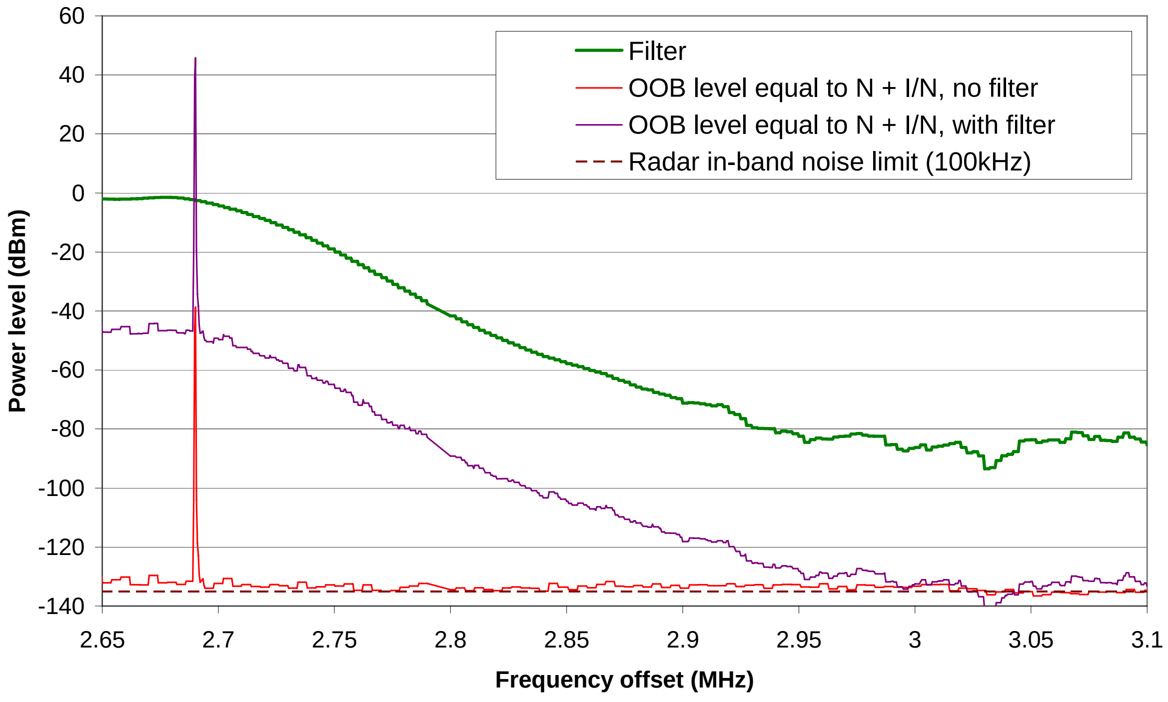


Figure 13: CW emissions mask with and without the filter (tuned for interference at 2690 MHz)

Measurements of the effect of interference on the probability of detection were made with and without the filter, using AWGN interference, and the results are shown in Figure 14.

Without the filter, the peak AWGN power required to cause degradation of the radar at 2690 MHz was about -50 dBm. This compares to the predicted value in Table 4 for the level of OOB emissions required to degrade radar performance of -53 dBm. For CW, the measured value was about -35 dBm and the predicted value in Table 4 was -38 dBm. These measurements without the filter are consistent with OOB emissions into the radar IF pass bands being the dominant mechanism for interference below 2900 MHz for the interference sources being used.

For an interference frequency of 2690 MHz and using the filter, the level of CW peak power required to degrade the radar performance was greater than 7 dBm, and the level of AWGN channel power was greater than -6 dBm. Insufficient power was available to affect the radar in both cases at 2690 MHz and this was the maximum power available after the loss of various RF combiners was included.

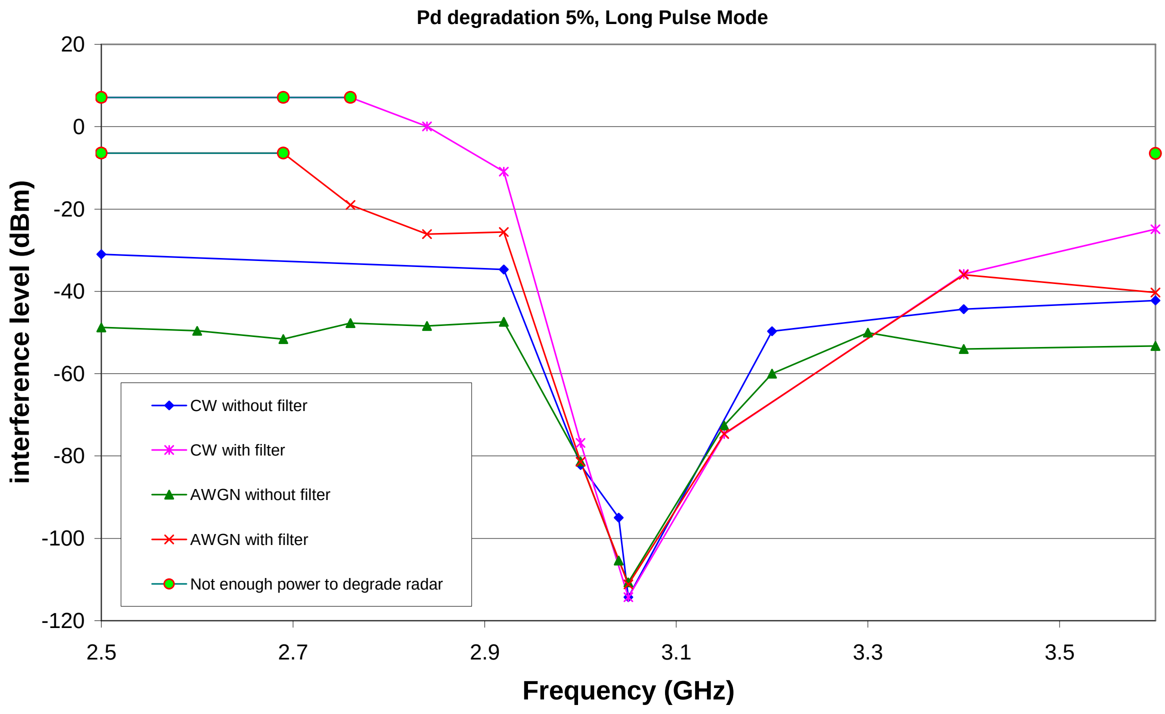


Figure 14: Comparison of Pd tests with and without filter for CW

4.2 Aggregate Interference

In order to replicate the various single and multiple base station interference scenarios the timing of the interference was considered. For multiple base stations, the interference can be injected at several different antenna orientations throughout each sweep, and at different levels if required. Some previous testing was done to investigate this [1]. The processing controlling the effective noise floor recovers quickly after any interference is removed. At any given antenna orientation experiencing interference in the antenna mainbeam, there is no accumulative effect of interference in the antenna mainbeam at other orientations. As an extreme example of multiple base station interference, the interference can be injected continuous throughout the full antenna rotation. Figure 15 shows the result of continuous interference compared to momentary interference at only one antenna orientation indicating no difference in the results. The narrow antenna azimuth beam width will provide some mitigation. Aggregate interference can however be present from multiple interferers in the antenna side lobes. A 3 dB factor has been included in the propagation modelling to account for aggregate effects.

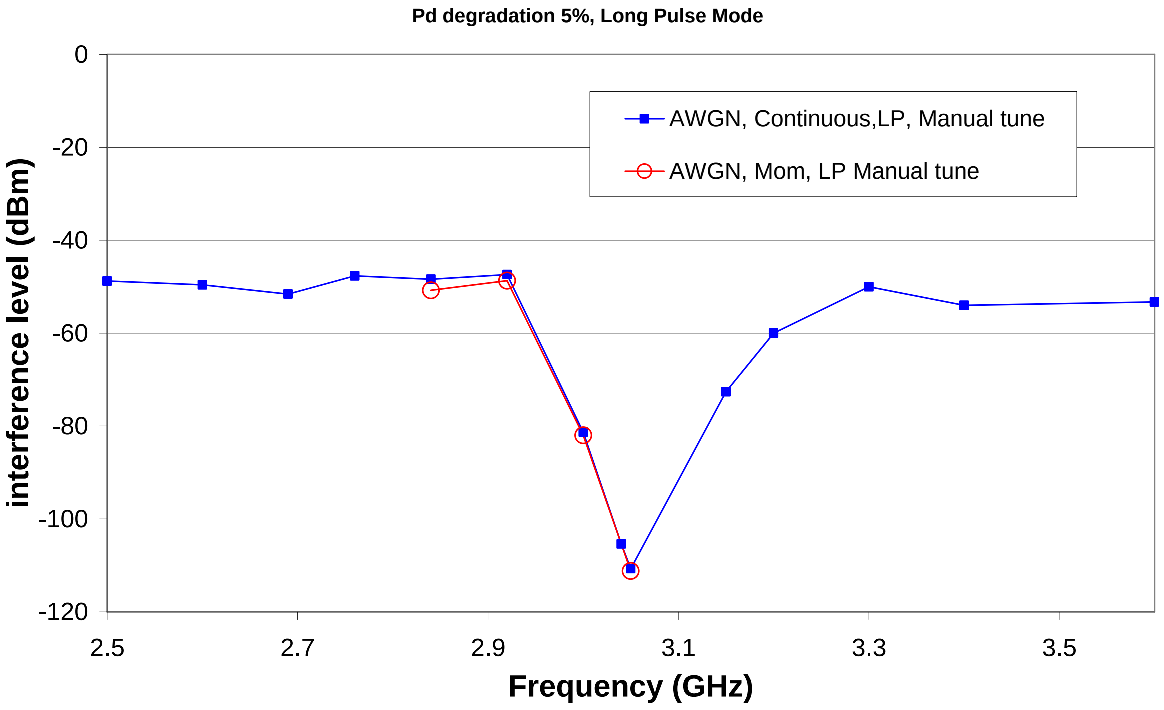


Figure 15: Continuous versus momentary interference for AWGN (20MHz) interference

4.3 Sensitivity Criteria

Sensitivity criteria are required for determining at what point a radar's performance is considered to be degraded. For amplifier saturation, the value often used is to identify the 1dB compression point. For OOB emissions falling into the radar IF pass band, the radar degradation is usually assessed by either the interference-to-noise (I/N) value or the degradation of the probability of detection (Pd). These values are related, as the 1dB compression and the I/N values both affect the signal-to-noise ratio (SNR) which in turn determines the Pd degradation.

Table 5 compares values of I/N, reduction in sensitivity and loss of Pd, which will vary for different radars. Previous work for Ofcom has identified that a loss of Pd of 5% should be considered for measuring radar degradation and that is what was used for this study. This is consistent with a conservative approach.

Table 5:
Loss of dynamic range for relative interference level

I / N	Reduction in sensitivity (SNR)	Approximate reduction in Pd
–15 dB	0.14 dB	5%
–10 dB	0.41 dB	15%
–6 dB	0.97 dB	30%

4.4 Assessment of Radar Probability of Detection

The effect on the radar probability of detection (Pd) from interference, using the filter, was assessed for the long pulse and medium pulse radar modes and a range of interference sources. The results using the radar long pulse mode are shown in Figure 16 for CW, WiMAX and AWGN (20 MHz) interference. The results for medium pulse mode are shown in Figure 17 for CW, WiMAX, AWGN (5 MHz) and AWGN (20 MHz) interference.

For communications systems in the band 2500 MHz to 2690 MHz, the worst-case interference frequency in all cases is 2690 MHz. For the long pulse mode, the worst-case at an interference frequency of 2690 MHz is the AWGN (20 MHz) source which required an interference power greater than -6 dBm. Due to the losses in the test configuration, resulting from the RF combining of several different signals, this was the maximum power that could be input to the radar for AWGN. CW results, which allowed a higher input power into the radar, indicate that the radar is likely to be less sensitive than the worst-case AWGN results suggest. For the medium pulse mode, the worst-case was AWGN (20 MHz) at 2690 MHz which required an interference power was in excess of -6 dBm and a CW power in excess of 7 dBm.

Above 3400 MHz, the worst-case sensitivity was at a frequency of 3400 MHz. For the long pulse mode, the worst-case sensitivity at an interference frequency of 3400 MHz was the WiMAX source which required an interference power of -42 dBm (although at higher frequencies the radar was more sensitive to AWGN (20 MHz) than WiMAX). For the medium pulse mode, the worst-case sensitivity at an interference frequency of 3400 MHz was the AWGN (5 MHz) source which required an interference power of -55 dBm.

However, the communications devices being considered in this study above 3400 MHz are fixed wireless access systems in the band 3480 MHz to 3500 MHz. For the long pulse mode, the worst-case at an interference frequency of 3490 MHz is the AWGN (20 MHz) source which required an interference power of -39 dBm. For the medium pulse mode, the worst-case sensitivity at an interference frequency of 3400 MHz is the AWGN (5 MHz) source which required an interference power of -50 dBm.

