A report prepared for the

Maritime and Coastguard Agency

CO42: Expert Advice – Radio Spectrum Liberalisation

Final Report
5 March 2008

Dr Andy Norris *Navigation Systems Consultancy*

12 Chandlers Quay, Maldon, Essex, CM9 4LF, UK

Tel: +44(0)1621 842107 *email:enquiries@DrAndyNorris.co.uk*

Executive Summary

1. Introduction

This is the final report of a brief study for the Maritime and Coastguard Agency which reviews spectrum liberalisation[1] activity to date that may have an influence on the marine radar bands. The report assesses the quality, extent and veracity of conclusions from the trials and studies, as applicable to marine radar. In particular, it looks at the following publicly available documents:

1. Independent Audit of Spectrum Holdings: Final Report, Professor Martin Cave, Her Majesty's Stationery Office, 2005
2. Independent Audit of Spectrum Holdings, Government Response and Action Plan, Cabinet Official Committee on UK Spectrum Strategy, March 2006
3. Forward Look 2007, A Strategy for Management of Major Public Sector Spectrum Holdings, UK Spectrum Strategy Committee
4. Aeronautical and maritime spectrum pricing: Final Report, Indepen Consulting Ltd on behalf of Ofcom, April 2007
5. Spectrum Framework Review Statement, Ofcom, 28 June 2005
6. Decision No 676/2002/EC of The European Parliament and of The Council of 7 March 2002 on a regulatory framework for radio spectrum policy in the European Community (Radio Spectrum Decision), Official Journal of the European Communities, 24 April 2002
7. Study to establish measurement parameters for testing radar bandsharing performance, QinetiQ Ltd on behalf of Ofcom, October 2007
8. Public Spectrum Safety Test Group, PSSTG Series: Introduction to PSSTG, ERA Technology Ltd on behalf of Ofcom, December 2006
9. Public Spectrum Safety Test Group, PSSTG Series Report 1: Initial Measurements of Radiated UWB Interference to Radar, ERA Technology Ltd on behalf of Ofcom, March 2006
10. Public Spectrum Safety Test Group, PSSTG Series Report 2: Initial Bandsharing Trial, ERA Technology Ltd on behalf of Ofcom, April 2006
11. Public Spectrum Safety Test Group, PSSTG Series Report 3: UWB Interference to Maritime Radars - Results of Feasibility Trials, ERA Technology Ltd on behalf of Ofcom, December 2006
12. Assessment of Interference to Maritime Radars - Oban Trial, ERA Technology Ltd on behalf of Ofcom, October 2006
13. Assessment of Interference to Maritime Radars - Oban Trial Report, ERA Technology Ltd on behalf of Ofcom, February 2007

2. Spectrum Liberalisation Proposals – Risk to Maritime

Shipborne radars have some particular characteristics in deployment that make them a special case to be considered: the radar platforms are mobile; the radars are

---

[1] *Spectrum liberalisation reduces restrictions on how spectrum is used while retaining necessary safeguards against harmful interference. Liberalisation enables spectrum to migrate to the most valuable use ….* .(Ofcom, January 2008)

mainly confined to the coast but there is also some extensive landward intrusion, such as in estuaries, ports, rivers and ship canals; many of the radars effectively fall outside the jurisdiction of any special UK or EU laws, providing the radars operate within ITU spectrum-use limits; and the radars are often used to their limit, detecting small targets with relatively low probabilities of detection within clutter.

Marine radars share one important characteristic with virtually all radars used within the UK – they are used to give necessary safety advantages. For this reason it is clear that unacceptable degradation in the performance of radars should not occur because of bandsharing. The prime issue is the definition of what amounts to ‘unacceptable degradation’.

There is no evidence that any of the examined technical studies on spectrum liberalisation form a fundamental threat to the safety of marine radar. Not least, no technical proposal has been put forward that is claiming to be definitive.

The strategic and economic-level reports also do not form a threat to marine radar safety. The importance of bandsharing possibilities cannot be denied and at least for marine (shipboard) radar it is difficult to see any safety threat to the possible application of AIP. However, it is also difficult to see how the application of AIP to shipborne radars in the UK will have any real international impact on making them become more efficient users of the spectrum.

There is a potential threat that the application of AIP may reduce the effectiveness of coastal maritime radars and also radar beacons (racons). Decisions on coverage may be unduly influenced by the cost of spectrum licences. If not carefully thought out, the application of AIP could result in less effective coastal surveillance and services, which is clearly undesirable.

3. What additional work is required?

3.1 Establishing human element safety margins

IMO has emphasised that when establishing acceptable interference levels it is important that the human element in radar observation is properly taken into account (MSC.Circ.1250). The list of factors affecting target visibility includes two main human element variables: the ability of the operator to optimally adjust the radar; and the operator perception of target visibility. It is expected that quantifying these effects can best be done by simulation, using an appropriate sample of experienced operators. The perception simulation should involve both moving and static targets in clear or cluttered conditions and the effective P_d (probability of detection) should be varied to determine the threshold of perception of an operator

3.2 Establishing definitive acceptable interference levels

None of the reports on the theoretical and experimental work examined in this report have established definitive acceptable interference levels for marine radars. It is agreed that encountered interference levels must not prevent a marine radar from achieving its safety-related tasks. The latest international standard for marine radars, IEC 62388, requires radars to operate within an environment where there are other approved marine radars, both in terms of having suitable interference rejection and without causing significant degradation to other approved marine radar systems. There are no system allowances made for any other types of interference. This implies that additional interference needs to create an imperceptible degradation of radar performance. Determining this limit has indeed been a major objective of most of the technical work reviewed in this present report.

In particular, it is the opinion of the author that sea trials cannot determine definitive levels at which interference starts causing degradation in radar performance. This is because of the near impossibility in performing repeatable measurements over a range of variables. A more feasible approach is to use real radars in artificial and therefore repeatable environments, provided these adequately reproduce realistic targets and clutter. Theoretical analysis, target/clutter synthesis and simulation need to be used together to establish quantitative levels for acceptable interference. Some sea trials must be undertaken subsequently to ensure that measured results in the available conditions are consistent with the detailed results obtained by modelling.

3.3 Examine the effects of interference on the detectability of small targets in clutter

It is argued strongly within this report that interference should be particularly evaluated in clutter conditions and for marginal targets, as these are the conditions where the marine radar is being used for safety critical tasks at the limit of its detection capability. It is true that in these conditions the radar is unlikely to be internal noise limited and therefore it may not be the limiting case for the determination of acceptable interference levels. However, it needs to be examined in depth, using appropriate statistical models and human perception trials. It may be the case that in high clutter very small decreases in target detectability can more quickly obscure the target as it merges with the clutter background.

3.4 Examine the effects of interference on coherent (NT) radars

The expected imminent use of coherent (New Technology) radars for shipboard and coastal radars must be examined. It should also be borne in mind that that this type of radar is likely to become the norm for newly fitted radars within 10 years or less, not least because basic versions will be able to be produced at a lower price than magnetron-based radars.

3.5 Examine the effects of ducting on safety

The safety effects caused by the possible ducting of interference in anomalous atmospheric conditions need to be examined. Such conditions, which can result in radars having a range of hundreds of miles, are not uncommon. Under these conditions, marine radar will also more severely interfere with bandsharing terrestrial systems.

3.6 Establish the effect of increased bandsharing of other radars in the marine band

If more aeronautical and defence radars operate in the marine bands the safety effects on all radars needs to be analysed.

3.7 Examine the implications of recently revised ITU Recommendations

There are three Recommendations that are particularly relevant to bandsharing aspects of radar: M1460-1, M.1461-1 and M.1796. The detailed study of these was outside the scope of this report. The implications of the ongoing work at ITU need to be fully understood. The UK must remain in a position to contribute to the work as it is essential to get international consensus on bandsharing within the marine radar bands. (Also see Section 5, below.)

4. Extension to X-Band

There is no doubt that successful implementation of bandsharing and AIP principles at S-Band will eventually result in its extension to X-Band. The technical aspects of bandsharing in either band are very similar and the economic arguments remain the same, including the issues regarding the application of AIP to internationally travelling mobile platforms. Although the use of racons at S-Band may diminish because of the latest IMO radar requirements, their importance at X-Band remains undiminished. AIS AtoNs do not provide an equivalent service to racons and so the replacement of existing racons with AIS-only systems is unlikely. SARTs operate at X-Band only and because they have to be visible to airborne search and rescue services they need to operate over 9.2 - 9.5 GHz, rather than just the marine X-Band (9.3 - 9.5 GHz).

5. Long term future of Spectrum Liberalisation

Even with increased use of fibre-optic links, undoubtedly in the future to every home and business, the pressure on the useable spectrum will inevitably rise. This will continue to put pressure on: increased bandsharing; using more effective modulations; and limiting peak powers

Clearly, marine radar will not be immune to this trend. Importantly, the use of pulse compression from solid-state transmitters has potential benefits in an increasingly congested future. It is likely that most new radars will use this technology within 10 years.

The pressure from the UK for spectrum liberalisation is likely to extend to the whole of the EU. However, on a global basis this is perhaps unlikely in the short to medium term, as many countries are locked into command and control hierarchies and would not support market forces leading the way

This makes it difficult to see how the use of AIP in the marine radar bands within the UK will markedly influence international requirements. Bandsharing principles within these bands should be regulated by the ITU. The UK should influence EU countries and other like-minded nations to get suitable changes made at ITU, which in the future could include radical changes to marine radar modulation requirements. In this way both safety and the efficient use of spectrum can be maintained.