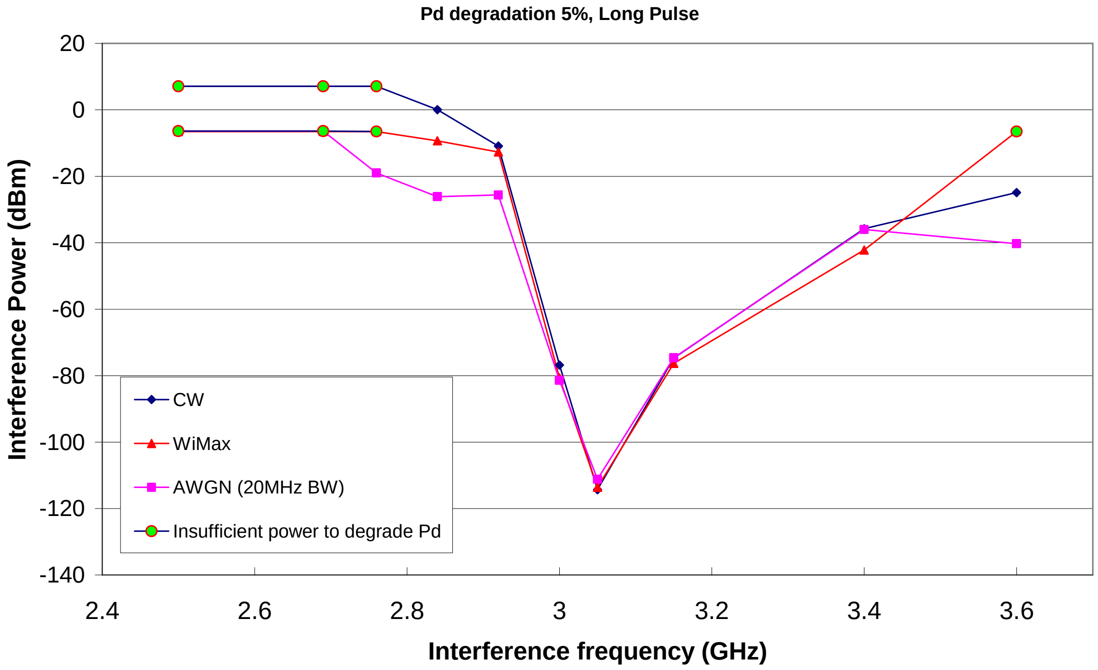


Figure 16: Effect of interference on the radar Pd, for long pulse mode and with filtering on the interference

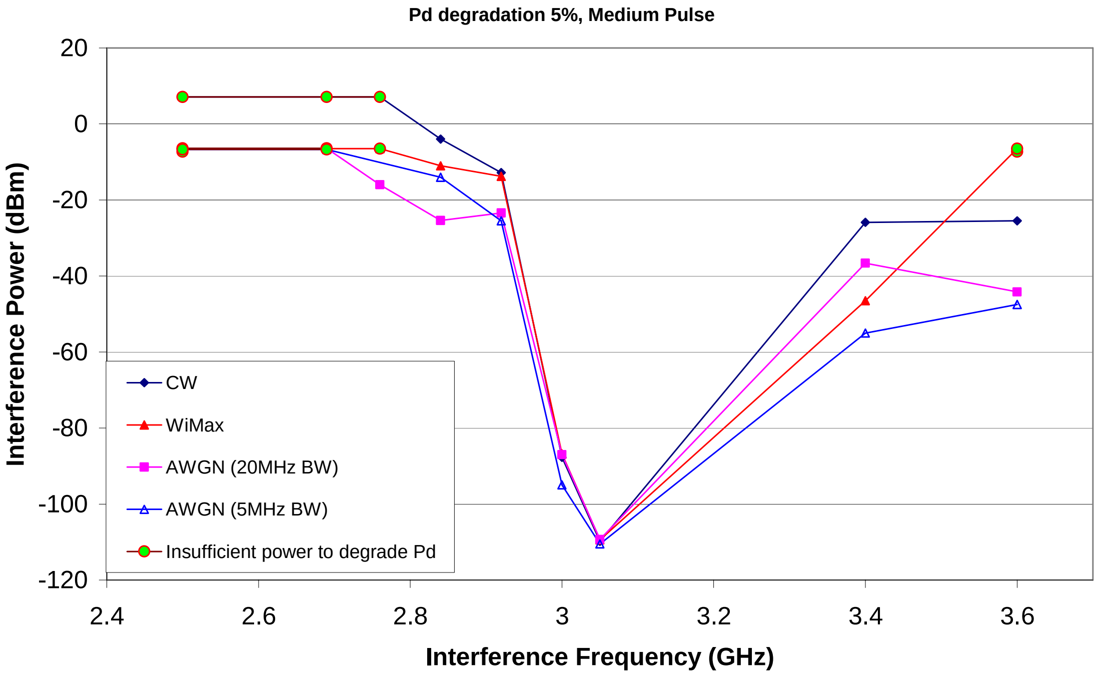


Figure 17: Effect of interference on the radar Pd, for medium pulse mode and with filtering on the interference

Table 6:
Summary of worst-case interference results into the antenna port

Mechanism	Interference Frequency	Long Pulse Mode	Medium Pulse Mode
Amplifier saturation	2690 MHz	>-6 dBm	>-6 dBm
Amplifier saturation	3490 MHz	-39 dBm	-50 dBm
OOB emissions in IF pass band	2690 MHz	-112 dBm	-112 dBm
OOB emissions in IF pass band	3490 MHz	-112 dBm	-112 dBm

Some of the phenomena could not be fully explained within these tests such as why the filter performance above 3400 MHz appeared to be considerably sensitive than that below 2690 MHz and why WiMAX gave such a different trend than AWGN above 3400 MHz.

4.5 Receiver Characterisation

The radar receiver was characterised by measuring the output of the amplifiers at several stages of the radar chain. The radar receiver, Figure 18, includes a limiter, and Low Noise Amplifier (LNA), the 1st IF pre-amplifier plus bandwidth selection stage, a log amplifier plus detector stage and a video amplifier plus AC coupler stage.

Three of the four stages (ports 1, 2 and 4) were characterized using CW and AWGN signals. There were some complications in measuring port 3. The output of each stage was measured against the input power level to observe the 1dB compression point where the amplifier goes into saturation.

The results are shown in Figure 19 and Figure 20 and are compared to the Pd degradation measurements for the long pulse mode. Figure 19 is for a Pd loss of 5% and a corresponding loss of sensitivity of about 0.15 dB (estimated from measurements). Figure 20 is for a Pd loss of 35% and a corresponding loss of sensitivity of 1dB.

Just before port 4 there is an AC coupler device which normalises the noise floor. For this reason, the AWGN results show no degradation in output level at port 4. However, with CW, the amplifier saturation can be observed. It can be seen that the amplifiers become more sensitive the closer the amplifier is to the radar detector, and therefore either the log amplifier or the video amplifier are the most sensitive. The port 4 results also correlate with the Pd results for interference with a filter, providing further evidence of the amplifier saturation mechanism observed when using a filter for the Pd results.

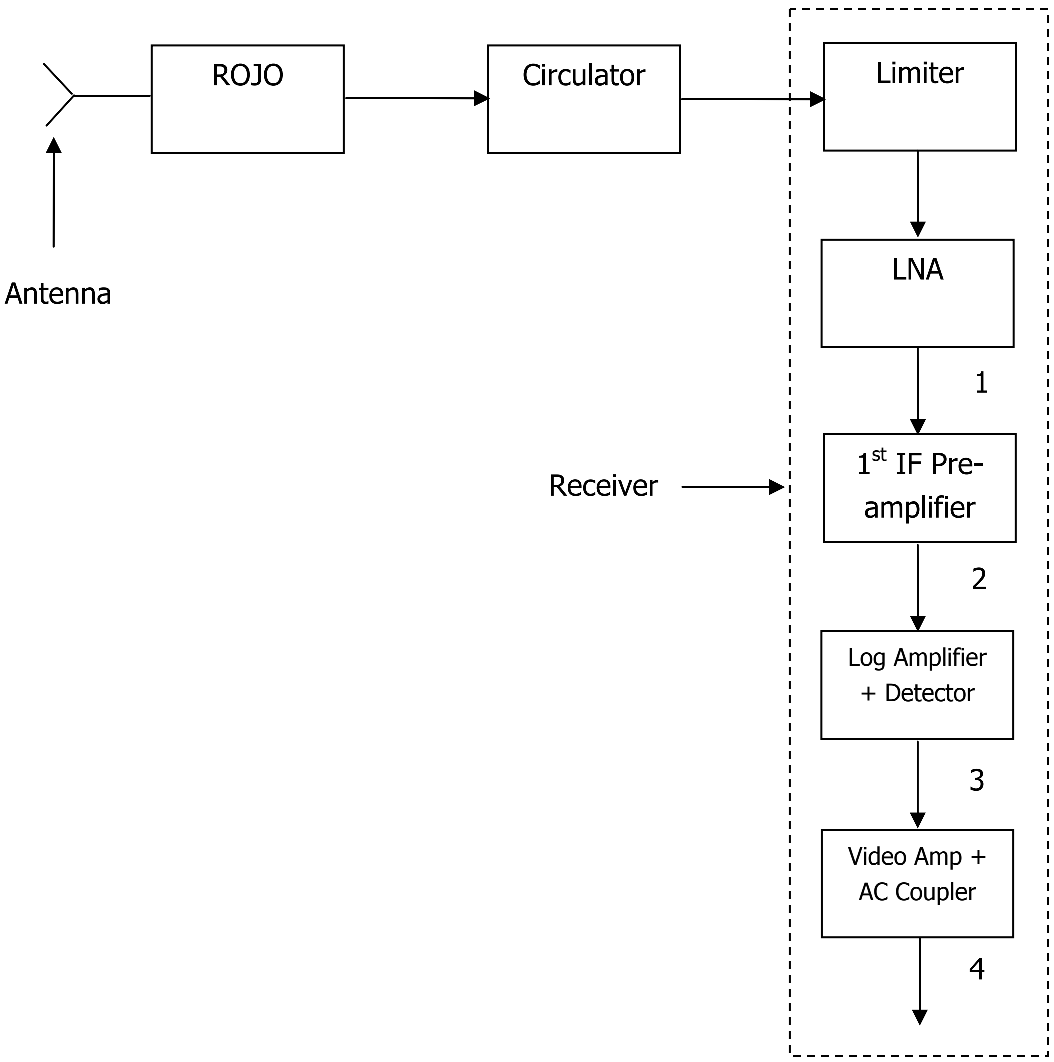


Figure 18: Block diagram of components in a radar receiver

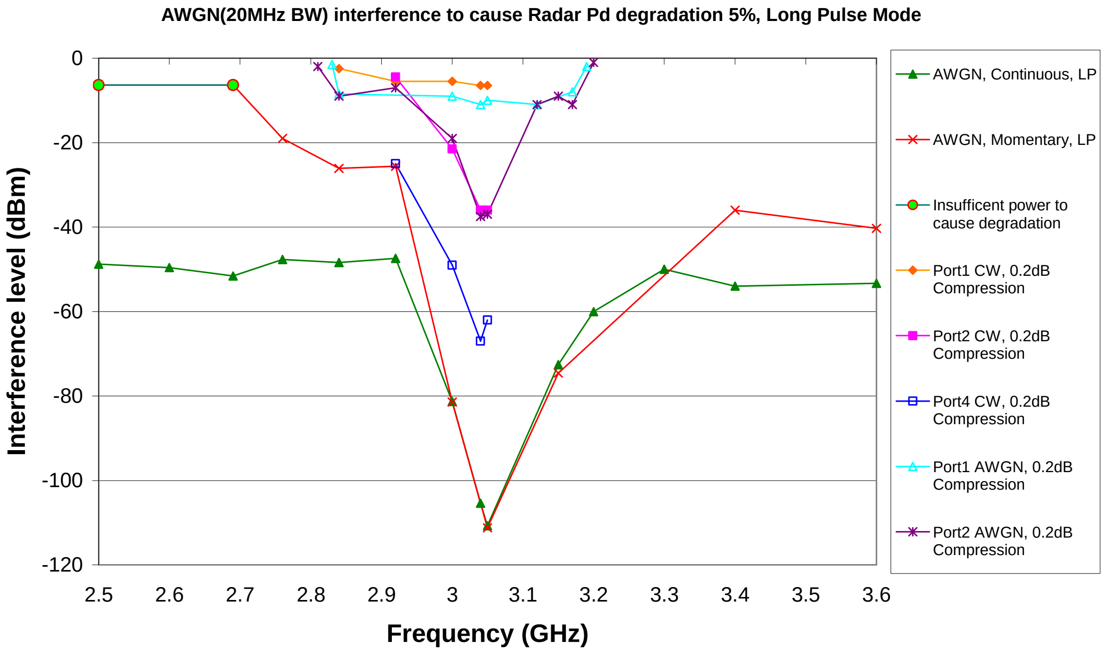


Figure 19: Receiver characterisation for Pd degradation of 5% and loss of sensitivity of 0.15 dB

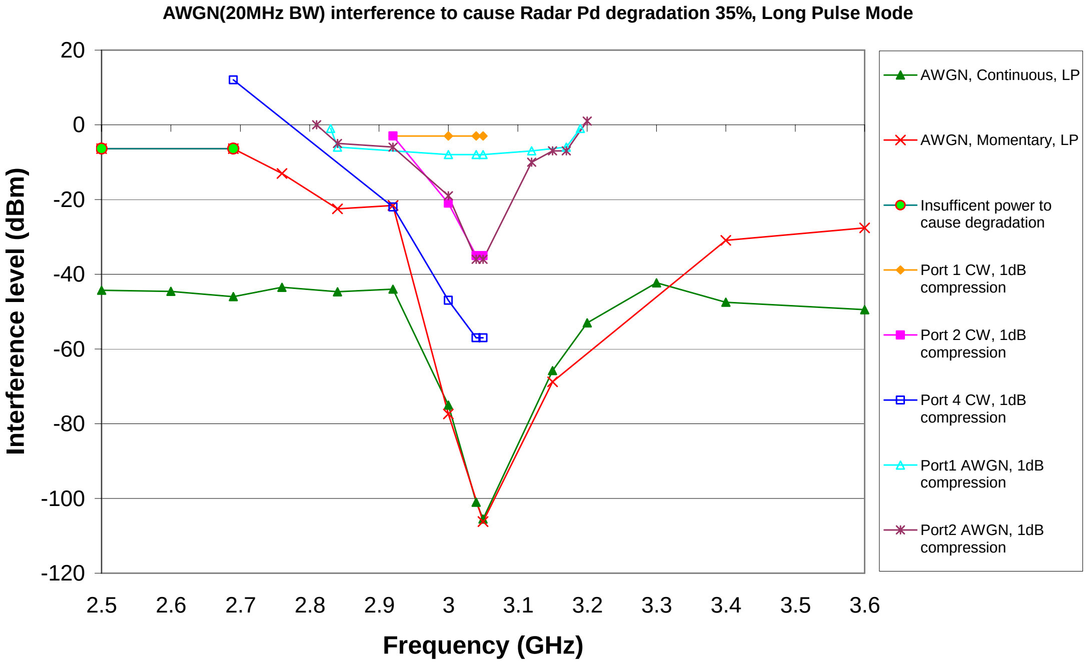


Figure 20: Receiver characterisation for Pd degradation of 35% and loss of sensitivity of 1dB

4.6 Antenna Losses

Measurements of the radar antenna gain frequency were provided by one of the radar manufacturers for a typical S-band maritime radar antenna. It can be seen that the maximum gain is about 27 dBi and that for a radar centred at 3050 MHz there is a reduction in the antenna gain at 2690 MHz compared to 3050 MHz of about 9 dB. At 3490 MHz, the reduction in antenna gain is about 13 dB. Other radar operating frequencies have been considered and the corresponding antenna gain losses have been determined using these measurements, assuming the antenna is tuned for the correct radar operating frequency.