List of Contents

1. Introduction

This is the final report of a brief study for the Maritime and Coastguard Agency which reviews spectrum liberalisation activity to date that may have an influence on the marine radar bands. Ofcom has noted that: *spectrum liberalisation reduces restrictions on how spectrum is used while retaining necessary safeguards against harmful interference. Liberalisation enables spectrum to migrate to the most valuable use …*[1]

This report assesses the quality, extent and veracity of conclusions from the trials and studies, as applicable to marine radar. In particular, it looks at the following publicly available documents:

1. Independent Audit of Spectrum Holdings: Final Report, Professor Martin Cave, Her Majesty's Stationery Office, 2005
2. Independent Audit of Spectrum Holdings, Government Response and Action Plan, Cabinet Official Committee on UK Spectrum Strategy, March 2006
3. Forward Look 2007, A Strategy for Management of Major Public Sector Spectrum Holdings, UK Spectrum Strategy Committee
4. Aeronautical and maritime spectrum pricing: Final Report, Indepen Consulting Ltd on behalf of Ofcom, April 2007
5. Spectrum Framework Review Statement, Ofcom, 28 June 2005
6. Decision No 676/2002/EC of The European Parliament and of The Council of 7 March 2002 on a regulatory framework for radio spectrum policy in the European Community (Radio Spectrum Decision), Official Journal of the European Communities, 24 April 2002
7. Study to establish measurement parameters for testing radar bandsharing performance, QinetiQ Ltd on behalf of Ofcom, October 2007
8. Public Spectrum Safety Test Group, PSSTG Series: Introduction to PSSTG, ERA Technology Ltd on behalf of Ofcom, December 2006
9. Public Spectrum Safety Test Group, PSSTG Series Report 1: Initial Measurements of Radiated UWB Interference to Radar, ERA Technology Ltd on behalf of Ofcom, March 2006
10. Public Spectrum Safety Test Group, PSSTG Series Report 2: Initial Bandsharing Trial, ERA Technology Ltd on behalf of Ofcom, April 2006
11. Public Spectrum Safety Test Group, PSSTG Series Report 3: UWB Interference to Maritime Radars - Results of Feasibility Trials, ERA Technology Ltd on behalf of Ofcom, December 2006
12. Assessment of Interference to Maritime Radars - Oban Trial, ERA Technology Ltd on behalf of Ofcom, October 2006
13. Assessment of Interference to Maritime Radars - Oban Trial Report, ERA Technology Ltd on behalf of Ofcom, February 2007

---

[1] Spectrum framework review for the public sector – statement, Ofcom, 31 January 2008.

The Report is organised into three main sections. **Increasing Spectrum Efficiency**, introduces the concept of frequency efficiency and discusses the recommendations from Documents 1-6 listed above that impact marine radar. These documents are mainly of a policy nature and set the overall framework. However, Document 4 discusses the application of more general policies to the specific areas of maritime and aeronautical.

The next section, **Bandsharing with Marine Radar**, starts off discussing the issues behind radar bandsharing in a manner that is as non-technical as possible. However, within the time limitation of the study it cannot double as a radar textbook and so it is assumed that the reader is acquainted with some basic knowledge of the subject. Documents 7 – 13, above, are reviewed in this section.

The final section, **The Way Forward**, firstly summarises the risk to maritime of the spectrum liberalisation proposals. It then:

- Proposes, at a practical level, what additional work is required to enable sharing with an acceptable level of safety
- Hypothesises how the impact might differ between S-Band (where most work has concentrated) and X-Band
- Takes a long-term look at spectrum liberalisation and trading

This section therefore contains the main conclusions of the study.

2. Increasing Spectrum Efficiency

2.1 Introduction

The radio frequency (RF) spectrum has been increasingly exploited since the turn of the 20th century, immediately following the invention of wireless telegraphy in 1896. It soon became clear that the available spectrum was very limited and there needed to be controls to ensure that it was used effectively. Both national and international controls were needed, as well as international standards to ensure compatibility of equipment. International discussions started as soon as 1903, leading to the first International Radiotelegraph Convention in 1906. The agreed regulations formed the Annex to the Convention and have evolved ever since. They are now known as the Radio Regulations and the conferences are held under the auspices of the International Telecommunication Union, a United Nations agency.

Throughout the 20th Century the need for increased spectrum for both commercial and military applications provoked the development of ever more sophisticated technological solutions. These expanded the available spectrum, with the invention of devices and circuitry that could operate at ever higher frequencies; and also enabled the spectrum to be used more effectively, with the development of better modulation technologies.

In the 21st Century it has become particularly clear that the upward spiral in using higher frequencies is becoming less limited by technology but more by fundamental limitations on propagation, including atmospheric and rain attenuation and line-of sight shielding by terrain and buildings. This has put increased emphasis on the development of spectrum efficient techniques, including band sharing. It is recognised that the usable spectrum currently ranges from 9 kHz to around 100 GHz[1].

Much of the detail of spectrum allocation remains in the remit of national governments. In the United Kingdom this is currently by means of the Communications Act (2003). In particular, this Act gives Ofcom specific duties, including ensuring the optimal use of the electromagnetic spectrum. Ofcom was established as a body corporate by the Office of Communications Act 2002. Of particular importance to the role of Ofcom is the “Independent Audit of Spectrum Holdings”[2], referred hereon as the *Cave Report*, which was prepared by Professor Martin Cave and his Audit Team in 2005. The Chancellor of the Exchequer announced the appointment of Professor Cave in 2004: *to undertake a review of major spectrum holdings, aimed at releasing the maximum amount of spectrum to the market and increasing opportunities for the development of innovative new services.*

The present report is confined to reviewing liberalisation activity with respect to marine radar and only covers other spectrum uses in passing. For historical reasons, radar has always had a wide frequency allocation. When there was no competing use for microwave frequencies it was not surprising that radar could demand and obtain large segments of the spectrum, aided by its need for defence and safety applications. However, radar signal bandwidths are necessarily high in order to achieve effective range resolution and accuracy. Also, in some situations, such as commercial marine, many radars need to operate within the same area and therefore need some frequency isolation. In defence applications, frequency hopping techniques are required to reduce the effects of jamming. All these considerations lead to a requirement for bandwidth that may seem extravagant compared to communications applications but are fundamental to radar.

Despite these observations, it does not mean that radar should be excluded from becoming more efficient in its use of spectrum but it does have to be carefully evaluated according to its own particular requirements. The protection that radar gives to human life and trillions of pounds of assets signifies its importance both in civil safety areas, such as marine and aeronautical, as well as defence applications.

2.2 Cave report

The *raison d’être* of the Cave Report is the need to establish an effective spectrum management regime for the public sector as spectrum is projected to outstrip supply in the “medium term”. It focuses on public spectrum holdings, which account for about half of the spectrum in the Audit’s remit. In particular, the Audit team analysed

---

[1] Spectrum Framework Review Statement, Ofcom, 28 June 2005. Section 2.1

[2] Independent Audit of Spectrum Holdings: Final Report, Professor Martin Cave, Her Majesty’s Stationery Office, 2005

selected major spectrum holdings in the defence and aeronautical fields, identifying areas where reallocation of spectrum in the short term was feasible, and also areas where something could be done in the medium term.

In essence, the recommendations from the report are structured around determining a financial value to the spectrum and incentivising government departments by applying financial measures to ensure that optimum use is made of the spectrum. This attempts to replicate what is already happening in the commercial sector. This extension of market mechanisms to the public sector, including a more comprehensive approach to the previously conceived Administered Incentive Pricing (AIP) policy is seen as the key mechanism to ensure that spectrum is optimally used. The Cave Report provides good arguments to encourage bandsharing, as well as supporting the notion that the right spectrum pricing encourages technological innovation.

Administered Incentive Pricing, first introduced in the 1998 Wireless Telegraphy Act, aims to encourage more efficient use of the spectrum. Spectrum freed up by licensees by, for instance by becoming more spectrally efficient, can be leased or traded by the licensee. Ofcom administers this process and sets license fees according to a calculation of market value, known as *opportunity cost*.[1]

Interestingly, the Cave Report is explicit in dismissing the use of AIP for both onboard ship radio equipment and onboard radar. For ship radio equipment it supports the lifetime licence approach recently adopted by Ofcom for the following reasons[2]:

- *All on-board frequencies are internationally mandated except for Coastal Station Radio (CSR) and two Coastal Station Marina frequencies* […]*. This means that the radio equipment is manufactured to internationally recognised standards, which are mandatory for all SOLAS (International Convention for the Safety of Life at Sea) vessels. Any change in spectrum use or related technology application would need to be agreed internationally. The UK does not therefore have scope for unilaterally introducing changes in spectrum use (the UK attempting to act alone would be impracticable; could lead to compatibility violations, and could generate or cause UK users to be subject to harmful interference). In these cases the opportunity cost of use is zero.*
- *Non-SOLAS vessels still need to conform to the RTTED (Radio Equipment and Telecommunications Terminal Equipment Directive) and UK Radio Interface requirements, which, due to the need for international compatibility and benefits on common radio systems with SOLAS vessels, again cannot be amended on a purely national level.*
- *As vessels will be mobile, any interference is likely to be minimal and transient. Spectrum is not generally congested and all vessels requesting and legally entitled to obtain a licence will be granted a licence.*

---

[1] Radio spectrum management, Postnote, Parliamentary Office of Science and Technology, July 2007 Number 292, www.parliament.uk/parliamentary_offices/post/pubs2007.cfm

[2] Cave Report, Section 7.2

- *Use of on-board systems will be mobile, in general communicating with a Coastal Station. The Audit feels that where pricing is justified, incentives could most effectively be applied at the Coastal station level* […]*. It appears to be more effective to target incentives at the operators who have control over the technology choice, rather than targeting a multiplicity of individual users. This also avoids any 'double charging'.*
- *On-board licences also cover the use of commercial equipment through the use of a Notice of Variation. However, the spectrum cost of these services, and therefore the incentive to make more efficient use of spectrum, are applied - where pricing is deemed appropriate - to the network operator rather than to the individual user (e.g. as is done with mobile phones, where the network operators pay the spectrum fee rather than each mobile user). As above this makes sense in terms of aiming incentives at the appropriate level.*
- *Spectrum frequency initiatives in many maritime areas may be best pursued through international bodies to achieve globally amended frequency allocations or equipment standard changes, rather than applying pricing on a national level.*

The Report goes on to say that onboard radars should also not be subjected to incentive pricing, because:

- *These on-board radars have to be internationally type-approved for SOLAS vessels, which, as above, means that there is little scope for the UK acting unilaterally;*
- *Pricing could in theory be applied to on-board radars on non-SOLAS vessels, as the same international restrictions do not apply. However, any beneficial effect this would have on spectrum use would be minimal due to the continued use of frequencies and equipment by SOLAS vessels;*
- *In addition, the UK must keep clear frequencies for use by visiting vessels. Therefore, as with radio equipment as covered above, the most appropriate route for encouraging spectrum efficiency would be through global changes rather than the UK acting alone.*
- *It is unlikely that applying pricing to a multiplicity of UK-registered individual users would have an effect in improving spectrum efficiency. Vessels may seek to register elsewhere in order to avoid the spectrum charge.*

When making conclusions on the situation concerning AIP for onboard radar and communications services the Cave Report states:

Where there are international requirements which mean that the UK has no scope to act unilaterally, the opportunity cost of use is zero and there is no merit in introducing AIP for these licences classes. In these cases, spectrum efficiency measures should instead be pursued through international negotiations to update frequency allocations or adopt new standards or through the prescription of carriage *requirements for more efficient technology (but again these would need to be implemented for equipment satisfying internationally recognised standards).*[1]

However, the report states that changes could be made through international technical regulation:

There may be cases where there is congestion around the UK and inefficient equipment is used but the UK has little or no unilateral power to act. In such cases, […] *improvements to spectrum efficiency need to be addressed through pursuing regulatory and standards changes through international fora. The Audit urges the MCA to engage with such discussions, for example the work suggested in chapter 6* [of the Cave Report] *on unwanted emissions. Where it is possible to use the tool of carriage requirements to require the use of more efficient technology within the constraints of international requirements, the MCA should do so.*[2]

The Report emphasises that the Coastal Station is a more effective point at which to apply incentive pricing. This includes coastal radar and radar beacons, as well as communications and VHF Differential Global Positioning System (DGPS) services. In particular, it offers the following recommendation:

Recommendation 7.1*: Ofcom, in conjunction with the MCA, should begin work to introduce Administered Incentive Pricing in the following licences classes: Navigational Aid (radar); Coastal Station (UK) radio; and Differential Global Positioning System (DGPS); including carrying out further work on future demand as indicated in this chapter. This should be carried out to the same timing as the development of aeronautical pricing where there are linkages.*

The nomenclature "Navigation Aid (radar)" used in Recommendation 7.1 includes both coastal radars and radar beacons. However, the Report makes the comment that:

It should be noted however that in-bound visiting vessels will continue to use existing technology specified by internationally mandated standards, potentially impeding benefits that might be achieved from freed up spectrum. In many ports (although not all), coast station radars operate "sector blanking" meaning that transmissions are inhibited when sweeping in the direction of land. There are some locations however where the angle of sector blanking possible may be minimal, in which case 360 degree operation is used.[3]

The Cave Report emphasises the possibilities of spectrum sharing, stating that there is already sharing of inland and maritime radars in the 2.9 - 3.1 GHz band. It references a report carried out for Ofcom into aeronautical and maritime efficiency[4], which recommended that the MCA should introduce sharing in the 3 GHz and 9 GHz maritime bands, for example with Programme Making and Special Events (PMSE) equipment, such as wireless cameras and microphones, programme links and

---

[1] Cave Report. Section 7.4

[2] Cave Report. Section 7.5

[3] Cave Report. Section 7.3

[4] "Assessment of the technical, regulatory and socio-economic constraints and feasibility of the implementation of more spectrally efficient radiocommunications techniques and technology within the aeronautical and maritime communities", Ofcom

associated communications. This prompted the following recommendation in the Cave Report:

Recommendation 7.2: *The MCA should examine in detail the possibility of increasing sharing in the 3 GHz and 9 GHz maritime radar bands, and should report on this issue to the Sharing Group for discussion with other users of these bands.*

Increased sharing of the marine radar bands with aeronautical and defence radars has also been postulated in the Cave Report (Annex C), with the possibility of civil aeronautical and military users being required to pay an appropriate price levy. Annex C has the intriguing statement:

In 2.9-3.1 GHz there is also significant inland civil and military aeronautical use in this band, which is primarily allocated to maritime navigation use. As aeronautical use in the 2.9-3.1 GHz band is likely to be a substitute for using 2.7-2.9 GHz individual users should be charged on a comparable basis. The need to co-ordinate between maritime and aeronautical use in this band argues for the inclusion of MCA in the joint aeronautical spectrum planning body we are proposing.[1]

Who would be the beneficiary of this charge – would it be the MCA, potentially offsetting other spectrum charges?

With regards to testing towards establishing bandsharing parameters the Report notes that:

The current occupiers of the 2.7-3.4GHz band operate safety and security critical services, and will require high levels of assurance that the introduction of new technologies and services into this band would not compromise operation. There will therefore be significant and stringent testing requirements to satisfy before a new bandsharing method could be admitted.[2]

With regards to this, the Report gives the following Recommendation:

Recommendation 4.3: *MoD, CAA, MCA and Ofcom should agree a specification for a test programme to be carried out on the use of bandsharing technologies to allow sharing between radars and communications systems. Once PSSTG requirements have been agreed, and the testing programme is underway, there should be a presumption in favour of sharing being admitted with any technology meeting these criteria. Ofcom should facilitate the test programme, providing testing capabilities; the incumbents should provide reasonable help as necessary. If the testing programme reveals specific technology barriers to a promising technique being introduced, Ofcom should consider whether this merits further research funding from the Spectrum Efficiency Scheme to address these problems.*

Also the following statement is made in the Report, regarding regulation and standardisation:

For effective bandsharing to be introduced, agreement needs to be reached between the new entrants and incumbents on parameters and performance characteristics such as the maximum level of cumulative interference that can be received by

---

[1] Cave Report. Annex C.

[2] Cave Report. Section 4.8

primary radar. A testing programme is needed, as above, to effectively 'type approve' any proposed systems. As long as the technology meets these interference limits, it could then be used in accordance with agreed operating conditions.[1]

The Report makes the following recommendation for a bandsharing group:

Recommendation 4.5*: A bandsharing group consisting of Ofcom, MoD, CAA and MCA should be established. Issues are suggested for early consideration by the group. The group should form a sub-group of the formal UKSSC structure.*

Marine radar related summary of Cave Report

The important considerations arising out of the Cave report that affect the marine radar bands may be paraphrased as follows:

1. The possibility of other users of the marine radar bands should be considered, such as PMSE
2. The MCA should be involved in tests to determine the levels of interference that would be acceptable to marine radars
3. Onboard marine radars should not be subject to AIP because all (SOLAS) ships need to comply with international standards for radar and foreign vessels are permitted to use UK waters and visit UK ports.
4. Because there is little scope for unilateral action, the MCA should engage in international fora to encourage the international marine radar requirements to become more spectrum efficient
5. The possibility of increased use of the marine radar bands for aeronautical and defence radars should be considered, with those users paying an appropriate price

2.3 Government response and Action Plan[2]

The Government provided a response to the Cave Report, which was published by the Cabinet Official Committee on UK Spectrum Strategy (UKSSC) in consultation with Ofcom. It welcomed the Cave Report and agreed that there was scope for more effective use of public sector spectrum through the introduction of spectrum trading and increased sharing with other users. The Government emphasised that sufficient spectrum will remain for national security, defence and essential public services. Also, that it will seek to minimise harmful interference and ensure continued compliance with international obligations.

With regards to any new spectrum requirements there is a presumption that public bodies will acquire it through the market. It is noteworthy that the Government Response supports all the recommendations quoted above from the Cave Report.

---

[1] Cave Report. Section 4.10

[2] Independent Audit of Spectrum Holdings, Government Response and Action Plan, Cabinet Official Committee on UK Spectrum Strategy, March 2006

2.4 Spectrum Framework Review Statement[1]

This document, issued in June 2005, explains how Ofcom will manage the radio spectrum, which is one of Ofcom's key statutory duties. It notes that the radio spectrum is a major asset to the UK, contributing £24bn to the economy each year. It recognises that there are three different ways to manage the spectrum, which can be used, as appropriate, for different parts of the spectrum:

- 'Command and Control' regulatory management
- The use of 'Market mechanisms' as recommended in the Cave Report
- 'Licence Exempt', with few constraints except power limits or other usage restrictions

Ofcom wishes to change the balance between the three mechanisms, which in 2005 was 95% Command and Control and 5% Licence Exempt. The stated aim by 2010 is to reduce the Command and Control element to 22% and increase the Market Mechanism to 72%.

The report recognises there are difficulties where signals cross international boundaries and where international mobility is critical, including maritime radar and communications. In particular, the maritime (and aviation) bands are included in the areas where trading and liberalisation cannot be fully applied because of the international nature of the bands and the treaties associated with them

In the report, Ofcom also re-stated its commitment to provide *effective safeguards against interference*. It will *remain engaged in interference investigation and vigilant against this risk*. This is important if bandsharing of the radar bands becomes a reality. One aspect that is considered as a possibility within the report is deploying a dense network of unattended monitoring stations across the country which would seek out and locate unusual activity across the spectrum.

2.5 Forward Look[2]

The Government has undertaken to publish a strategic Forward Look, assessing current spectrum use and forecasting future need. The first of these was published in March 2007. It is planned that they will be published every two years thereafter.

The current Forward Look is mainly a summary of the work that has been undertaken since the Cave Report. It recognises, for instance, that a programme of theoretical modelling and practical testing is underway to identify opportunities for sharing in certain public sector spectrum bands and that significant work has already been completed. (This is discussed in detail in Section 3 of this report).

Regarding S-Band radar it makes the following comments:

---

[1] Spectrum Framework Review Statement, Ofcom, 28 June 2005
[2] Forward Look 2007, A Strategy for Management of Major Public Sector

S Band radar operating in the band 2900 to 3100 MHz (Radionavigation) is widely used by larger ships because of its good performance in rain. Carriage is a requirement under SOLAS for ships over 3000 gross tonnage and IMO sees the need for this band for at least the next few decades. Shore based use is limited to four sites in the UK as S band there has limited advantages, although racons which are associated with lighthouses and larger buoys to provide a distinct mark on a ship's radar screen are generally dual S/X band.

For X-Band radar it states:

X band radar operating in 9300 to 9500 MHz (Radionavigation) is widely used by SOLAS ships and very extensively by non-SOLAS including leisure vessels. It is a carriage requirement for all SOLAS ships and the use of the band is likely to be required for the foreseeable future.

The band 9200 to 9300 MHz (Maritime Radionavigation) is not used by ships (apart from those in distress using Search and Rescue Transponders - SARTS), but used by some shore based radars of which there are 8 in the UK. Overall shore based 'X band' radar is used at 128 sites in the UK including three by HM Coastguard. There are additionally 93 racons (of which 79 are dual band).

Regarding the potential for changes to civil marine allocations, the report notes:

Most maritime spectrum is, as previously noted, allocated globally by the ITU. The UK therefore, within its international obligations for maintaining interoperability within the global maritime community and ensuring safety of life at sea, has limited scope for unilateral action in regard to changes to the management and use of these allocations.

It also notes that:

The availability of a published official benchmark for assessment of third party proposals for sharing, plus the introduction of AIP and potential for trading will provide the necessary incentive for improving efficiency in the management of these valuable areas of spectrum. It should be noted that any future sharing of radar bands by services meeting the safeguarding criteria will also necessarily be subject to an open and transparent awards process.