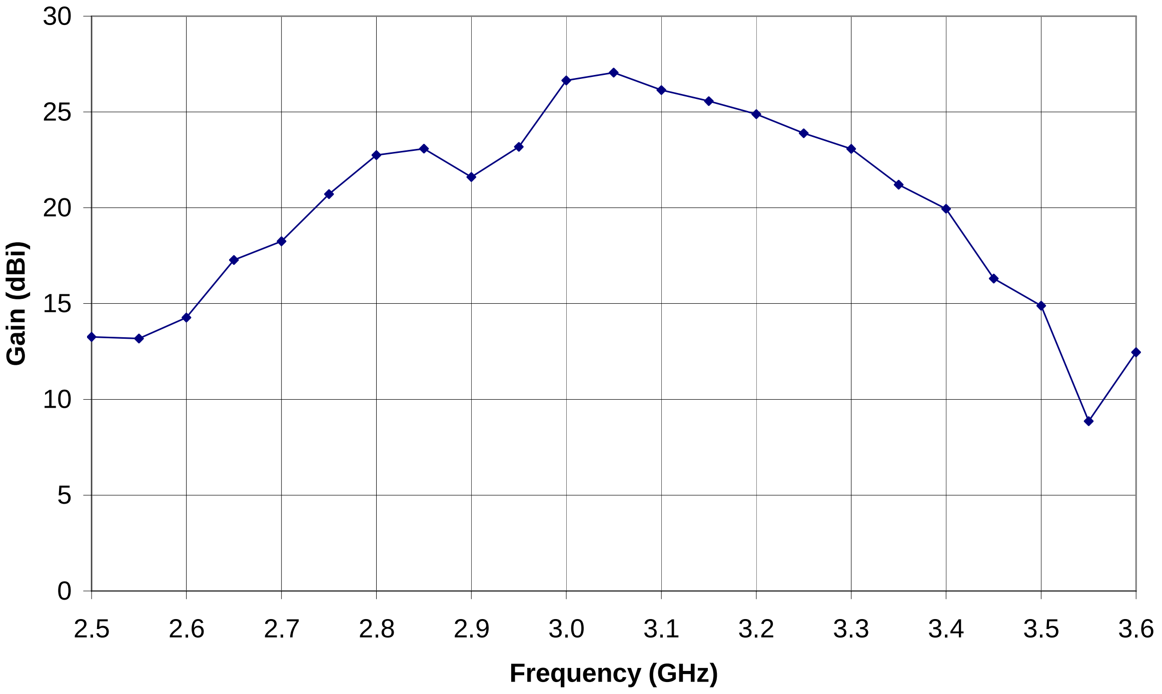


Figure 21: Antenna gain versus frequency

For OOB interference at the radar operating frequency, the communications antenna gain reduction of the transmitting communications systems due to frequency offset is implicitly included in the EIRP mask assumptions used. However, due to the large frequency separations, additional antenna loss is possible and a factor of 2 dB has been included, although this figure could be higher in practice. Measurements of the antenna gain versus frequency offset are shown in Figure 22 for a WiMAX antenna tuned for 5500 MHz.

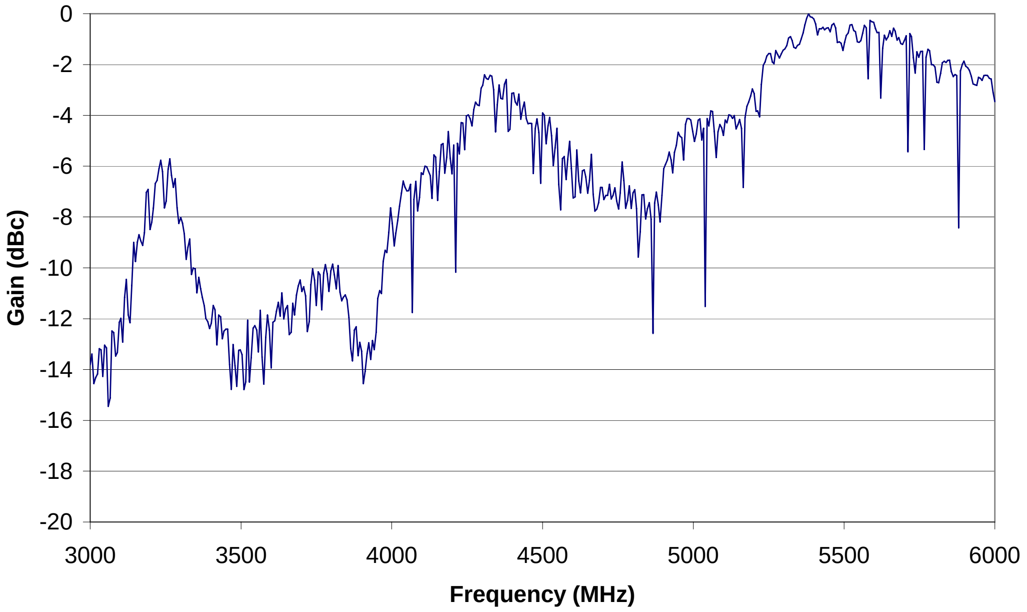


Figure 22: Example measurements of gain versus frequency offset for a WiMAX antenna tuned for 5500 MHz

4.7 Comparison of Different Radar Types

4.7.1 Comparison of Different Magnetron Radars

Discussions were held with the two main S-band radar manufacturers in the UK. Although no off-frequency radar sensitivity measurement results were available for other magnetron radars, these discussions indicated that the effect on both manufacturers S-band magnetron radars are likely to be similar.

4.7.2 Comparison of Magnetron and Solid State Radars

Discussions were held with a radar manufacturer of S-band maritime solid-state radar. This radar can operate anywhere in the band 2900 MHz to 3100 MHz. The design of this radar is similar in many ways to the design of the Watchman radar and the manufacturer expects that the sensitivity of the radar to interference which is below 2690 MHz and above 3400 MHz may be comparable with the previous Watchman results. However, testing would be required to confirm this. For the purpose of estimating the separation distances, the profile of the Watchman OOB response has been assumed for a solid-state maritime radar at the bottom, middle and top edge of the band, 2900 MHz, 3000 MHz and 3100 MHz.

4.8 Frequency Separations

The communications systems assumed for this study are those that will be introduced into the band 2500 MHz to 2690 MHz and existing fixed wireless access systems in the band 3480 MHz to 3500 MHz. These are discussed in more detail in Section 5.1. The frequency separations assumed for the estimated separation distance calculations are shown in Table 7.

Table 7:
Frequency separations used for estimated separation calculations

Radar Type	Radar Frequency	Interference Frequency	Frequency Separation
Magnetron	3050 MHz	2690 MHz	-360 MHz
Magnetron	3050 MHz	3490 MHz	+440 MHz
Magnetron	2900 MHz	2690 MHz	-210 MHz
Magnetron	2900 MHz	3490 MHz	+590 MHz
Solid-State	2900 MHz	2690 MHz	-210 MHz
Solid-State	2900 MHz	3490 MHz	+590 MHz
Solid-State	3000 MHz	2690 MHz	-310 MHz
Solid-State	3000 MHz	3490 MHz	+490 MHz
Solid-State	3100 MHz	2690 MHz	-410 MHz
Solid-State	3100 MHz	3490 MHz	+390 MHz

4.9 Sensitivity Levels

The sensitivity levels of the radar, taking account of the reduction in radar antenna gain off-frequency, are shown in Table 8. For radar amplifier saturation due to the channel power of the communications device, the radar antenna has been considered. For OOB emissions in the radar IF pass band, a 2 dB antenna gain reduction for the communications systems antenna has been included for large frequency separations.

The sensitivity to OOB emissions in the radar IF pass band are based on previous radar sensitivity testing [1].

Table 8: Summary of worst-case sensitivity results for magnetron radar, taking account of antenna gain reductions off-frequency

Mechanism	Radar Frequency	Interference Frequency	Frequency Separation	Antenna gain reduction	Long Pulse Mode	Medium Pulse Mode	Worst-Case sensitivity
Amplifier saturation	3050MHz	2690MHz	-360MHz	9dB	>-6dBm*+9dB=3dBm	>-6dBm*+9dB=3dBm	>3dBm
Amplifier saturation	3050MHz	3490MHz	+440MHz	12dB	-39dBm*+12dB= -27dBm	-50dBm*+12dB= -38dBm	-38dBm
OOB emissions in IF pass band	3050MHz	2690MHz	-360MHz	2dB	-112dBm+2dB=-110dBm	-112dBm	-110dBm**
OOB emissions in IF pass band	3050MHz	3490MHz	+440MHz	2dB	-112dBm+2dB=-110dBm	-112dBm	-110dBm**
Amplifier saturation	2900MHz	2690MHz	-210MHz	4dB	-22dBm*+4dB=-18dBm	-25dBm*+4dB>-11dBm	-18dBm
Amplifier saturation	2900MHz	3490MHz	+590MHz	15dB	-40dBm*+15dB= -25dBm	-50dBm*+15dB= -35dBm	-35dBm
OOB emissions in IF pass band	2900MHz	2690MHz	-210MHz	2dB	-112dBm+2dB=-110dBm	-112dBm	-110dBm**
OOB emissions in IF pass band	2900MHz	3490MHz	+590MHz	2dB	-112dBm+2dB=-110dBm	-112dBm	-110dBm**

*Sensitivity before antenna gain reduction; ** in bandwidth of 20 MHz.

Table 9: Summary of worst-case sensitivity results for solid-state radar, taking account of antenna gain reductions off-frequency, assuming similar sensitivity to Watchman radar

Mechanism	Radar Frequency	Interference Frequency	Frequency Separation	Antenna gain reduction	All Pulse Modes	Worst-Case sensitivity
Amplifier saturation	2900MHz	2690MHz	-210MHz	4dB	-40dBm*+4dB=-36dBm	-36dBm
Amplifier saturation	2900MHz	3490MHz	+590MHz	15dB	-31dBm*+15dB=-16dBm	-16dBm
Amplifier saturation	3000MHz	2690MHz	-310MHz	7dB	-40dBm*+7dB=-33dBm	-33dBm
Amplifier saturation	3000MHz	3490MHz	+490MHz	16dB	-31dBm*+16dB=-15dBm	-15dBm
Amplifier saturation	3100MHz	2690MHz	-410MHz	10dB	-40dBm*+10dB=-30dBm	-30dBm
Amplifier saturation	3100MHz	3490MHz	+390MHz	11dB	-31dBm*+11dB=-20dBm	-20dBm
OOB emissions in IF pass band	2900MHz, 3000MHz, 3100MHz	2690MHz, 3400MHz	All	2dB	-112dBm+2dB=-110dBm	-110dBm**

*Sensitivity before antenna gain reduction; ** in bandwidth of 20 MHz.

5. Estimation of Separation Distances

5.1 Modelling Parameters

For calculating the estimated separation distances the modelling parameters in Table 10 were used. Only the proposed communications systems in the band 2500 MHz to 2690 MHz and the existing fixed wireless access systems in 3480 MHz to 3500 MHz were considered.

Table 10:
Parameters for calculating estimated separation distances

Parameter	Value
Transmit Characteristics	
Interference frequencies	Worst-cases 2690 MHz and 3490 MHz
Transmitter antenna heights	10m, 20m above ground 10m, 50m, 100m above sea level
Transmit channel EIRP: 2500-2690MHz source	61 dBm/5 MHz
Transmit OOB EIRP: 2500-2690MHz source	-45 dBm/MHz -32 dBm for 20 MHz receiver bandwidth
Transmit channel EIRP: 3480-3500MHz source	44 dBm/MHz 57 dBm for 20 MHz channel bandwidth
Transmit OOB EIRP: 3480-3500MHz source	-14 dBm/MHz -1 dBm for 20 MHz receiver bandwidth
Receiver Characteristics	
Radar frequencies	Magnetron 2900 MHz, 3050 MHz Solid-state 2900 MHz, 3000 MHz, 3100 MHz
Antenna receive height	10m above sea level
Loss of sensitivity criteria	1 dB compression of receiver chain amplifier or 5% loss of Pd for OOB interference in IF pass band. Figures given in Table 8 and Table 9.
Assumed effective radar antenna gain towards the horizon	28 dBi for both magnetron and solid-state
Antenna site variation factor	0 dB
Antenna cross-polarisation factor	3 dB (conservative value for vertical to horizontal)

Parameter	Value
Feederlink loss	0 dB
Propagation	
Propagation model	Free-space, Free-space + 6dB enhancement, P.1546, P.452
Short-term enhancement factors	This has been included as a free space + 6dB loss calculation
Aggregate interference factor	3 dB
Additional safety margin factor	0 dB

5.2 Interference Scenarios for Mobile Radar and VTS

The scenarios considered are listed below and shown in Figure 23 for mobile radar and Figure 24 for VTS radar:

1. emissions from the mainbeam of a base station at the edge of the coast to mainbeam of mobile maritime radar;
2. emissions from the side lobes of a base station at the edge of the coast to mainbeam of mobile maritime radar;
3. emissions from the mainbeam of a base station 1km in from the coast to mainbeam of mobile maritime radar;
4. emissions from the side lobes of a base station at the edge of the coast to side lobes of mobile maritime radar;
5. emissions from the mainbeam of a base station pointing along the coast to the mainbeam of a VTS radar antenna;
6. emissions from the mainbeam of an in-land base station pointing towards the side-lobes of a VTS radar antenna;
7. emissions from the side-lobes of a base station pointing along the coast to the mainbeam of a VTS radar antenna;
8. emissions from the side-lobes of a base station pointing along the coast to the side-lobes of a VTS radar antenna.