The Forward Look emphasises that:

Most maritime spectrum is, as previously noted, allocated globally by the ITU. The UK therefore, within its international obligations for maintaining interoperability within the global maritime community and ensuring safety of life at sea, has limited scope for unilateral action in regard to changes to the management and use of these allocations.

Furthermore, it acknowledges the aspirations of the IMO e-Navigation programme by stating:

Current activities in the maritime industry are directed towards development of suitable solutions for e-navigation, a requirement for ships to be permanently on line to shore networks. This will require access to additional satellite spectrum in ocean areas and VHF/UHF spectrum in coastal areas. E-navigation will not be an *alternative to the use of radar on board ships, for which no alternative has been proposed at the present time.*

2.6 Indepen Report[1]

The Indepen Report on Aeronautical and Maritime Spectrum Pricing *follows recommendations from the Independent Audit of Spectrum Holdings1[2] for applying incentive pricing to use of spectrum by aeronautical and maritime radars and VHF communications, maritime differential global positioning system (DGPS) and possibly aeronautical navigation aids.* It focuses on opportunity cost and recognises that spectrum has a non-zero opportunity cost, and that this is the case even for bands subject to significant constraints, (presumably such as the internationally harmonised marine bands). It looks at a number of aspects, including: establishing a list of priority bands within the maritime and aeronautical sectors for the initial application of AIP; establishing whether there are non-market factors that might influence the application of AIP; and at developing pricing options and a methodology for calculating costs and prices. Additionally, it looks at AIP options that could take into account unwanted emissions, such as those from radars into neighbouring bands.

Although not specifically stated it does not appear to accept the Cave Report's statements that AIP should not be applied to the internationally agreed maritime bands. Instead, by reference to certain academic studies, it is argued that AIP should not be adjusted for market externalities. However, at a practical level it does not really address how a unilateral UK AIP policy on marine radar spectrum pricing will create more efficient spectrum management at an international level, or how UK ports will not lose out to those in Europe, if it affects port dues. However, this is not relevant to bandsharing, which is a common and undisputed theme throughout all the examined reports.

The Report discusses possible licensing and charging arrangements and attention is given to Figure 4.1 in the Report, which identifies the proposed flow of funds. The reasonableness of the arguments for and against AIP being applied to the marine bands is considered outside the scope of this present study and will not be considered further.

Table 4.2 of the Report lists the organisations involved in maritime spectrum management. Surprisingly, it does not mention the International Electrotechnical Commission; its Technical Committee 80, inter alia, is responsible for the technical and test standards for radars meeting the requirements for carriage on ships conforming to the Safety of Life at Sea (SOLAS) Convention[3] and is referenced within the EU Marine Equipment Directive.

In Section 4.5.2 of the Report it is stated that:

---

[1] Aeronautical and maritime spectrum pricing: Final Report, Indepen Consulting Ltd on behalf of Ofcom, April 2007

[2] Forward Look 2007, A Strategy for Management of Major Public Sector Spectrum Holdings, UK Spectrum Strategy Committee

[3] IEC 62388

RACONs, SARTs and active radar target enhancers (RTEs) share spectrum at 9 GHz with radars. RACONs, SARTs and RTEs are relatively low power uses of spectrum and it is possible that their use does not lead to any increase in spectrum constrained over and above that restricted or denied by radars. If this is the case then any spectrum pricing applied to the 9 GHz bands would be focussed on radar use.

This is reasonable, although it conflicts with the detailed view of the Cave Report, which suggests that navigational aids should be included in AIP. (It should be remembered that racons and RTEs can also operate at S-Band.)

The Report discusses radar out-of-band emissions and, given the application of AIP, it is reasonable to argue that these emissions should affect pricing. It goes on to say that these emissions are effectively quite low from most marine radars, when compared to aeronautical radars. It does, however, assume that most marine radars work near the band centre. This cannot be assumed to be the case into the future, not least because the international regulations do not specify this. Also, the marine radar bands are likely to be used to their maximum extent with the advent of pulse compressed marine radars, although they should generally exhibit a much better controlled spectrum than magnetron-based radars.

The Report mentions that maritime radars satisfactorily operate on the same frequency. This is true but in interference rejection (IR) mode a radar has less detection capability because of the rejection correlation process. When assessing interference effects, both normal and IR working should be taken into account.

The desirability and limitations of sector blanking for land based maritime radars are sensibly discussed within the report. The possibility of regulating the use of S-Band radars in a port area is also discussed. One suggestion is to prohibit the use of S-Band in port areas. This is a possibility but there will be cases when the ship's X-Band radar has failed and S-Band will then have to be used. Also, it is not uncommon in difficult situations, such as entering a port area in conditions of poor visibility, that individual bridge officers will be observing both the X and S-Band radar displays to aid the navigation process. The Report also suggests that reduced power is used when transmitting towards the shore. This is not an option for magnetron-based radars. In some coastal waters, away from ports, ships can be relatively close to the shore but the S-Band radar is unarguably needed as a primary sensor. Any bandsharing option must be able to cope with this situation.

The Report considers the possibility that inland radars currently operating in the 2.7 - 2.9 GHz band may be able to relocate to the marine band (2.9 - 3.1 GHz). It notes that studies need to be undertaken to assess this possibility.

.Within the main conclusions of the Report, two are particularly applicable to radar:

- *There is demand from alternative services for the radar bands at 2.9 – 3.1 GHz and 9.3 – 9.5 GHz, particularly the former, and so there is a case for applying AIP in these cases. Furthermore, encouragement should be given to controlling unwanted emissions as this has the potential to reduce band usage and/or reduce the impact on users in adjacent frequency bands*

- *Provided spectrum charges for ship/land based systems are not levied on the radio equipment on ships* [radar is probably also implied here]*, there should be no disincentive to commercial and private vessel operators carrying equipment – even in the absence of effective safety regulations. Requirements on ports to adhere to the Port Marine Safety Code mean that AIP should not have any impact on safety in and around ports.*

2.7 EU Decision[1]

This Decision, published in 2002, concerns the regulatory framework for radio spectrum policy in the European Community and is known as the Radio Spectrum Decision. It concerns the policy and legal framework needed to be created by the Community to ensure the coordination of policy approaches. It emphasises the need to have harmonised conditions to ensure the availability and efficient use of radio spectrum.

It is obviously necessary for Ofcom and the UK Government to work within the given framework defined in the Decision.

3. Bandsharing with marine radar

3.1 Radar attributes

Radar was introduced to commercial shipping in the late 1940s, originally as optional equipment. For many years it has been compulsorily fitted to all ships above 150 gt covered by the Safety of Life at Sea Convention of the International Maritime Organization (IMO). In practice, SOLAS compliance at least applies to all internationally trading vessels. The International Regulations for Preventing Collisions at Sea (COLREGs), another IMO Convention, explicitly mentions the use of radar, especially when vessels are operating in conditions of restricted visibility, (Rule 19).

IMO has adopted performance standards for radar; the latest of these[2] comes into effect on 1 July 2008 when all new radars must comply with the new standards. The International Electrotechnical Commission (IEC), working closely with IMO, has issued technical and test standards for marine radar[3] that allow manufacturers and type approval authorities to determine whether a particular radar design meets the IMO performance standards.

---

[1] Decision No 676/2002/EC of The European Parliament and of The Council of 7 March 2002 on a regulatory framework for radio spectrum policy in the European Community (Radio Spectrum Decision), Official Journal of the European Communities, 24 April 2002

[2] IMO MSC.192(79):2004, Performance standards for radar equipment

[3] IEC 62388, Shipborne Radar – Performance requirements – Methods of testing and required test results

The fitting of marine radar was a 'quantum leap' when it was first introduced, and ever since then it has grown in importance as radar technology has improved. In conditions of restricted visibility, radar can be the sole sensor to detect other vessels, as well as other floating or fixed navigational hazards. In coastal waters it can be used as a backup position-fixing device by determining range and bearing from radar conspicuous charted objects.

It has two particular attributes that are particularly respected by bridge officers:

1. It is ship-centric, not fundamentally depending on any system external to own-ship. Great confidence can therefore be obtained in its use by familiarity, including the conditions when radar data may become suspect
2. It is basically a ship-relative sensor. Its data is therefore naturally aligned to the visual scene and the ship-relative domain on which the COLREGs are based

Despite this, no user would agree that radar was anything near perfect. Many critical targets remain difficult or impossible to detect, especially in adverse conditions. The use of radar becomes most critical in conditions of *restricted visibility*. (Night time, on its own, is not included in this COLREGS term, as ships have navigation lights, which are clearly visible in normal night conditions, and many aids-to-navigation (AtoNs), such as buoys and beacons, also include lights.) However, precipitation, mist or fog can rapidly reduce visibility in day or night conditions, even to effectively zero range. Many conditions of low visibility are also associated with rough seas and high levels of precipitation. The performance of radar is considerably reduced when rainfall and sea-state increase. Perversely, these are just the conditions when the use of radar becomes essential. Marine radar is epitomised by its need to see marginally detected targets in the presence of large unwanted radar reflections from waves and precipitation.

Although not introduced primarily as a collision avoidance aid all SOLAS ships (generally above 300 gt) need to carry an Automatic Identification System (AIS) [1]. This became compulsory during 2002 - 2004. Ships broadcast their own position and other data, which is received by shore authorities and surrounding vessels. The use of radar with AIS data is encouraged by IMO and is reflected in the latest radar performance standards. However, AIS or even a future enhanced AIS, would never remove the significance of radar. AIS and radar data used together improve the integrity of the instrument-displayed situation. This allows the navigator to be either more confident or cautious regarding the displayed situation (depending on whether radar and AIS data are, or are not correlated), particularly when the ship is operating in conditions of restricted visibility. It also allows more use of automated functions to alert bridge staff of dangers that may have been unnoticed. Many accidents are caused by the lack of attention of the officer of the watch (OOW). Therefore, the combined use of radar and AIS with appropriate automatic alerts is likely to result in a reduction of accidents.

---

[1] IMO MSC.74(69) Recommendation on Performance Standards for a Universal Automatic Identification System (AIS)

AIS is basically a VHF communications system and is therefore relatively unaffected by precipitation and sea-state, but its data must always be treated with caution, unless it correlates with independent data, such as radar or visual. In particular, AIS is dependent on correct transmissions. Equipment on the transmitting vessel may be at fault, either causing erroneous data to be transmitted or no data at all; also it is easy for pirates, terrorists and 'hackers' to spoof AIS transmissions. Many floating or fixed hazards will not have AIS, including some AtoNs, as well as floating debris, ice, rocks, etc. Also, since there are no plans to make AIS compulsory on other than SOLAS ships, leisure craft remain particularly vulnerable. All these considerations underline the primary importance of radar.

3.2 Radar spectrum considerations

The particular demands of marine radar dictate many features of its use of spectrum. Its operation in two frequency bands, S and X, is necessitated by the following considerations:

- The increasing rain attenuation with frequency prevents marine radars easily achieving their maximum range requirements at frequencies much above X-Band
- At frequencies below S-Band the antenna becomes unacceptably large to achieve the required azimuth resolution
- At X-Band, antennas can be quite small, for example down to about 30 cms, allowing use on small vessels
- On larger vessels, large X-Band antennas give excellent azimuth resolution. This can considerably help discrimination of targets in difficult and congested coastal and harbour approach waters
- S-Band gives a considerable advantage in reducing rain clutter, compared to X-Band. Assuming identical antenna beamwidths the S-Band system will have 17 dB (ie a factor of 50) less performance degradation in rain
- The carriage of both X- and S-Band radars not only provides the benefits of both systems but, in addition, they give quite different 'vertical lobing patterns' from sea reflections due to their different frequencies[1]. In some circumstances targets can be lost in vertical nulls if only one radar band is being used
- In principle, the dual use of X- and S-Band systems give other frequency diversity benefits, such as independence in target fading characteristics and continued navigational operation when there is gross interference in one or other of the bands

The signal bandwidth required for a SOLAS approved marine radar has at least to get the range discrimination defined in the IMO performance standard. This states that two point targets on the same bearing with 40 metres separation should be

---

[1] Radar Handbook, Chapter 22, Civil Marine Radar, Andy Norris, Editor Merrill Skolnik, McGraw-Hill, 2008

distinguishable. On simplified theoretical grounds, this requires a pulse length of less than 267nS and therefore a minimum bandwidth of greater than about 3.75 MHz. In practice, other considerations come into play. In particular, to reduce both rain and sea clutter the range cell size should be a small as possible. Commonly, this has been chosen to be about 50nS in order to get adequate performance. This implies a bandwidth of a least 20 MHz. In theory, the use of larger bandwidths would further improve performance in clutter – it has already been mentioned that clutter performance does not yet meet user requirements. However, the possibility of getting sub-clutter visibility by using coherent radar technology is perhaps a better way forward than by increasing bandwidth.

A further consideration concerning existing spectrum use is the operation of many marine (and other) radars in the same band. A major advance in this area was made in the early 1970s, when Marconi Marine first introduced the concept of interference rejection using correlation processing. This was soon copied by all the marine radar suppliers. The basic system is to compare (correlate) the detection of targets and interfering pulsed signals on a pulse-by pulse basis. A target would only be declared if it was detected at the same range in two consecutive pulses. For a number of reasons, marine radars do not have an entirely regular pulse repetition frequency (PRF) – that is they use PRF jitter – and so consecutive interfering pulses would not occur at the same apparent range and so would not be correlated and therefore not displayed as a false target.

This means that many radars can operate on exactly the same frequency, provided the reduction in detection performance is acceptable. In fact, radars from one or more manufacturers do transmit on virtually the same frequency, initially to make magnetron replacement more straightforward and, more recently, often at centre band to help reduce out-of-band emissions. There is a reduction in performance because a target will only be declared if it was visible for two or more consecutive pulses. Marginally detected targets and rapidly fading targets will sometimes fail this test thereby reducing the probability of detection of such targets when IR is operating.

The action of the radar antenna itself also considerably helps mitigate mutual interference. The antenna main beams of two radars are unlikely to coincide in time. If they do, the gross interference effect normally only occur for a small number of revolutions because their antenna rotation rates will be different, even if only slightly. Main beam to sidelobe interference is common but generally will be rather less than 30 dB (1000 times) compared with main beam to main beam interference. Signals transmitted from the sidelobes of a radar are generally unlikely to cause an interference problem when entering through sidelobes of the receiving system. Because of the specification that IMO puts on radar antenna sidelobes the combined sidelobe protection is likely to be better than 60 dB (a factor of one million) and never worse than 46 dB (400,000).

As well as limiting radar performance, interference rejection is perhaps not ideal to be used to reject long pulses from pulse compression radars. These are now being developed for shipboard applications; a well advertised example being the Kelvin

Hughes SharpEye radar[1]. In the marine world these are called New Technology (NT) radars. An uncompressed pulse of 1 mS from such a radar could result in all the range cells in the direction of the interfering radar being 'blanked' from time-to-time. A proper analysis is outside the scope of this project. However, it is probably best that these radars operate at frequencies away from conventional magnetron-based systems. The solid state transmitters used for NT radars mean that frequency selection is easy and could be an automatic or a semi-automatic process, such that they can operate in non-congested parts of the radar band.

The potential advantages of NT radar are immensely important to the user as they can give far better performance in sea and rain clutter and they also should be much more reliable than magnetron-based systems. In particular, unlike conventional radars, they do not need the replacement of magnetrons on a near-yearly basis. For this reason adequate spectrum needs to be retained for their use.

3.3 Bandsharing

Because spectrum is a finite resource, it is important that great effort is put into considering whether increased sharing can be applied to the marine radar bands. This has been discussed fully in Section 2. Bandsharing could involve other radar users as well as non-radar applications. The marine radar bands of 2.9 – 3.1 GHz and 9.3 – 9.5 GHz are already shared with other radar services, such as aeronautical and defence, but the wider radar bands that these services can occupy, especially as is currently the case for defence applications, could conceivably be forced into a more restricted band and therefore may more densely occupy the 'marine' bands. In general, this may not be a significant issue for marine, although its effects will need to be comprehensively assessed before this should happen. In particular, continuous wave (CW) radars of any appreciable power would be a potential problem in the marine bands as the methods used by marine radars for interference rejection are only effective for pulsed radars.

The possible sharing of communications services in the radar bands, including the marine bands, has been the focus of much recent study[2], prompted by the Cave Report. Depending on the proximity, effective radiated power and the actual modulation of the interfering source, the effect on radar performance can range from severe to zero. Two distinct types of radar performance degradation can be experienced. One is that real targets are fully or partially obscured, that is the probability of detection (P_d) is reduced; the other is that false targets are generated, that is the probability of false alarm (PFA) is increased. Both of these obviously affect radar performance. If a radar is totally disabled through interference, for instance, if its display becomes a jumble of lines, speckles and blotches, at least the effect is visible to the operator and appropriate emergency action can be taken. More insidious, is that effects may not be obvious to the operator, such as the non-appearance or disappearance of real targets or the generation of a small number of

---

[1] www.sharpeye.biz
[2] References 7 - 13 quoted in Section 1 of this report

false (but realistic) targets. These can result in significant safety hazards in many circumstances.

Gross levels of interference can cause saturation of the receiver front-end. Although this is sometimes seen in the marine environment it is generally caused by nearby military radar systems. It is most unlikely that receiver saturation will be a real problem for legitimate bandsharing communications systems.

Lost or false detections due to interference could possibly introduce errors into the azimuth accuracy of a radar. This effect will be small compared to the much grosser effect of interference on P_d and PFA.

3.4 Radar interference

A significant problem in determining acceptable interference criteria for radars is that they can have quite different characteristics, with at least all the following being variables:

- Transmit signal characteristics
- Front end filtering
- Receiver noise figure
- Detection processes, including scan-to-scan and pulse-to-pulse correlation
- Tracking algorithms

Some aspects of the above list may also have options or aspects under operator control. For instance, even on a simple pulsed radar, the operator normally has some control over the pulse length. This could affect the applied front end filtering, the noise figure and detection processes. A simple change by the operator of the displayed maximum range on a marine radar often automatically changes the pulse length, pulse repetition frequency and the detailed detection process. Adjustment of the gain, rain and sea clutter controls significantly affects the detection process.

The transmit signal characteristics naturally affect all the receive parameters of a radar. In particular, a radar that relies on defined frequency and phase variations across the transmitted signal to extract target Doppler[1] (such as a marine NT radar) will have a different sensitivity to interference than a non-coherent magnetron-based radar. Furthermore, different coherent radars can have vastly different transmit signals and therefore different receiver and detection processes.

Marine radar has a speciality in use that makes it quite different to an air traffic control radar. The latter is designed to reliably detect targets down to a specific radar cross section (RCS) within a specific range of interest. Operation at greater than 90% P_d is common. It is greatly helped in this by use of Moving Target Indicator or Moving Detector (MTI/MTD) technology, which reduces precipitation, ground and sea clutter significantly but its operation relies on fast moving targets. As previously stated, a marine radar is used as the primary hazard warning system in poor

---

[1] Effectively, instantaneous motion related data

conditions of visibility, when there is likely to be heavy precipitation and sea clutter. MTI and basic MTD techniques do not work in this type of environment as there is not a clear difference in the velocities of wanted targets and unwanted clutter. Some critical targets can have a low probability of detection and be partially or fully obscured within the clutter.

It can be the case that a critical target (eg a small fishing boat) is only just visible on the radar display but it still allows the OOW to take avoiding action. This is not too dissimilar from the situation where a naval surveillance radar is trying to detect a submarine periscope with sufficient time to take defensive action. Unlike the general case for aeronautical radars, naval and marine radars are operating at the limits of detectability to ensure safety.

It is important, therefore, that potential interference from bandsharing carefully considers the operation of marine radars in extreme conditions, as well as radars operating in benign conditions. To take a relatively extreme case to illustrate the point, a target that has a probability of detection (P_d) of 90% that reduces to 60% in conditions of interference will probably only have a marginal effect on safety. However, a target with a P_d of 30% reducing to 0% with interference will have an immense safety implication. However, it should be borne in mind that from the point of view of the user it will be very unsettling if interference causes a noticeable affect on the radar display, even for a strong target with 90% or more probability of detection.

For a target clear of clutter the limiting effects are the noise entering via the antenna and the noise generated within the radar receiver system. The noise entering the radar antenna includes any interfering signal as well as naturally generated noise. When attempting to detect a target in clutter there is additional ‘noise’ generated by the unwanted radar reflections from the clutter, for example, from rain droplets and sea-wave structures. In general, these are mathematically noise-like (but non-Gaussian); also there can be longer lasting returns from macro sea-wave structures that may be target-like rather than noise-like, lasting for some seconds or even minutes. Automatic target trackers can lock onto these, which can cause confusion.