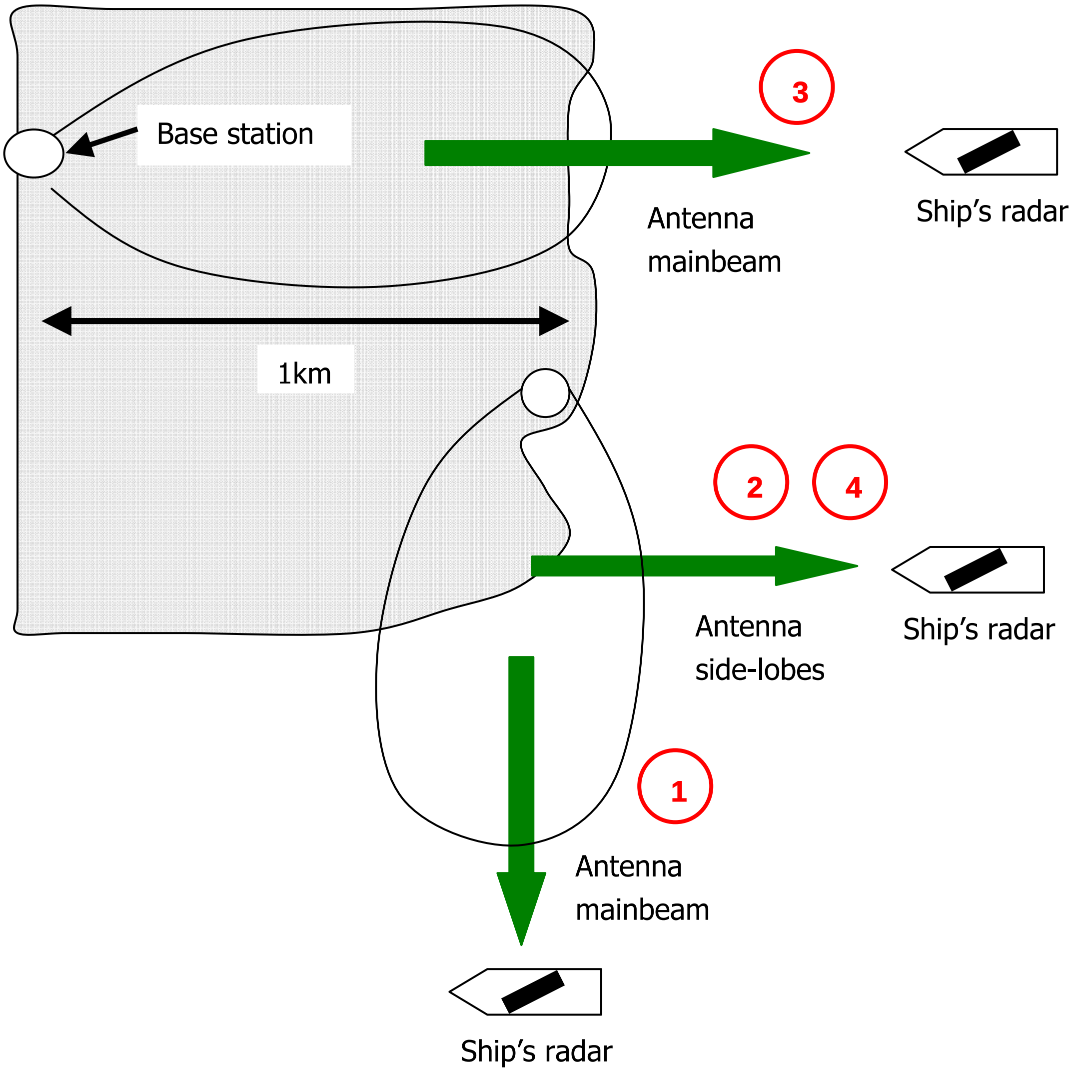


Figure 23: Mobile radar scenarios considered for propagation assessment

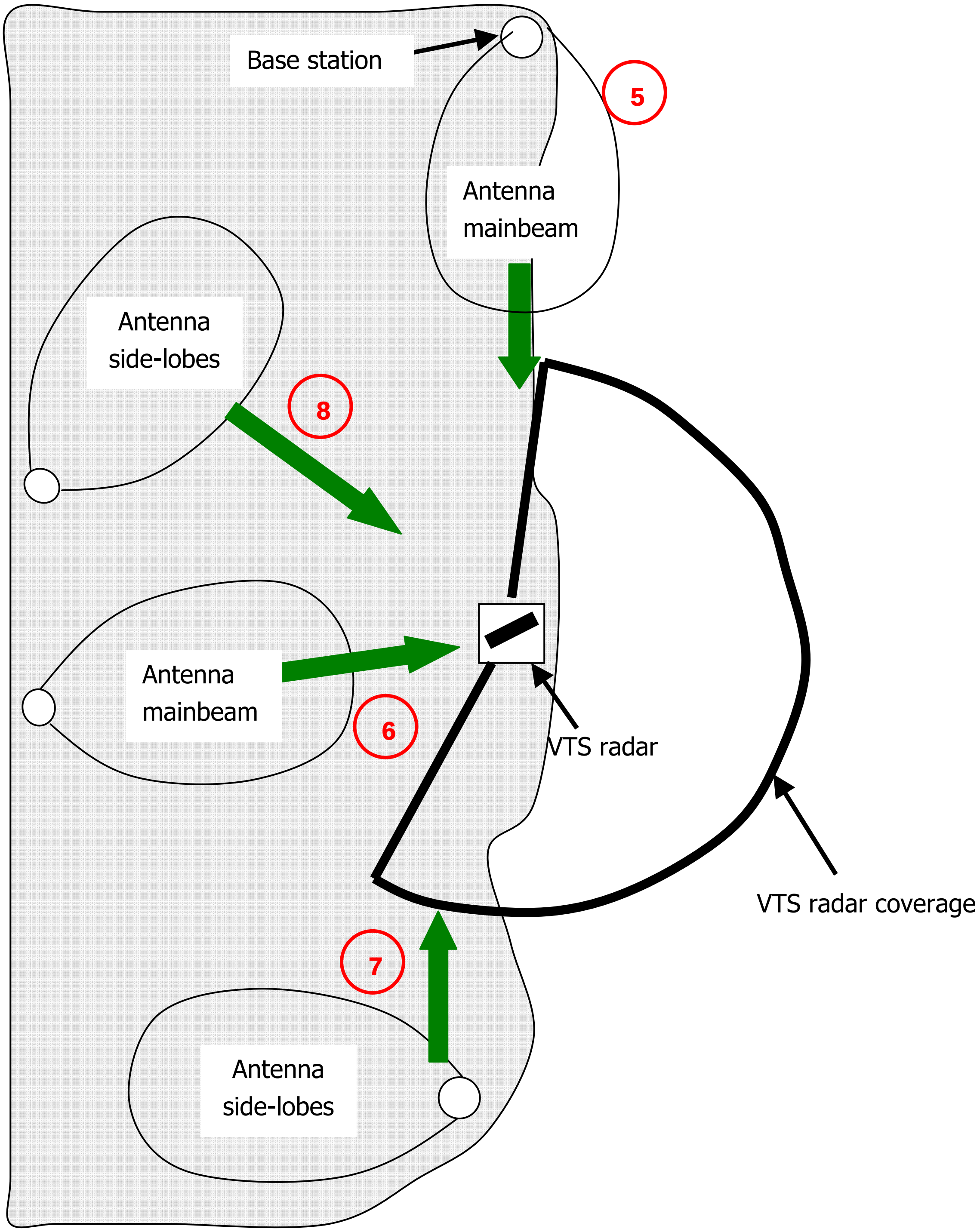


Figure 24: VTS radar scenarios considered for propagation assessment

5.3 Functional Impact of Interference

The relative position and movement, if any, of ship radars, base stations and radar targets may reduce the functional impact of interference to some extent. Some examples are given in Figure 25.

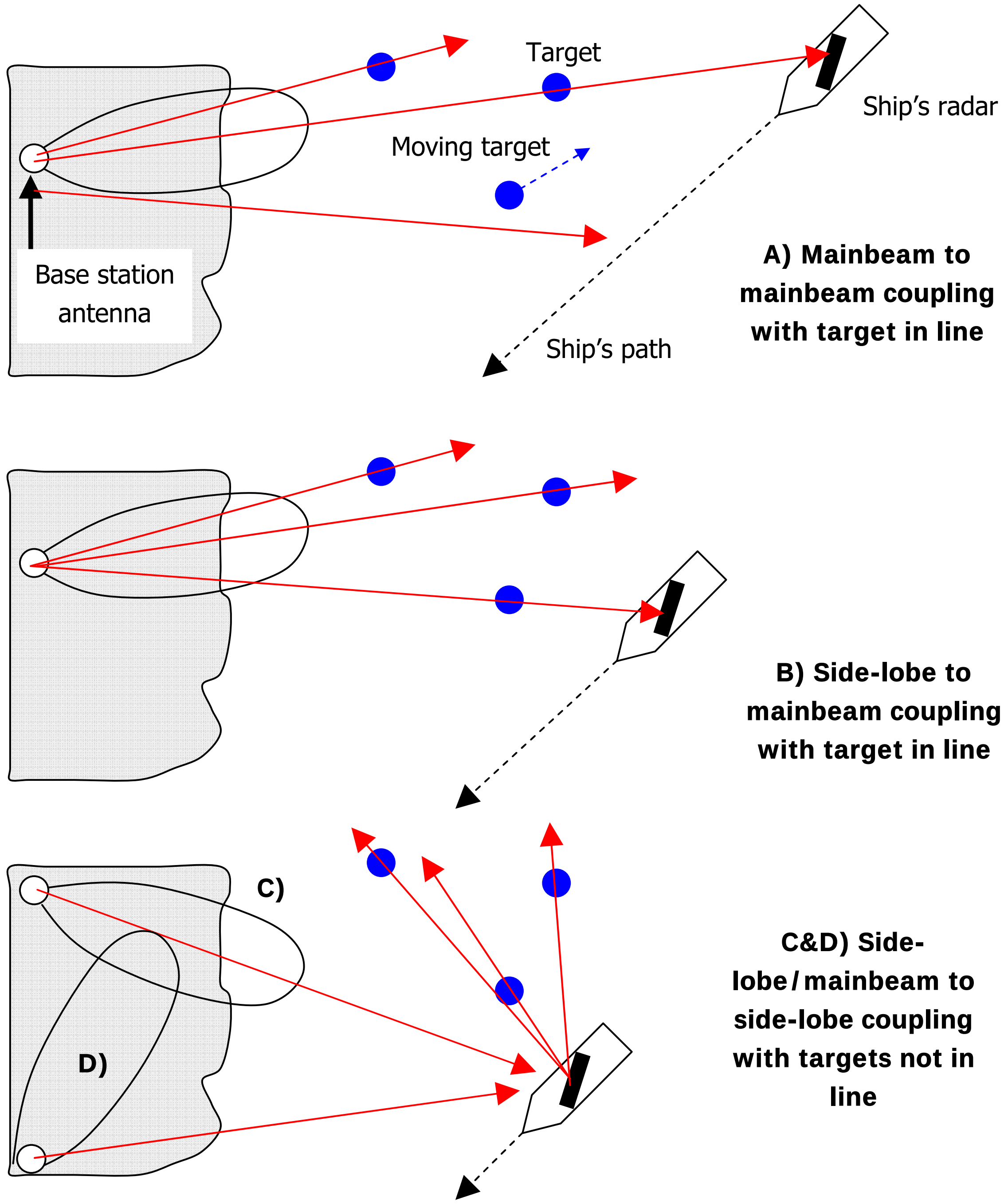


Figure 25: Examples of scenarios for moving ship's radar and targets

In order to get base-station antenna mainbeam to radar antenna mainbeam interference, the base station, target and ship's radar need to be in alignment, Figure 25 a). This is likely to happen for small periods of time unless the ship is travelling along the line towards both a stationary target and the base station, Figure 26.