Marine radars use signal processing techniques, which can include analogue circuitry, to idealise the detection of targets in clutter. Different techniques are used for rain and sea clutter and the clutter controls on a marine radar fine-tune this operation. The marine radar manufacturers are reluctant to discuss the actual techniques in use as they are often based on years of accumulated experience. It is the one area that really discriminates between a good marine radar and an inferior one. The conventional rain clutter control is a differentiator, which prevents the high returns from rain saturating the receiver process. The conventional sea clutter control affects the rate of cut-off of the applied receiver attenuation with range, known as the sensitivity time control (STC).

Interference will adversely affect the clutter processing with effects that are perhaps difficult to quantify. However, if the interference is much less than the clutter imposed noise, it may not pose a significant additional problem. However, the effect does need to be quantified.

If a coherent radar uses Doppler processing to isolate the target from the surrounding clutter and therefore achieves ‘sub-clutter visibility’ then the effect of moderate levels of interference may become more critical. This needs to be addressed. Solid state coherent radars typically use pulse compression. This can give isolation from some types of interference and similarly needs to be addressed.

3.5 Determination of radar interference effects

There are three main techniques available to determine the effects of interference on a radar:

1. Theoretical study.
2. Modelling, using a mixture of real and simulated equipment and data
3. Trials using real equipment in representative scenarios

Each of these is briefly reviewed.

3.5.1 Theoretical study

This is always a useful starting point. The theory used can range from basic through to a complex simulation. Theoretical studies can give valuable insights into the critical areas. In particular, computer simulations can be used to extensively investigate many variations in parameters. Verification of the theory on selected practical tests can very often give confidence in the theory to predict the results where practical tests become difficult or impossible. This is the standard process used for the advancement of scientific knowledge.

The problem with modelling radar comes with defining sea clutter models. Much study has gone into this over many years but due to the wide variation that can be found in real sea clutter, models are not necessarily representative of any sea used for experimental verification. In fact, this is also a problem for sea trials. Even with similar nominal sea conditions different results can arise.

3.5.2 Physical Modelling

This is a useful process as it can use all or much of a physical radar and a mixture of real and simulated data from targets, clutter and interference in a reasonably controlled environment. It gives particular insight into areas where it is impossibly difficult to simulate entirely theoretically. In modelling, the simulated clutter could come from recorded real life data or use theoretical models. Either way, this data can be introduced into the radar as a simulated but physically created signal. Care should be taken to ensure that any recorded data and its injection point accurately reflects real conditions: for instance has it been filtered inappropriately or changed by any A/D or D/A[1] process. Even recorded clutter is only representative of the time and

---

[1] Analogue-to-digital and digital-to-analogue conversion

place that it was recorded. It may not be representative of the wider situation and so this has always to be borne in mind.

The major advantage of physical modelling is that it creates a repeatable environment that can be used for quantitative testing.

3.5.3 Trials

In many ways it can look that sea trials in representative scenarios is the ideal technique to evaluate performance. Actually, this is far from the truth for a number of reasons:

- It is an expensive process. Waiting for or finding the right scenario (for example rain, sea-state, tidal conditions, representative targets) can be prohibitively expensive
- Replicating scenarios is almost impossible due to variations on different days and locations and so repeatability becomes a major problem
- At sea it is difficult to create standard targets with any accuracy
- Targets of opportunity are enormously varied and offer limited repeatability

These and other issues mean that trials are never definitive, unless they are expensively exhaustive, but they provide an essential qualitative or confirmatory process.

It is therefore essential that any establishment of bandsharing criteria involves all three techniques: theoretical, physical modelling and trials, in an appropriate mix.

3.6 PSSTG Series: Introduction to PSSTG

This Report[1] provides an overview of the PSSTG (Public Spectrum Safety Test Group). The PSSTG was formed in 2005 by Ofcom to define, oversee and ensure independence of trials concerning the sharing of safety-related spectrum.

The Report rightly recognises that there are practical limits on radar testing:

There is an element of subjectivity in terms of how individual radar operators configure and make judgements on data. It is not practical to test every radar variation and therefore any test data obtained on any particular radar must be able to be extrapolated to give generic data for at least of range of radars. In this way, in order to provide credible test data for all radars in a given band, testing might just need to be restricted to a limited number of radars.

---

[1] Public Spectrum Safety Test Group, PSSTG Series: Introduction to PSSTG, ERA Technology Ltd on behalf of Ofcom, December 2006

Although not stated explicitly, it means that a good theoretical understanding of interference issues must be made to ensure that the extrapolation process is not flawed.

The report emphasises that the immediate scope of work for the PSSTG is concentrated on UWB[1] interference to S- and X-Band radars and also bandsharing between such radars with a range of demonstration communications systems. The communication systems technologies of interest include Wi-Fi, WiMax, 3G and GSM.

The report particularly recognises that onboard marine radars are used in bad weather and poor visibility. However it also goes on to say that: *due to the characteristics of the transmitters, techniques such as coherent pulse integration and pulse compression are not used.* As previously mentioned in the present report, Kelvin Hughes Ltd has announced SharpEye a range of S- and X-Band radars aimed at the maritime market, including onboard systems. The radar standards introduced by IMO for all radars fitted after 1 July 2008 have been explicitly written to allow the use of such coherent radars, in order to encourage the development of radars with improved performance in clutter. This must be given proper consideration in future bandsharing studies.

The issues concerning bandsharing criteria are stated by the Report to include:

- *Radar parameters used for defining the criteria e.g.* P_d, *I/N*
- *Representative radar sets*
- *Test methodology (Radar configuration, test site set up, monitoring methods, test specifications etc)*
- *Propagation and aggregation models (for extrapolation of data for distance and multiple threat devices)*
- *Extrapolation of results from tests on small numbers of radars to produce generic results*
- *Safety margins*

On page 25 of the Report it has given radar parameters that need to be considered for the trials (Table 4), which is a reasonably comprehensive and useful list.

The report recognises the importance of P_d on the evaluation of interference effects. It states that: *A provisional value of Pd has been agreed for the initial testing phases. This is a non-interference probability of target detection (Pd) level of 90% and assessing where the onset of interference occurs*.

There is no justification given for using this figure and for marine radars it does not seem to be a particularly relevant operating point, as previously discussed. A really surprising statement on page 27 is that: *the Pd in the maritime scenario* [compared to 90% for the aeronautical scenario] *may tend to be significantly stronger and possibly always greater than 100%*. This is not only nonsensical (P_d cannot be greater than 100% because it is a probability) but it is certainly not the case that they

---

[1] Ultra wide band communications systems

should be assumed to be in the 90-100% range for the reasons previously explained in this report.

The simplified theoretical analysis on pages 28 - 30 must not be taken too literally, as it is based on gross assumptions. Also, there is a statement on page 30 concerning interference from UWB systems, which says:

Maritime radar requires an I/N ratio of -10 dB for aggregate interference and for a single interferer. The I/N ratio of -10 dB is contained in a proposed revision to ITU-R M.1313-1 under consideration by ITU-R Study Group 8 titled, "Technical Characteristics of Maritime Radionavigation Radars".

The use of the word 'requires' is inappropriate, as a main objective of the PSSTG work is to establish such a figure. The proposed revision to M.1313-1 was superseded by the issue of other ITU documents; see Section 4.2.7 of this report. Although these contain specific recommendations, it is made clear that the tests were done under very specific conditions and that other conditions may result is different recommendations.

3.7 PSSTG Series Report 1: Initial measurements of radiated UWB interference to radar

This Report[1] used two naval S-Band surveillance radars to assess the effects of UWB interference and the results were compared to theory. Limited information was given about the radars as their details were classified. No UWB devices were available for the tests so these were simulated by signal generators. A target generator was used to provide a set of simulated targets.

The interference tests included simulations of Multi-band Orthogonal Frequency Division Multiplexing (MB-OFDM) and gated Direct Sequence Ultra-Wideband (DS-UWB), which are stated to be the two main candidates for UWB communications. The OFDM simulation only used a single band, whereas MB-OFDM would hop between at least three bands. A pulsed UWB signal was used to simulate the DS-UWB but it was thought that DS-USB signals would be more noise-like than pulse like.

Because of problems the actual measurement time was very limited and reliable measurements on P_d were only made on one radar, and just using MTI[2] (Doppler) mode. When used in Early Warning (EW) mode unreliable results were obtained, which seemed to be due to the clutter map. This emphasises the comments made in Section 3.4 of this report saying that the actual signal processing used can affect the performance in interference.

Data from three simulated radar targets was gathered. The target generator worked at RF and fed into the radar system antenna via a horn antenna. The target

---

[1] Public Spectrum Safety Test Group, PSSTG Series Report 1: Initial Measurements of Radiated UWB Interference to Radar, ERA Technology Ltd on behalf of Ofcom, March 2006

[2] Moving target indicator. Signal processing which only shows relatively fast targets such as aircraft and not showing slow moving clutter

generator technology is based on digital RF memory (DRFM). The simulated interference was also fed into the radar system antenna from a horn. The test radar operated into the local environment and the targets were electronically placed in an area where there was low ground clutter. Target velocities of 200 kts were used. One major problem was that it was found difficult to get a steady P_d from the radar on the simulated targets. In fact, over a three hour period it could vary from approximately 78% to 98%. Because of this instability, and the short timescales involved, measurements of P_d were taken over a very short time interval – 3 to 5 minutes, which affects the accuracy of the tests.

For different interference modulation schemes, the measured P_d was plotted against the Effective Isotropic Radiated Power (EIRP) of the interference source. Numerous plots for different case are included within Section 5.5 of the Report

Interference to noise measurements (I/N) were made on both radars. The point of measurement was made within the IF amplification chain, before detection so that the onset of visible interference could be compared to the measured value of I/N. The onset of interference was effectively when false targets became obvious. Not surprisingly, this was hugely affected (up to 30 dB difference) by the selected signal processing option of the radars. The researchers estimated that the onset of interference occurred with an I/N of -5 to -12 dB, which they considered to be consistent with other reports.

The experimental work for this report was plagued with problems and many measurements had to be rushed. Although interesting work was performed, the measured results do not form a basis for which rigorous protection criteria can be established.

3.8 PSSTG Series Report 2: Initial Bandsharing Trial

This report[1] uses a similar experimental set up to the previous report. The following interference sources were used:

- Additive White Gaussian Noise (AWGN), as a reference source
- GSM
- 3G
- WiFi (802.11.a and 802.11.g)
- WiMax (OFDM)

Two radars were assessed. The first was an S-Band naval surveillance radar which uses a multibeam phased-array antenna, rotating at 30 rpm. This radar has a range of modes that allow the detection of different target classes. The second radar was a conventional S-Band marine navigation radar using a 30kW magnetron.

---

[1] Public Spectrum Safety Test Group, PSSTG Series Report 2: Initial Bandsharing Trial, ERA Technology Ltd on behalf of Ofcom, April 2006

As with the previous report*: a limited set of data was obtained due to problems with the setup of the radars and the target generator. More detailed measurements would be required in order to reduce measurement uncertainties.*

Within the relatively brief set of conclusions it is stated:

The results show the relative impact of different modulation schemes and demonstrate that systems with channel allocations significantly less than the radar channel width might be able to operate at higher powers than wideband systems such as 3G or Wi-Fi but further investigation of the results is required.

This is consistent with basic theory and is therefore unsurprising. There are no estimates made of allowable degradation of P_d; graphs were given of P_d plotted against increasing levels of interference.

3.9 PSSTG Series Report 3: UWB interference to maritime radars – results of feasibility trials

This is a Report[1] of a trial over a short sea range using S- and X-Band conventional marine radar systems designed to meet IMO requirements[2]. The radars were shore mounted. Tri-lens radar reflectors were used as targets deployed at sea on buoys. The main aim of the trial was to prove the concept of undertaking UWB interference measurements on maritime radars over water and not necessarily to obtain definitive results in terms of P_d or interference levels. An MB-OFDM signal limited to a single band at the radar operating frequency source was simulated by a signal generator. This was installed on an MCA vessel.

A number of difficulties were noted with conducting the tests; many of these are well known to engineers engaged on marine radar test programmes. These included:

- Effects due to tidal range
- Isolating reflections from standard radar reflectors from their mounts
- Limitations caused by other marine traffic in the area
- The need for adequate personnel support

The presented results were only indicative, with P_d being shown as just the number of target reflectors being counted; from 0 to 4 for decreasing transmit EIRP of the interference.

---

[1] Public Spectrum Safety Test Group, PSSTG Series Report 3: UWB Interference to Maritime Radars - Results of Feasibility Trials, ERA Technology Ltd on behalf of Ofcom, December 2006

[2] These radars would have met the earlier IMO requirements for radar embedded in the IEC standards IEC 60936-1 and IEC 60872-1, rather than IEC 62388

3.10 Assessment of interference to maritime radars – Oban trial and Oban Trials Report

These reports[1,2] are assessed concurrently as they refer to the same trial. The trial used IMO-compliant X- and S-Band radars (compliant with the older IMO radar standards), mounted on the 1200 gt Northern Lighthouse Board support vessel, the NLV Pole Star. This can be considered to be a typical example of the size of a small internationally trading vessel. It has a considerable advantage for radar trials over most vessels as it boasts a dynamic positioning system, allowing it to remain accurately at a fixed position and heading over the sea bed, even in relatively high winds and sea. The trials were carried out in Oban Harbour in late 2006.

It attempted to reflect reality, not only by the radars being ship-mounted but also by using two qualified ship radar operators and a range of sample targets that consisted of an 85 cm buoy, a small unmanned inflatable dinghy, and small, medium and large rigid inflatable boats (RIBs). The trials were performed in coastal and harbour areas and employed the following shore-based interference sources:

- Additive white Gaussian noise (AWGN)
- MB-OFDM USB (Signal generator and real equipment)
- GSM
- 3G
- 802.11.b/g
- WiMAX

Only P_d measurements were made since there was no access to the radars' IF to measure I/N. However, the report correctly emphasises: *there is some debate about how well* [I/N] *defines the actual radar performance.*

The radar operators were permitted to set the gain, sea and rain controls to optimise the picture. It was noted that the two operators would select different settings. Short pulse mode was used. In any case this was needed as the trials were conducted at short ranges. Interference rejection was set to 'on'. Wind speed was noted as a variable but not sea-state. Sea-state is a more direct parameter but can be difficult to estimate. The report states: a*s the weather tends to deteriorate, it becomes more likely that the* P_d *of a target will tend to reduce, particularly for weaker target returns.* This is necessarily true because thresholds have to rise to prevent clutter obscuring the targets.

Harbour location trials data was collected with the vessel at distances of 900m, 640m and 330m from the quayside. A coastal location was used for other trials where the wave structure was likely to be different, although the location was still close to the land to allow the positioning of interference sources. The report notes

---

[1] Assessment of Interference to Maritime Radars - Oban Trial, ERA Technology Ltd on behalf of Ofcom, October 2006

[2] Assessment of Interference to Maritime Radars - Oban Trial Report, ERA Technology Ltd on behalf of Ofcom, February 2007

that the $1/R^4$ law of radar and the $1/R^2$ law of a communications link create special situations when considering target and interference source distances to the radar. These need to be properly taken into account to make the best use of a trial. Multipath from sea reflections also needs to be considered as it affects the level of the received signal.

It was observed that the P_d of the dinghy, except at very close distances was typically 45 - 70% even in good conditions. This is a good example of a marine radar typically having to operate at a P_d of less than 90% on targets that are critical.

Tables 1-3 in the Report give much of the critical data collected during the trials. Unfortunately there is no real definition of the term 'Target not affected'. Data was collected in 5 minute periods. Assuming that the antenna rotation rate was 30 rpm, although this is not stated in either Report, this would result in a maximum of 150 paints for each target. P_d was given at a granularity of 5 %. Does it perhaps imply that 'Target not affected' means less than a 2.5% change in threshold; was 5% chosen or some other figure? It is perhaps difficult to believe that a non-100% average P_d (eg 90%) from a real target could be steadily maintained within a few percentage points, with or without interference, averaged only over a period of 5 minutes.

The trials were only conducted with the interference rejection set to on. This control will certainly affect how the radar deals with some types of interference and so trials need to be performed with and without IR on. As mentioned in Section 3.2 of this report, the use of IR does desensitise the radar to real targets and at sea it is best to be turned off, unless there is interference from other radars.

Despite the points of criticism, the trial was quite effective and is a possible basis for future confirmatory trials. In particular the dynamic positioning capability of the vessel makes it a most useful trials platform.

3.11 Study to establish measurement parameters for testing radar bandsharing performance

This Report[1] tackled an important aspect of radar bandsharing; that is, evolving a methodology to assess the impact of bandsharing on the use of radar. It is subsequently referred to here as the QinetiQ Report. As a major part of the study it attempts to answer the question 'what degradation of performance is acceptable'. There is a lot of useful information and discussion of the issues in the report, which should be read-over into future work on this subject. For instance, Section 3 (with Annexes A and B) provide a search of recent relevant literature and also includes the results from interviews of key stakeholders; Section 4 provides a useful overview of radar 'families' operating at S-Band; and Section 5 gives a good description of interference mechanisms and their impact on radar performance.

---

[1] Study to establish measurement parameters for testing radar bandsharing performance, QinetiQ Ltd on behalf of Ofcom, October 2007

The direction of the Report is towards providing an answer that is based on the following statement (from page 39):

For this study, based on our understanding of radar operators' requirements, we have assumed that the protection criterion is chosen to provide a protection level which defines the maximum permissible interference level which produces 'no perceived degradation in performance' of the radar.

In line with this it argues on page 25 that:

[The latest marine radar standards[1]] *effectively demand that the minimum performance is almost equal to the best performance achieved by the current set of existing S-band navigation radars. This effectively means that there is very little excess performance or interference margin headroom within which bandsharing technologies could be introduced without causing degradation.*

Various operators and manufacturers have already identified that there is a significant need to detect smaller / more difficult targets, particularly in difficult operations such as collision avoidance in a port/harbour situation, at night and under the worst weather conditions for those targets. This has translated into the need for a safety margin but the level of this margin is open to debate.

This underlines the need to ensure that the performance of marine radar is not compromised by interference when attempting to detect small targets in clutter, as already argued in the present report. The QinetiQ Report is firmly based on there not being any operator discernable degradation for 'in-the-clear' conditions. Importantly, IMO has recently issued a Circular[2] stating the need to have adequate safety margins when considering bandsharing. This is examined in more detail in Section 4.2.1 of the present report.

The QinetiQ Report argues that a 5% change in P_d may not be discernable to users. This has not been established from user trials – the report notes that this is the case and should be part of future work but uses a loose method of deduction that may have more relevance to relatively slowly moving ATC radars (6rpm) than other radars. It then notes that the fastest rate of change of P_d with increasing noise (interference) occurs at a P_d of about 60%. Finally, it notes that a Swerling 0 target (that is one that does not have any fluctuation in time) also experiences the most variation in P_d with noise.

From these criteria it calculates that, for a Swerling 0 target at a P_d of 60%, the interference level has to be less than -13 dB to -15dB with respect to noise (depending on actual radar used) for the P_d to drop to 55%. It therefore recommends that these interference levels should be used as the basis for controlled test and field trials. This will ascertain whether these nominal figures are appropriate. The proposed tests are included in the report.

In general this is a good and interesting report but the suggested levels of interference protection may be difficult to justify, not least as they apply to a Swerling 0 target, which is certainly not a typical case for marine targets. Of particular note are

---

[1] IEC 62388

[2] IMO MSC.Circ.1250 Safety margins to protect radar systems, October 2007

the recommendations to use structured human factors trials to assess the limits of human perception to radar degradation. This is an important aspect and needs to be followed up and forms a significant conclusion to the present report

4. The way forward

4.1 Spectrum Liberalisation Proposals – Risk to Maritime

Radar currently occupies wide spectrum bands. This has not been problematic until recent times, as the interrelated factors of available and affordable communications technology and the spectrum requirements of non-radar services has not needed to put any pressure on these bands. This is no longer the case, and in particular, the extensive spectrum contained within the entire radar S-Band (2.7 - 3.4 GHz) is rightfully under close scrutiny. Marine only occupies a small part of this (2.9 - 3.1 GHz), which it also shares with other radar services, but it is entirely justified that it is similarly scrutinised.

Shipborne radars have some particular characteristics in deployment that make them a special case to be considered:

- The radar platforms are mobile
- The radar platforms are mainly confined to the coast but there is also some extensive landward intrusion, such as in estuaries, ports, rivers and ship canals
- Many of the radar platforms effectively fall outside the jurisdiction of any special UK or EU laws, providing the radars operate within ITU spectrum-use limits
- The radars are often used to their limit, detecting small targets with relatively low probabilities of detection within clutter

Marine radars share one important characteristic with virtually all radars used within the UK – they are used to give necessary safety advantages, (given that the fundamental role of UK defence radars is to protect the lives of UK citizens). For this reason it is clear that unacceptable degradation in the performance of radars should not occur because of bandsharing. As argued elsewhere in this report, the prime issue is the definition of what amounts to ‘unacceptable degradation’.