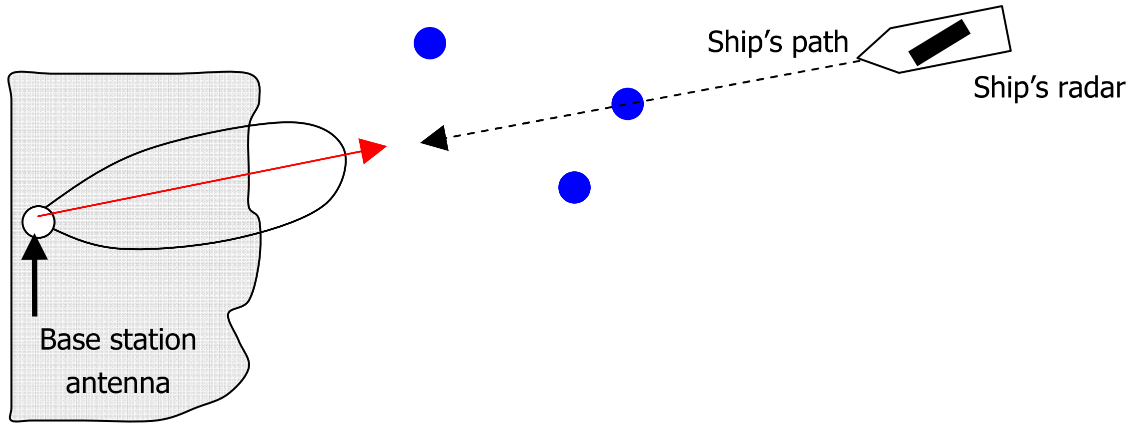


Figure 26: Ship moving on line towards base station and stationary target

The side-lobe of the base station's antenna could point towards a target and ship radar's antenna mainbeam which are in alignment, Figure 25 b), which would reduce the coupling by for example about 20 dB. The base-station antenna mainbeam could point towards the ships radar's antenna side lobes, Figure 25 c), and this would also reduce the coupling by for example 20 dB. If the base station side lobes were pointing towards the radar antenna side lobes then the antenna coupling would reduce by about 40 dB in total. The situation that is likely to occur for the most time and that there is at least a 20 dB reduction in the antenna coupling, although the situation of antenna mainbeam-to-mainbeam is possible.

A probability of detection over a period of time incorporating these statistical variations due to base station, radar and target locations could be included in an assessment of radar degradation as a further stage.

5.4 Path Loss Models

It was intended that industry standard software could be used for the propagation assessment and in particular the software "CARPET" used for calculations in the new maritime radar standard BS EN 62388. However, is not designed to allow such interference type calculations as it is based on specific formulas for reflections of radar targets and the resulting low angle propagation over different sea conditions. Instead, a number of standard propagation models were considered. This included free-space, two-ray model using correct surface characteristics for sea water, ITU-R P.452 and ITU-R P.1546.

The land height above sea level around the south-east of England towards the English Channel is shown in Figure 27. This showed a spread of land heights above sea-level, mainly in the region of 0 to 100m.

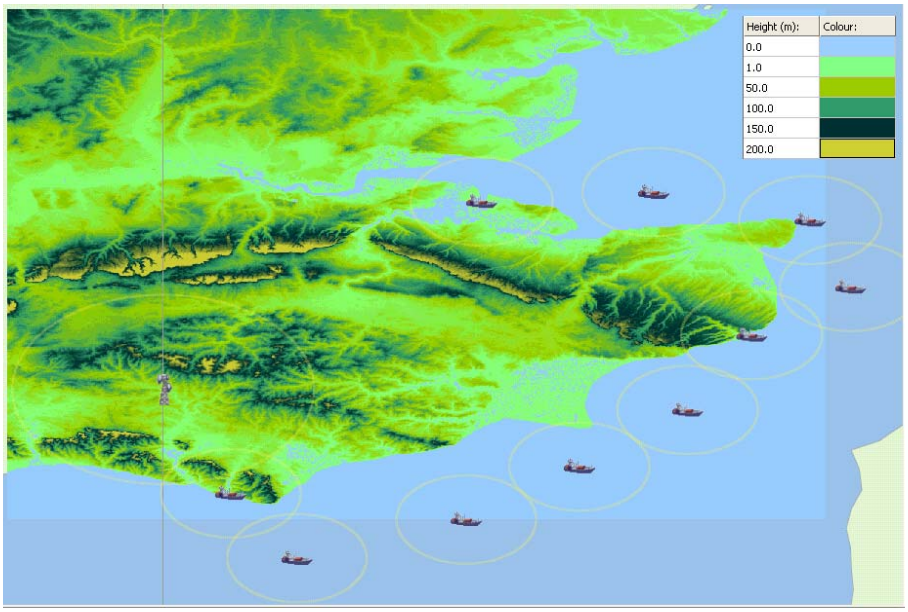


Figure 27: Land height above sea level in the south-east of England towards the English Channel

The path loss from each of these models is compared for a range of transmitter heights above sea level of 10m, 50m and 100m, and a receiver height of 10m above sea level. For scenarios 1) and 2), where the base station is at the coast and the propagation is essentially all over water, the path loss for the three base station antenna heights of 10m, 50m, and 100m above sea level are shown in Figure 28, Figure 29, and Figure 30 respectively for a propagation frequency of 2690 MHz. These models do not take sea state into account. The propagation losses increases slightly for higher propagation frequencies and one example at 3490 MHz is shown in Figure 31 for a base station height of 10m above sea level and Figure 32 for a base station height of 100m above sea level.

The propagation models used are free-space (FS) with a 6dB enhancement, free-space with no enhancement and ITU-R P.452.

ITU-R P.1546 and P.452 allow a number of parameters to be varied. The following parameters were used to calculate path loss in the figures above:

- Rec P.1546-3:
    - Wanted time percentage, 10%
    - Percent of path over water, 100%
    - Percentage of locations, 50%
- Rec P.452-13
    - Delta N: 70, N-units/km
    - Sea level surface refractivity, 325.0
    - Percentage of path over water, 100%

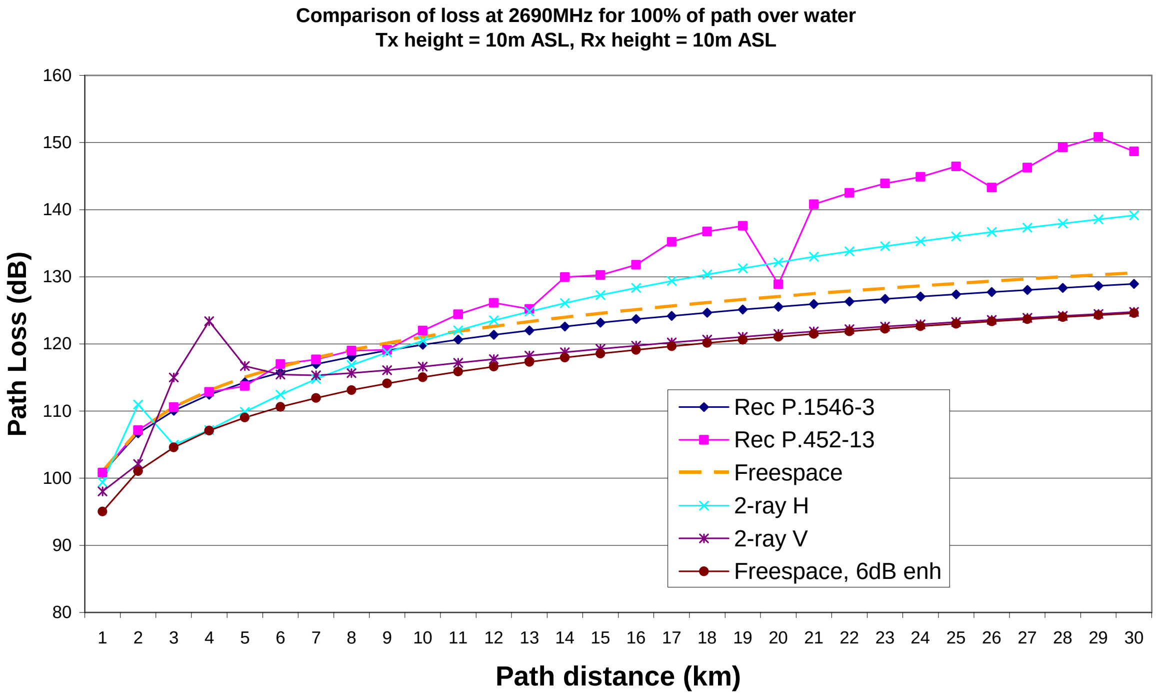


Figure 28: Path loss over sea water at 2690 MHz for mobile ship radar scenarios, for the various propagation models, with a base station antenna height of 10m above sea level

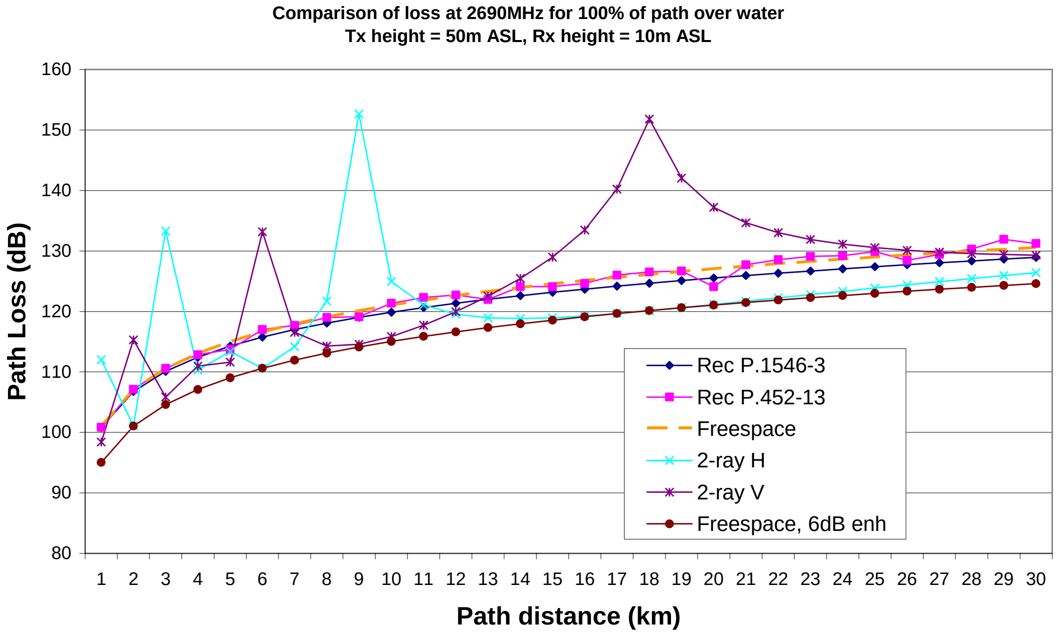


Figure 29: Path loss over sea water at 2690 MHz for mobile ship radar scenarios, for the various propagation models, with a base station antenna height of 50m above sea level

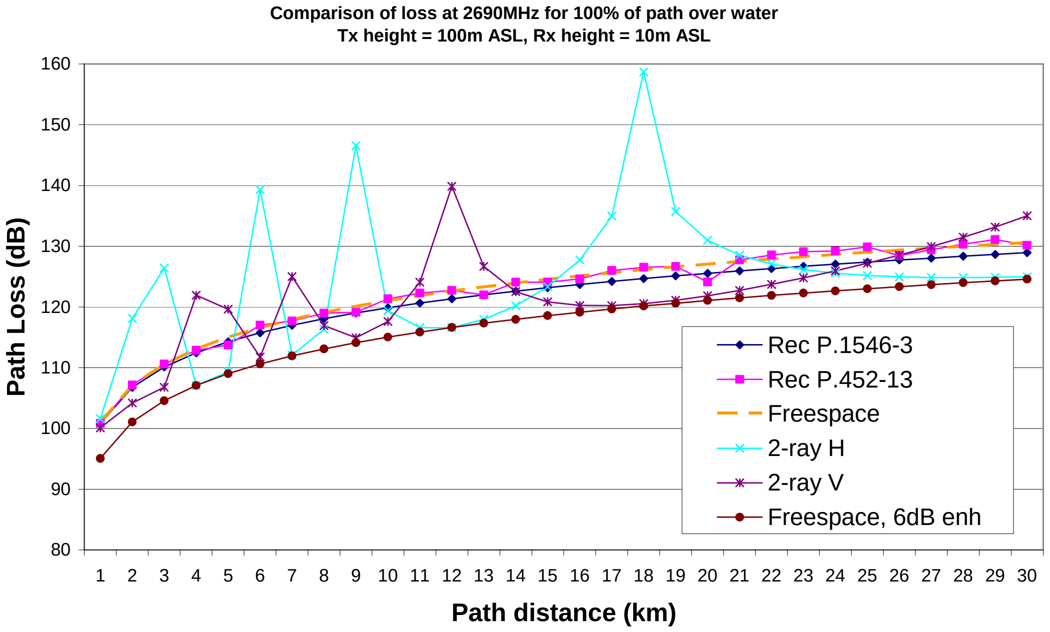


Figure 30: Path loss over sea water at 2690 MHz for mobile ship radar scenarios, for the various propagation models, with a base station antenna height of 100m above sea level

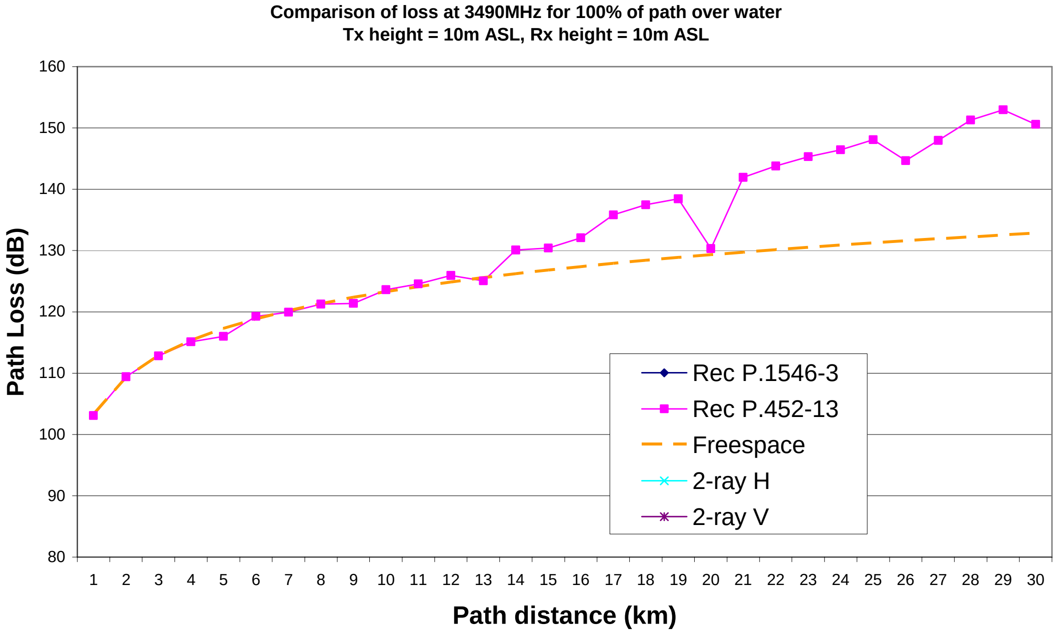


Figure 31: Path loss over sea water at 3490 MHz for mobile ship radar scenarios, for the various propagation models, with a base station antenna height of 10m above sea level

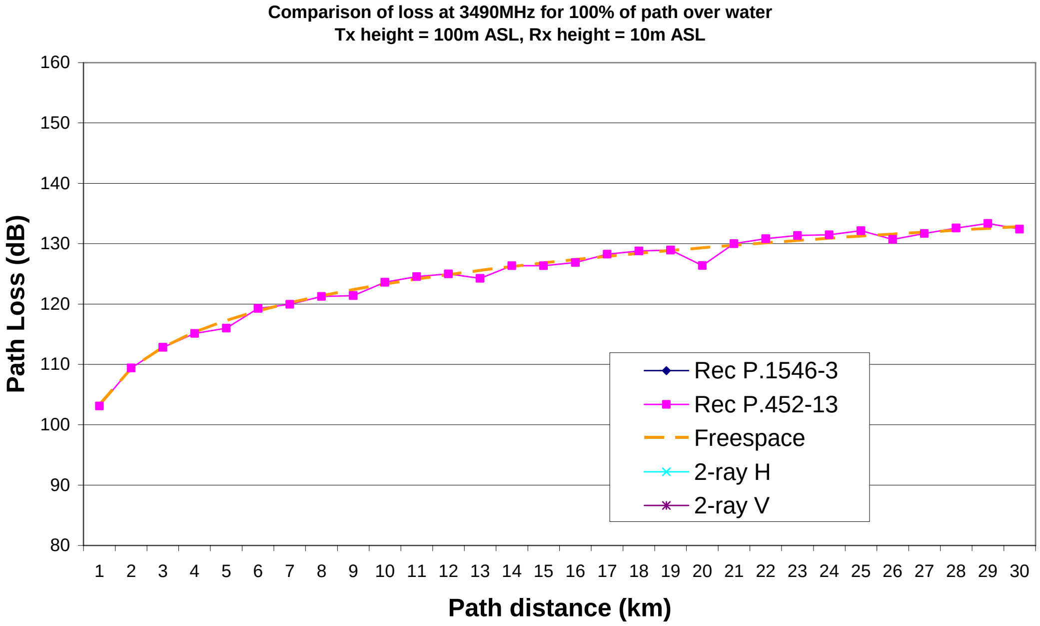


Figure 32: Path loss over sea water at 3490 MHz for mobile ship radar scenarios, for the various propagation models, with a base station antenna height of 100m above sea level

For VTS scenarios, where the interference is over land, the propagation model has assumed base station heights of 10m and 20m above ground level and a receiver height of 10m above ground level. A comparison of path loss using free-space, P.452 and P.1546 at both 2690 MHz and 3490 MHz is given in Figure 33 for a base station height of 10m above ground level and in Figure 34 for a base station height of 20m above ground level. The estimated separation distances results in Section 5.5 also use the modified Hata model. Some propagation models (e.g. P.1546 and modified Hata) are limited to frequencies below 3 GHz, however, these have also been used for frequencies above 3 GHz by extrapolating the data.

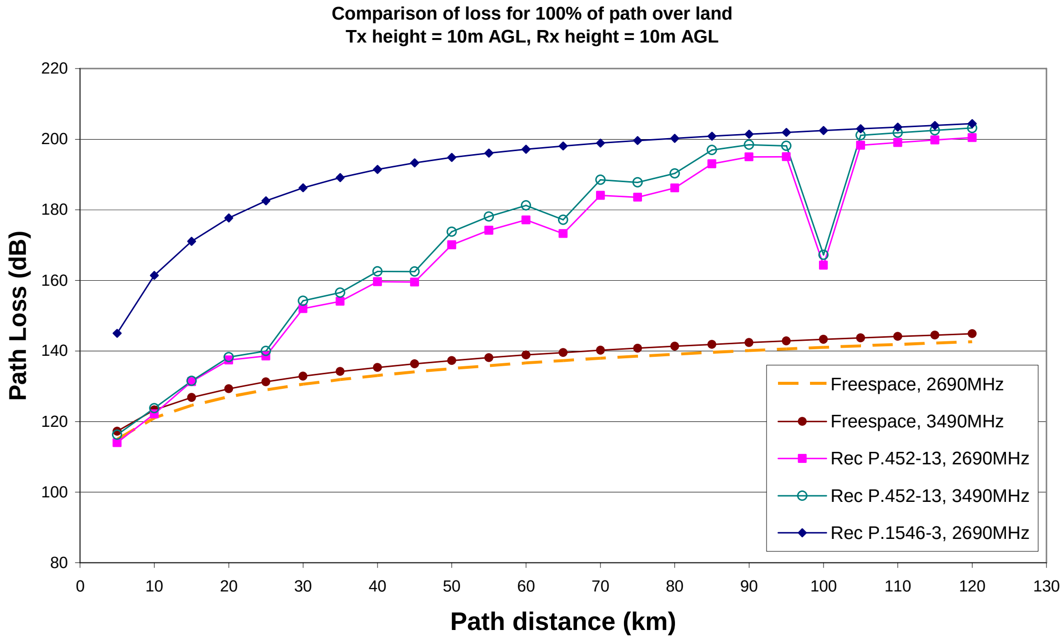


Figure 33: Path loss over land at 2690 MHz and 3490 MHz for VTS scenarios, for the various propagation models, with a base station antenna height of 10m above ground level

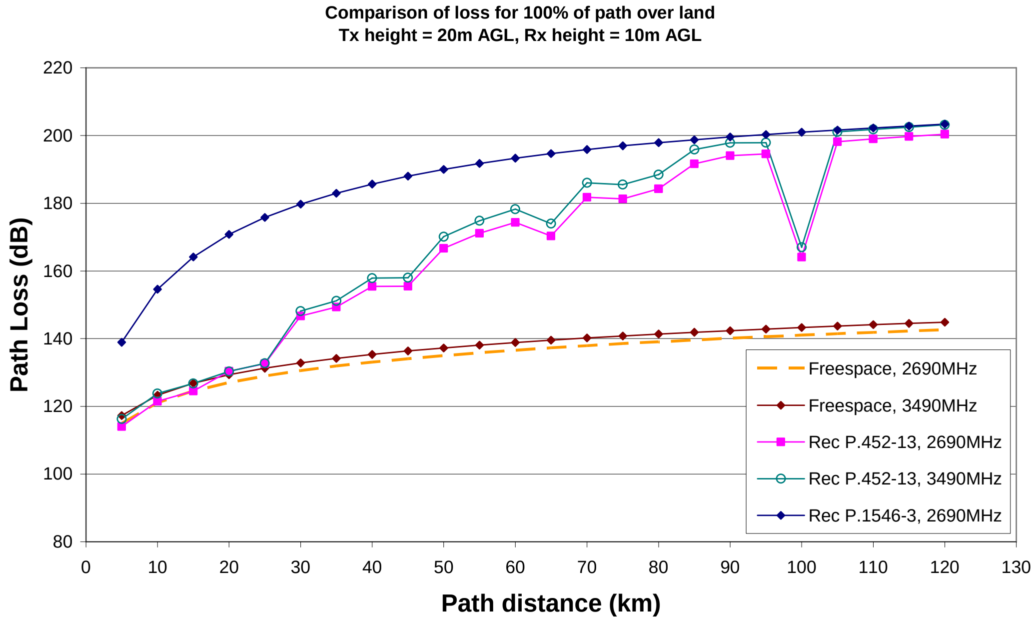


Figure 34: Path loss over land at 2690 MHz and 3490 MHz for VTS scenarios, for the various propagation models, with a base station antenna height of 20m above ground level

5.5 Estimated Separation Distances

For mobile maritime radar, scenario 1) represents the worst-case and scenario 2) represents the best-case. Scenario 3) will be slightly less worst-case than scenario 1). Therefore, just scenario 1) and 2) are calculated here.

The estimated separation distances have been calculated for scenario 1), emissions from the mainbeam of a base station at the edge of the coast to mobile maritime radar, in Table 11 for magnetron radar and Table 12 for solid-state radar.

For scenarios 2), 6) and 7) the antenna to antenna coupling is reduced by 20 dB, either by the base station antenna or the radar antenna. For scenario 2), the estimated separation distances have been calculated, in Table 13 for magnetron radar and in Table 14 for solid-state radar. For scenarios 6) and 7), the estimated separation distances have been calculated, in Table 15 for magnetron radar.

For scenarios 4) and 8) the antenna to antenna coupling is reduced by 40 dB, 20 dB for the base station antenna and 20 dB for the radar antenna. For scenario 4), the estimated separation distances have been calculated, in Table 16 for magnetron radar and Table 17 for solid-state radar. For scenario 8), the estimated separation distances have been calculated, in Table 18 for magnetron radar and Table 19 for solid-state radar.

Table 11: Estimated separation distances for magnetron radar for scenario 1), emissions from base station antenna mainbeam over sea

Mechanism	Radar Frequency	Interference Frequency	Worst-Case sensitivity*	Required Path Loss	Estimated Separation Distance					
					FS + 6dB, Tx height = 10m, 50m, 100m	FS, Tx height = 10m, 50m, 100m	P.452, Tx height = 10m	P.452, Tx height = 50m	P.452, Tx height = 100m	P.1546
Amplifier saturation	3050MHz	2690MHz	3dBm	86dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3050MHz	3490MHz	-38dBm	123dB	18km	9km	9km	9km	9km	10km
OOB in IF pass band	2900MHz; 3050MHz	2690MHz	-110dBm**	106dB	3km	1.6km	1.6km	1.6km	1.6km	1.6km
Amplifier saturation	2900MHz	2690MHz	-18dBm	107dB	3km	1.8km	1.8km	1.8km	1.8km	2.0km
Amplifier saturation	2900MHz	3490MHz	-35dBm	120dB	13km	6km	6km	6km	6km	7km
OOB in IF pass band	2900MHz	3490MHz	-110dBm**	137dB	116km	58km	17km	58km	58km	70km
OOB in IF pass band	3050MHz	3490MHz	-110dBm**	137dB	110km	55km	17km	55km	55km	66km

*Sensitivity including antenna gain reduction; **in 20MHz bandwidth.

Table 12: Estimated separation distances over sea for solid-state radar for scenario 1), emissions from base station antenna mainbeam

Mechanism	Radar Frequency	Interference Frequency	Worst-Case sensitivity*	Required Path Loss	Estimated Separation Distance					
					FS + 6dB, Tx height = 10m, 50m, 100m	FS, Tx height = 10m, 50m, 100m	P.452, Tx height = 10m	P.452, Tx height = 50m	P.452, Tx height = 100m	P.1546
Amplifier saturation	2900MHz	2690MHz	-36dBm	125dB	31km	15km	11km	16km	16km	18km
Amplifier saturation	2900MHz	3490MHz	-16dBm	101dB	1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3000MHz	2690MHz	-33dBm	122dB	17km	8km	9km	9km	9km	10km
Amplifier saturation	3000MHz	3490MHz	-15dBm	100dB	1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3100MHz	2690MHz	-30dBm	119dB	12km	6km	5km	5km	5km	7km
Amplifier saturation	3100MHz	3490MHz	-20dBm	105dB	1km	<1km	<1km	<1km	<1km	<1km
OOB in IF pass band	2900MHz, 3000MHz, 3100MHz	2690MHz	-110dBm**	106dB	3km	1.6km	1.6km	1.6km	1.6km	1.6km
OOB in IF pass band	2900MHz	3490MHz	-110dBm**	137dB	116km	58km	17km	58km	58km	70km
OOB in IF pass band	3000MHz	3490MHz	-110dBm**	137dB	112km	56km	17km	56km	56km	67km
OOB in IF pass band	3100MHz	3490MHz	-110dBm**	137dB	108km	54km	17km	54km	54km	65km

*Sensitivity including antenna gain reduction; **in 20MHz bandwidth.

Table 13: Estimated separation distances over sea for magnetron radar for scenario 2) for total antenna-antenna coupling reduction of 20dB

Mechanism	Radar Frequency	Interference Frequency	Worst-Case sensitivity*	Required Path Loss	Estimated Separation Distance					
					FS + 6dB, Tx height = 10m, 50m, 100m	FS, Tx height = 10m, 50m, 100m	P.452, Tx height = 10m	P.452, Tx height = 50m	P.452, Tx height = 100m	P.1546
Amplifier saturation	3050MHz	2690MHz	3dBm	66dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3050MHz	3400MHz	-38dBm	103dB	1.8km	<1km	<1km	<1km	<1km	<1km
OOB in IF pass band	2900MHz; 3050MHz	2690MHz	-110dBm**	86dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	2900MHz	2690MHz	-18dBm	87dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	2900MHz	3400MHz	-35dBm	100dB	1.4km	<1km	<1km	<1km	<1km	<1km
OOB in IF pass band	2900MHz	3400MHz	-110dBm**	117dB	12km	6km	6km	6km	6km	7km
OOB in IF pass band	3050MHz	3400MHz	-110dBm**	117dB	11km	5km	5km	5km	5km	6km

*Sensitivity including antenna gain reduction; **in 20MHz bandwidth.

Table 14: Estimated separation distances over sea for solid-state radar for scenarios 2), for total antenna-antenna coupling reduction of 20dB

Mechanism	Radar Frequency	Interference Frequency	Worst-Case sensitivity*	Required Path Loss	Estimated Separation Distance					
					FS + 6dB, Tx height = 10m, 50m, 100m	FS, Tx height = 10m, 50m, 100m	P.452, Tx height = 10m	P.452, Tx height = 50m	P.452, Tx height = 100m	P.1546
Amplifier saturation	2900MHz	2690MHz	-36dBm	105dB	3km	1.6km	1.6km	1.6km	1.6km	1.6km
Amplifier saturation	2900MHz	3400MHz	-16dBm	81dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3000MHz	2690MHz	-33dBm	102dB	2.2km	1.0km	1.0km	1.0km	1.0km	<1.0km
Amplifier saturation	3000MHz	3400MHz	-15dBm	80dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3100MHz	2690MHz	-30dBm	99dB	1.6km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3100MHz	3400MHz	-20dBm	85dB	<1km	<1km	<1km	<1km	<1km	<1km
OOB in IF pass band	2900MHz, 3000MHz, 3100MHz	2690MHz	-110dBm**	86dB	<1km	<1km	<1km	<1km	<1km	<1km
OOB in IF pass band	2900MHz	3400MHz	-110dBm**	117dB	12km	6km	6km	6km	6km	7km
OOB in IF pass band	3000MHz	3400MHz	-110dBm**	117dB	11km	5km	5km	5km	5km	6km
OOB in IF pass band	3100MHz	3400MHz	-110dBm**	117dB	10km	5km	5km	5km	5km	5km

*Sensitivity including antenna gain reduction; **in 20MHz bandwidth.

Table 15: Estimated separation distances over land for magnetron radar for scenarios 6) and 7), for total antenna-antenna coupling reduction of 20dB

Mechanism	**Radar Frequency**	**Interference Frequency**	**Worst-Case sensitivity***	**Required Path Loss**	**Estimated Separation Distance, Worst-case for Tx heights of 10m and 20m**				
					FS + 6dB	**FS**	**P.1546 *****	**P.452 *****	**Modified-Hata, Open Area**
Amplifier saturation	3050MHz	2690MHz	3dBm	66dB	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3050MHz	3400MHz	-38dBm	103dB	1.8km	<1km	<1km	<1km	<1km
OOB in IF pass band	2900MHz; 3050MHz	2690MHz	-110dBm**	86dB	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	2900MHz	2690MHz	-18dBm	87dB	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	2900MHz	3400MHz	-35dBm	100dB	1.4km	<1km	<1km	<1km	<1km
OOB in IF pass band	3050MHz	3400MHz	-110dBm**	117dB	12km	6km	<1km	6km	5.8km
OOB in IF pass band	3050MHz	3400MHz	-110dBm**	117dB	11km	5km	<1km	5km	5.5km

*Sensitivity including antenna gain reduction; **in 20MHz bandwidth; ***Assumes flat terrain

Table 16: Estimated separation distances over sea for magnetron radar for scenario 4), for total antenna-antenna coupling reduction of 40dB

Mechanism	Radar Frequency	Interference Frequency	Worst-Case sensitivity*	Required Path Loss	Estimated Separation Distance					
					FS + 6dB, Tx height = 10m, 50m, 100m	FS, Tx height = 10m, 50m, 100m	P.452, Tx height = 10m	P.452, Tx height = 50m	P.452, Tx height = 100m	P.1546
Amplifier saturation	3050MHz	2690MHz	3dBm	46dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3050MHz	3400MHz	-38dBm	83dB	<1km	<1km	<1km	<1km	<1km	<1km
OOB in IF pass band	2900MHz; 3050MHz	2690MHz	-110dBm**	66dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	2900MHz	2690MHz	-18dBm	67dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	2900MHz	3400MHz	-35dBm	80dB	<1km	<1km	<1km	<1km	<1km	<1km
OOB in IF pass band	2900MHz; 3050MHz	3400MHz	-110dBm**	97dB	1.2km	1km	1km	1km	1km	1km
OOB in IF pass band	2900MHz; 3050MHz	3400MHz	-110dBm**	97dB	1.0km	1km	1km	1km	1km	1km

*Sensitivity including antenna gain reduction; **in 20MHz bandwidth

Table 17: Estimated separation distances over sea for solid-state radar for scenarios 4), for total antenna-antenna coupling reduction of 40dB

Mechanism	Radar Frequency	Interference Frequency	Worst-Case sensitivity*	Required Path Loss	Estimated Separation Distance					
					FS + 6dB, Tx height = 10m, 50m, 100m	FS, Tx height = 10m, 50m, 100m	P.452, Tx height = 10m	P.452, Tx height = 50m	P.452, Tx height = 100m	P.1546
Amplifier saturation	2900MHz	2690MHz	-36dBm	85dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	2900MHz	3400MHz	-16dBm	61dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3000MHz	2690MHz	-33dBm	82dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3000MHz	3400MHz	-15dBm	60dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3100MHz	2690MHz	-30dBm	79dB	<1km	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3100MHz	3400MHz	-20dBm	65dB	<1km	<1km	<1km	<1km	<1km	<1km
OOB in IF pass band	2900MHz, 3000MHz, 3100MHz	2690MHz	-110dBm**	66dB	<1km	<1km	<1km	<1km	<1km	<1km
OOB in IF pass band	2900MHz	3400MHz	-110dBm**	97dB	1.2km	<1km	<1km	<1km	<1km	<1km
OOB in IF pass band	3000MHz; 3100MHz	3400MHz	-110dBm**	97dB	1.0km	<1km	<1km	<1km	<1km	<1km

*Sensitivity including antenna gain reduction; **in 20MHz bandwidth.

Table 18: Estimated separation distances over land for magnetron radar for scenarios 8), for total antenna-antenna coupling reduction of 40dB

Mechanism	Radar Frequency	Interference Frequency	Worst-Case sensitivity*	Required Path Loss	Estimated Separation Distance, Worst-case for Tx heights of 10m and 20m				
					FS + 6dB	FS	P.1546**	P.452**	Modified-Hata, Open Area
Amplifier saturation	3050MHz	2690MHz	3dBm	66dB	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3050MHz	3400MHz	-38dBm	103dB	<1km	<1km	<1km	<1km	<1km
OOB emissions in IF pass band	2900MHz; 3050MHz	2690MHz	-110dBm**	86dB	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	2900MHz	2690MHz	-18dBm	87dB	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	2900MHz	3490MHz	-35dBm	100dB	<1km	<1km	<1km	<1km	<1km
OOB in IF pass band	2900MHz;	3490MHz	-110dBm**	117dB	1.2km	<1km	<1km	<1km	<1km
OOB in IF pass band	3050MHz	3490MHz	-110dBm**	117dB	1.0km	<1km	<1km	<1km	<1km

*Sensitivity including antenna gain reduction; **in 20MHz bandwidth; ***Assumes flat terrain.

Table 19: Estimated separation distances over land for solid-state radar for scenarios 8), for total antenna-antenna coupling reduction of 40dB

Mechanism	Radar Frequency	Interference Frequency	Worst-Case sensitivity*	Required Path Loss	Estimated Separation Distance, Worst-case for Tx heights of 10m and 20m				
					FS + 6dB	FS	P.1546**	P.452**	Modified-Hata, Open Area
Amplifier saturation	2900MHz	2690MHz	-36dBm	85dB	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	2900MHz	3400MHz	-16dBm	61dB	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3000MHz	2690MHz	-33dBm	82dB	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3000MHz	3400MHz	-15dBm	60dB	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3100MHz	2690MHz	-30dBm	79dB	<1km	<1km	<1km	<1km	<1km
Amplifier saturation	3100MHz	3400MHz	-20dBm	65dB	<1km	<1km	<1km	<1km	<1km
OOB in IF pass band	2900MHz, 3000MHz, 3100MHz	2690MHz	-110dBm**	66dB	<1km	<1km	<1km	<1km	<1km
OOB in IF pass band	2900MHz,	3400MHz	-110dBm**	97dB	1.2km	<1km	<1km	<1km	<1km
OOB in IF pass band	3000MHz	3400MHz	-110dBm**	97dB	1.0km	<1km	<1km	<1km	<1km
OOB in IF pass band	3100MHz	3400MHz	-110dBm**	97dB	1.0km	<1km	<1km	<1km	<1km

*Sensitivity including antenna gain reduction; **in 20MHz bandwidth; ***Assumes flat terrain.

5.6 Summary of Estimated Separation Distances

The separation distances estimate in Section 5.5 have been summarised for each of the main interference mechanisms and scenarios. For mobile ship radar, two scenarios are considered, mainbeam-to-mainbeam interference and mainbeam-to-sidelobe interference where an antenna coupling loss of 20 dB has been used. In both cases, all of the propagation is considered to be over sea. For magnetron radar, the results are shown in Table 20 and Table 21. For solid state radar, the results are shown in Table 22 and Table 23.

For proposed communications services in the band 2500 MHz to 2690 MHz, assuming worst-case mainbeam-to-mainbeam antenna coupling, the required separation distances for magnetron radar appear to be below 2 km for both amplifier saturation and OOB emissions falling in the radar IF pass band. For solid-state radar, the required separation distances appear to be below 2 km for OOB emissions falling in the radar IF pass band, but about 15 km for amplifier saturation.

For existing communications services in the band 3480 MHz to 3500 MHz, assuming worst-case mainbeam-to-mainbeam antenna coupling, the required separation distances for magnetron radar are estimated to be about 9km for amplifier saturation and about 60 km to 70 km for OOB emissions falling in the radar IF pass band. For solid-state radar, the required separation distances appear to be less than 2 km for amplifier saturation, but about 60 km to 70 km for OOB emissions falling in the radar IF pass band.

Therefore, for mobile ship radar, OOB emissions in the band 3480 MHz to 3500 MHz appear to require the largest separation distances for both magnetron and solid-state radar. In terms of amplifier saturation, magnetron radar appears to be most susceptible to existing systems in the 3480 MHz to 3500 MHz band (~ 9 km) whereas solid-state radar appears to be most susceptible to proposed systems in the 2500 MHz to 2690 MHz band (~15 km). However, it should be stressed that the solid-state radar performance was based on a first-pass estimate by the radar manufacturer as being similar to the Watchman radar and this would require further investigation.

For OOB emissions falling into the radar IF pass band of either magnetron or solid-state radar, there might be some reduction in estimated separation distances due to any further transmitting antenna gain reduction at the radar operating frequency (in addition to the 2 dB assumed), and also if the actual OOB emissions are below regulatory limits. In addition, all of these calculations do not include terrain effects, as they are generic and have assumed a flat terrain. Some calculations including terrain effects are discussed in Section 5.7. The potential low probability of achieving mainbeam-to-mainbeam interference might also provide some mitigation although this would need further justification. If mainbeam-to-sidelobe interference could be considered the appropriate mechanism then estimated separation distances for all ship radar scenarios would be below about 7 km.

If in reality the effective EIRP of the OOB emissions from the 3480 MHz to 3500 MHz band was 10 dB lower than the assumed worst-case for example, then the estimated separation distance would reduced from about 75 km to about 25 km. A reduction of about 27 dB would be required to reduce the estimated separation distance from about 75 km to about 3 km. If this does not already exist then it is expected that better filtering and antenna selection for services in the band 3480 MHz to 3500 MHz should be able to achieve this.

For VTS radar, only mainbeam-to-sidelobe interference is considered and all of the interference is over land. The results are shown in Table 24. The only scenario that results in estimated separation distances in excess of 1km are OOB emissions from existing services in the band 3480 MHz to 3500 MHz (~6 km).

Table 20:
Mobile ship magnetron radar, with mainbeam-to-mainbeam interference and all propagation over sea

Interference Mode	Interference Channel Frequency	Free-space	P1546	P.452	Comments
Amplifier saturation	<2690MHz	1.8 km	2.0 km	1.8 km	Worst-case for radar centred at 2900MHz
OOB emissions	<2690MHz	1.6 km	1.6 km	1.6 km	Might be further reduction due to transmitting antenna gain reduction at 2900MHz, and OOB emissions below regulatory limits
Amplifier saturation	3490MHz	9.0 km	10.0 km	9.0 km	Worst-case for radar centred at 3050MHz
OOB emissions	3490MHz	58.0 km	70.0 km	58.0 km	Might be further reduction due to transmitting antenna gain reduction at 3050MHz, and OOB emissions below regulatory limits

Table 21:
Mobile ship magnetron radar, with mainbeam-to-sidelobe interference and all propagation over sea

Interference Mode	Interference Channel Frequency	Free-space	P1546	P.452	Comments
Amplifier saturation	<2690MHz	<1 km	<1 km	<1 km	Worst-case for radar centred at 2900MHz
OOB emissions	<2690MHz	<1 km	<1 km	<1 km	Might be further reduction due to transmitting antenna gain reduction at 2900MHz, and OOB emissions below regulatory limits
Amplifier saturation	3490MHz	<1 km	<1 km	<1 km	Worst-case for radar centred at 3050MHz
OOB emissions	3490MHz	6.0 km	7.0 km	6.0 km	Might be further reduction due to transmitting antenna gain reduction at 3100MHz, and OOB emissions below regulatory limits

Table 22:
Mobile ship solid-state radar, with mainbeam-to-mainbeam interference and all propagation over sea

Interference Mode	Interference Channel Frequency	Free-space	P1546	P.452	Comments
Amplifier saturation	<2690MHz	15 km	18 km	16 km	Worst-case for radar centred at 2900MHz
OOB emissions	<2690MHz	1.6 km	1.6 km	1.6 km	Might be further reduction due to transmitting antenna gain reduction at 2900MHz, and OOB emissions below regulatory limits
Amplifier saturation	3490MHz	1.2 km	1.2 km	1.2 km	Worst-case for radar centred at 3050MHz
OOB emissions	3490MHz	58.0 km	70.0 km	58.0 km	Might be further reduction due to transmitting antenna gain reduction at 3050MHz, and OOB emissions below regulatory limits

Table 23:
Mobile ship solid-state radar, with mainbeam-to-sidelobe interference and all propagation over sea

Interference Mode	Interference Channel Frequency	Free-space	P1546	P.452	Comments
Amplifier saturation	<2690MHz	1.6 km	1.6 km	1.6 km	Worst-case for radar centred at 2900MHz
OOB emissions	<2690MHz	<1 km	<1 km	<1 km	Might be further reduction due to transmitting antenna gain reduction at 2900MHz, and OOB emissions below regulatory limits
Amplifier saturation	3490MHz	<1 km	<1 km	<1 km	Worst-case for radar centred at 3050MHz
OOB emissions	3490MHz	6.0 km	7.0 km	6.0 km	Might be further reduction due to transmitting antenna gain reduction at 3100MHz, and OOB emissions below regulatory limits

Table 24:
VTS magnetron radar, with mainbeam-to-sidelobe interference and all propagation over land

Interference Mode	Interference Channel Frequency	Free-space	P1546	P.452	Modified Hata	Comments
Amplifier saturation	<2690MHz	<1 km	<1 km	<1 km	<1 km	Worst-case for radar centred at 2900MHz
OOB emissions	<2690MHz	<1 km	<1 km	<1 km	<1 km	
Amplifier saturation	3490MHz	<1 km	<1 km	<1 km	<1 km	Worst-case for radar centred at 3050MHz
OOB emissions	3490MHz	6.0 km	<1km	6.0 km	5.8 km	Might be further reduction due to transmitting antenna gain reduction at 3050MHz, and OOB emissions below regulatory limits

5.7 Inclusion of Terrain Effects and Shipping Lanes

The MCA have provided information on typical shipping routes in the most congested area of the UK, in the English Channel. This information was obtained from Automatic Identification System (AIS) data.

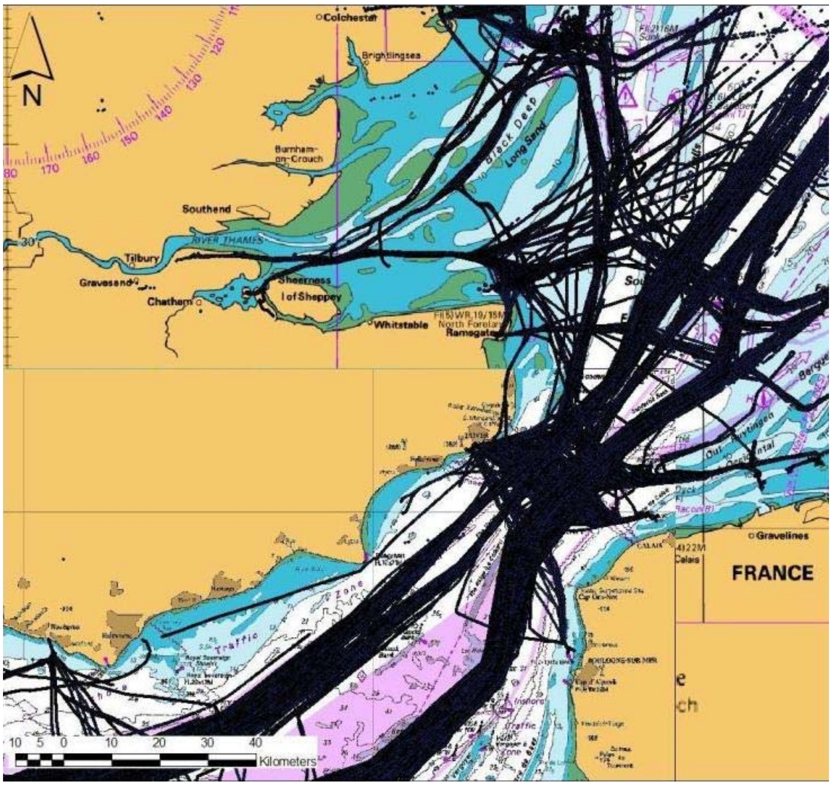


Figure 35: AIS data for typical traffic routes in the English Channel

This main routes which are closest to the coast, Figure 36, have been used to calculate the estimated protection areas on land based on the parameters used in previous sections but including land terrain. The propagation model P.452 has been used and a base station transmitter height of 20m above ground and a radar receiver height of 10m above sea level were used.

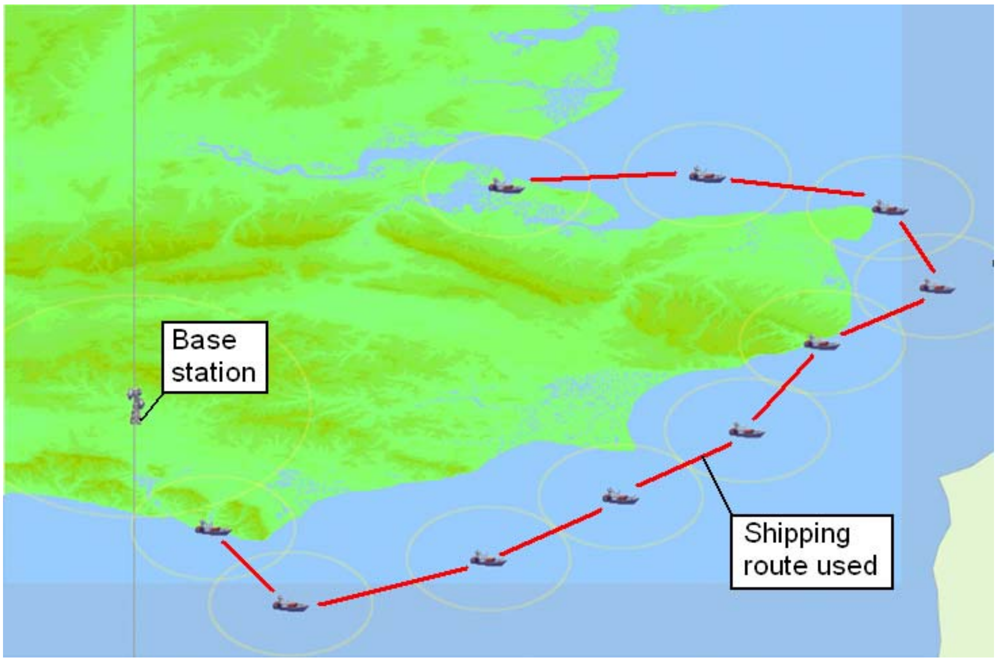


Figure 36: Shipping route used for terrain modelling

The estimated protection areas required for OOB emissions from existing services in the band 3480 MHz to 3500 MHz to ship magnetron radar are shown in Figure 37. This estimates required protection areas around the entire coast which extend up to between about 5 km to 20 km inland. This compares to generic separation distances assuming flat terrain of about 24 km to 27 km using P.452 and the Modified-Hata model and assuming flat terrain.

The estimated protection areas required for amplifier saturation from existing services in the band 3480 MHz to 3500 MHz to ship magnetron radar are shown in Figure 38. There are 4 small areas where the required protection area extends up to about 1km inland and one area where it extends about 10 km inland.

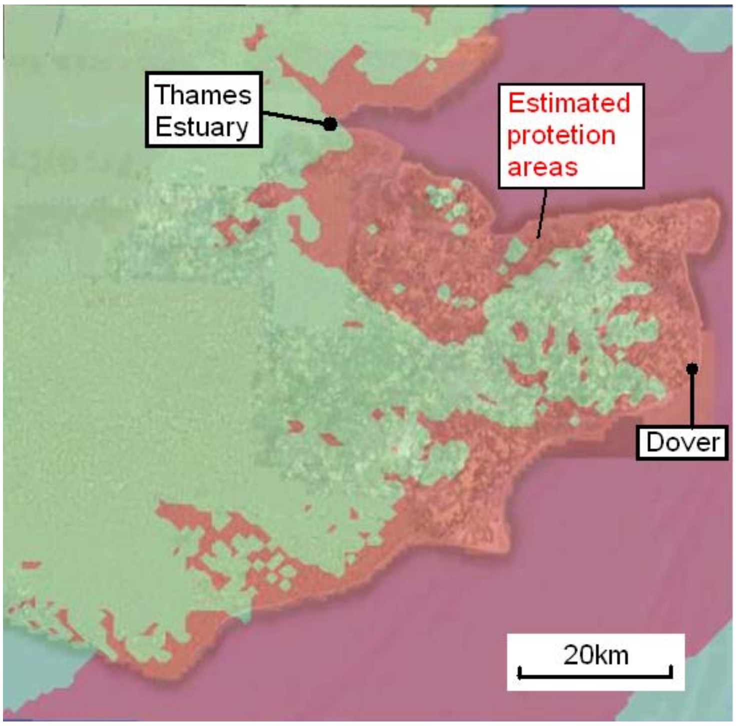


Figure 37: OOB emissions from existing services in the band 3480 MHz to 3500 MHz to ship magnetron radar

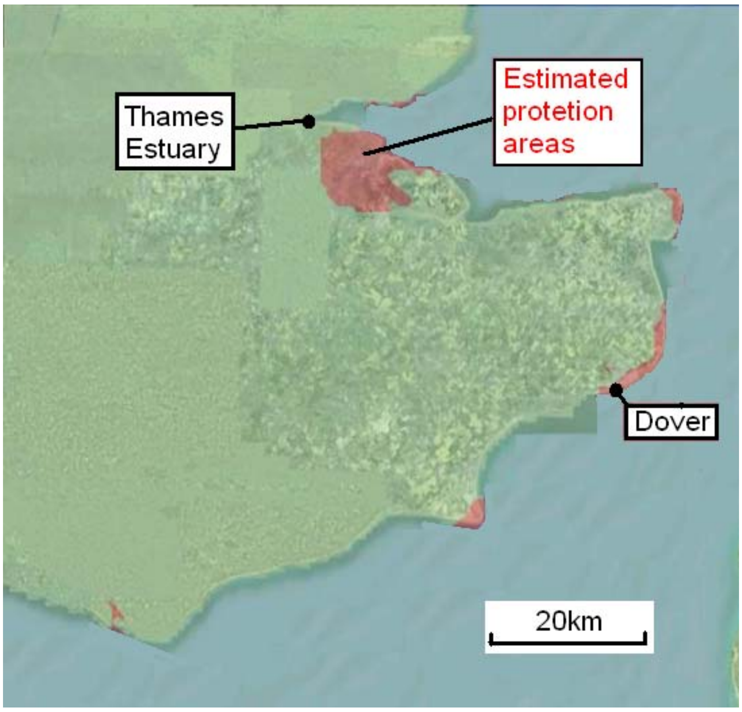


Figure 38: Amplifier saturation from existing services in the band 3480 MHz to 3500 MHz to ship magnetron radar

6. Possible Further Work

Possible further work is listed below:

- Further investigation of the sensitivity at 3400 MHz on the current magnetron radar as this appears to be one of the limiting cases; Some limited laboratory testing on a second manufacturer's magnetron radar to confirm the similarity in sensitivity;
- Laboratory testing of the sensitivity of the solid-state radar as this is currently based on the manufacturers best guess that this might be similar to the watchman radar.
- Consideration of any practical mitigations. Investigate potential mitigations for 3480 MHz including measurement of antenna gain loss and EIRP reduction at the radar frequencies, potential for quick and low cost filtering to provide additional mitigation if required. Investigate the potential for providing filtering on solid-state radar if required.
- Full terrain modelling of scenarios.
- Further consideration of the functional impact on radar by consideration of the scenarios, movement of ships and targets and the statistical probability of being affected;
- Field tests to give confidence of the predicted separation distances under live conditions;

7. Conclusions

Testing was performed on a magnetron S-band maritime radar in a laboratory to investigate the radar's sensitivity to communications systems in the band 2500 MHz to 2690 MHz and the band 3400 MHz to 3600 MHz. Discussions were held with radar manufacturers to identify how similar the results of the radar being tested was likely to be to other mobile ship radars and VTS radar. There is no measurement data available on the sensitivity of solid-state radars to interference below 2690 MHz and above 3400 MHz. One of the sold-state radars manufacturers has suggested that, as a first-pass assumption, the sensitivity of the Watchman radar is used as there are significant similarities in the design of both.

Two interference mechanisms were investigated, the communications system channel power saturating amplifiers in the radar receiver chain and out-of-band (OOB) emissions falling into the radar IF pass band. An additional filter was used to reduce the OOB emission levels to help identify which was the dominant interference mechanism in each case.

Required protection distances were estimated using a number of different propagation models and these separation distances ranged from less than 1km up to distances in the region of 60 km to 70 km, assuming flat terrain. Some limited terrain simulations have been performed to demonstrate how this might help reduce these protection distances. A number of other potential mitigations have also been identified and these would require further investigation. A more detailed summary in given in the Executive Summary section at the front of the report.

8. References

[1] ERA Technology Report 2008-0491, "Proof-of-Concept Testing for Bandsharing: Maritime Radar", September 2008

[2] NTIA Report TR-06-444, "Effect of RF interference on radar receivers", September 2006.

[3] "Study to establish measurement parameters for testing radar bandsharing performance", QinetiQ study for Ofcom, October 2007.