Because marine radars are generally confined to coastal regions and that transmissions are basically restricted by line of sight, it immediately suggests that the band can be extensively shared, at least by sharers operating in regions of the UK away from the coast. When interference becomes within line-of-sight it is essential that consideration is given as to what is an acceptable level of radar performance degradation. Of course, in reality, even when there is no line-of-sight to the interfering source, there may be radar degradation caused by diffraction and refraction, including atmospheric ducting, of interfering signals. Reciprocally, these effects could also cause radar-induced interference to bandsharing services. All of these aspects must be covered in the work to establish suitable interference criteria.

There is no evidence that any of the examined technical studies on spectrum liberalisation form a fundamental threat to the safety of marine radar. In any case, no technical proposal has been put forward that is claiming to be definitive.

The economic-level reports also do not form a threat to marine radar safety. The importance of bandsharing possibilities cannot be denied and at least for shipboard radar it is difficult to see any safety threat to the possible application of AIP. However, it is also difficult to see how the application of AIP to shipborne radars in the UK will have any real international impact on making them become more efficient users of the spectrum.

There is a potential threat that the application of AIP may reduce the effectiveness of coastal maritime radars and also radar beacons (racons). Decisions on coverage may be unduly influenced by the cost of spectrum licences. If not carefully thought out, the application of AIP could result in less effective coastal surveillance and services, which is clearly very undesirable.

4.2 What additional work is required?

4.2.1 Establish human element safety margins

IMO has emphasised the importance of the human element in radar in its recent Circular concerning radar interference, previously referenced in this report (MSC.Circ.1250):

Recent sea trials had been reported which used radars required to be carried under SOLAS regulation V/19 on an operational ship, together with (non-radar) interference sources located on shore, using realistic small maritime targets and experienced maritime radar operators. These trials indicated that there were significant variations in the detection of the targets which can be attributed to the human element.

The Circular goes on to say:

The Sub-Committee concluded that there was a need to ensure that a safety margin was taken into account to give additional protection, should sharing with other services become an active possibility, to ensure that the maritime radar as a safety device was adequately protected.

This emphasises the importance of the human element and it needs to be quantified at an early stage in bandsharing studies. The list of factors affecting target visibility includes two main human element variables: the ability of the operator to optimally adjust the radar; and the operator perception of target visibility. Clearly, there may be some correlation between these aspects. It is expected that the perception task can best be done by simulation, using an appropriate sample of experienced operators. Potentially, existing radar simulators could be adapted for this task or could even consist of specially developed software running on a general purpose PC, driving a professional but standard display.

The perception simulation should involve both moving and static targets in clear or cluttered conditions and the effective P_d should be varied to determine the threshold of perception of an operator. This will provide useful input into the human factors work identified in the QinetiQ Report[1] .

Although this sounds straightforward, it rather oversimplifies the problem as the actual radar processing used, together with many detailed radar design decisions (such as the particular use of colour and the algorithms for displaying potential targets) greatly influence the look of the display and presumably its perceptibility. This needs to be carefully examined in the design of the tests. These issues are overcome if simulated targets and clutter can be injected into a test radar, but this involves a lot of extra expense, as it ties up a costly experimental set-up for a long time while a number of operators perform the tests.

The optimal setting-up of radars may not be easy to reproduce accurately on a standard radar simulator used in marine training institutions. It is possible that this is best performed on a system that uses good quality high bandwidth recorded data, with the recording being performed on a suitable system prior to the point that is affected by the main operator controls (particularly for gain, rain and sea clutter adjustment). The feasibility of this should be investigated – unfortunately such recorders are expensive, particularly if the signal is analogue at this stage. It can be expected that some radars are easier to optimally set up than others. Unfortunately, it complicates the analysis process if more than one radar is to be adapted in this way for quantitative trials.

For any human element tests it is vital that the subjects tested use identical data and so the use of some form of simulation is vital. There may be other ways of doing this, as well as those postulated above; great thought needs to given to this important task. This report emphasises that the use of sea trials for quantitative tests is not recommended.

4.2.2 Establish definitive acceptable interference levels

None of the reports on the theoretical and experimental work examined in this report have established definitive acceptable interference levels for marine radars. It is agreed that encountered interference levels must not prevent a marine radar from achieving its safety-related tasks. The latest IMO Performance Standards for radar state that:

T*he radar system shall be capable of operating in typical interference conditions as encountered in a normal marine environment*[2]*.*

This is interpreted within IEC 62388[3] as being able to operate within an environment where there are other approved marine radars, both in terms of having suitable interference rejection and without causing significant degradation to other approved

---

[1] Study to establish measurement parameters for testing radar bandsharing performance, QinetiQ Ltd on behalf of Ofcom, October 2007, Section 6.8

[2] IMO MSC.192, Section 5.1.3

[3] IEC 62388, Section 5.2.2

marine radar systems*.* There are no system allowances made for any other types of interference.

This implies that additional interference needs to create an imperceptible degradation of radar performance. Determining this limit has indeed been a major objective of most of the technical work reviewed in this present report. Target visibility is a function of a number of parameters, including but not limited to:

1. Target radar-reflecting properties, including temporal variations
2. Returns from rain and sea clutter, including temporal variations
3. The interference present, including its particular signal characteristics
4. Radar parameters, including the specific signal processing applied
5. Ability of the operator to optimally set the radar
6. Operator perception of target visibility

What is unfortunately true is that it is extremely difficult to examine this list of variables in a systematic way, as each item has so many variations and many of the variables are difficult to quantify and reproduce.

In particular, it is the opinion of Professor Andy Norris, based on extensive experience, that affordable sea trials can rarely determine radar performance sufficiently quantitatively. This would include determining the levels at which interference starts causing degradation in radar performance. It is because of the near impossibility in performing repeatable measurements over a range of variables. In particular, target and clutter parameters are nearly impossible to control and multipath effects can create a mathematically chaotic situation as they can vary rapidly with small changes of effective target and radar antenna height above the sea.

Radars tested on a shore site across water also have limited flexibility. For instance:

- The clutter conditions are at the whim of the weather, sea-state and tides;
- The conditions experienced in the trials will be quite limited in variability, even over an extended test period and will just reflect conditions in a specific location
- Test targets are difficult to use on water and can be quite unrepresentative of real targets.
- Multipath from the sea surface can give immense variations in detection with small changes in tidal height

A more feasible approach, as previously discussed, is to use real radars in artificial and therefore repeatable environments, provided these adequately reproduce realistic targets and clutter. Different simulation data or settings can be used to reflect widely varying conditions. It involves injecting signals from synthesised targets and clutter into the radar under test. There is a lot of detailed experience of this type of simulation being accumulated. It is unfortunate that the PSSTG trials that used these general techniques should have experienced special problems, which were not effectively resolved in the timescales available. The basic technique appears to be sound and should not be dismissed too easily. There are significant experimental issues and it is not an easy task but in principle, once regularised, it should result in repeatable and accurate results.

However, to perform comprehensive tests using a variety of targets, clutter scenarios, different radars, operator set-ups and operator perceptions, as well as a range of interference scenarios, soon leads to an impossibly lengthy operation. For this reason great care has to be taken in establishing an affordable way forward.

A mixture of theoretical analysis, and synthetic target/clutter injection should be used to determine acceptable interference levels. These results should be backed up by some sea trials to ensure that measured results in the available conditions are generally consistent with the detailed results obtained by modelling.

4.2.3 Examine the effects of interference on the detectability of small targets in clutter

Although this is effectively part of Recommendation 4.2.2 above, it is included separately to emphasis its importance.

It has been argued strongly within this report that interference should be particularly evaluated in clutter conditions and for marginal targets, as these are the conditions where the marine radar is being used for safety critical tasks at the limit of its detection capability. It is true that in these conditions the radar is unlikely to be internal noise limited and therefore it may not be the limiting case for the determination of acceptable interference levels. However, it needs to be examined in depth, using appropriate statistical models and human perception trials. It may be the case that in high clutter very small decreases in target detectability can more quickly obscure the target as it merges with the clutter background.

4.2.4 Examine the effects of interference on coherent (NT) radars

The expected imminent use of coherent (New Technology) radars for shipboard and coastal radars must be examined. On the plus side they may be more immune to some types of interference because of their pulse compression waveforms; they also have a well defined and more controllable spectrum than a magnetron radar. On the negative side they may need to use frequencies not occupied by magnetron-based radars, therefore increasing the use of available spectrum. Also, to achieve sub-clutter visibility it is likely that they will need to operate within lower levels of interference than a conventional magnetron radar.

In particular, it should be noted that common use of these radars would negate the assumption that most radars operate close to the band centre, as has been previously reported. It should also be borne in mind that that this type of radar is likely to become the norm for newly fitted radars within 10 years or less, not least because it can be expected in just a few years that basic versions will be able to be produced at a lower price than magnetron-based radars.

4.2.5 Examine the effects of ducting on safety

The safety effects caused by the possible ducting of interference in anomalous atmospheric conditions need to be examined. Such conditions, which can result in radars having a range of hundreds of miles, are not uncommon. Under these conditions, marine radar will also more severely interfere with bandsharing terrestrial systems.

4.2.6 Determine the effects on safety if increased sharing of the marine radar bands with other radars is implemented (re-farming)

If more aeronautical and defence radars are to operate in the marine bands the safety effects of increased mutual interference possibilities need to be analysed. It should not be assumed that marine radars will all operate at centre band frequencies, particularly with the advent of marine NT radars.

4.2.7 Examine the implications of recently revised ITU Recommendations

Although ITU withdrew M.1313[1] in October 2007, there are three Recommendations that are particularly relevant to bandsharing aspects of radar; M1460-1[2], M.1461-1[3] and M.1796[4]. The detailed study of these was outside the scope of this report. The implications of the ongoing work at ITU need to be fully understood. The UK must remain in a position to contribute to the work as it is essential to get international consensus on bandsharing within the marine radar bands. (See Section 4.4)

4.3 Extension to X-Band

There is no doubt that successful implementation of bandsharing and AIP principles at S-Band will eventually result in its extension to X-Band. The technical aspects of bandsharing in either band are very similar and the economic arguments remain the same, including the issues regarding the application of AIP to internationally travelling mobile platforms. Although the use of racons at S-Band may diminish because of the latest IMO radar requirements, their importance at X-Band remains undiminished. AIS AtoNs do not provide an equivalent service to racons and the replacement of existing racons with AIS-only systems is unlikely. SARTs operate at

---

[1] Technical characteristic of maritime radionavigation radars

[2] Technical and operational characteristic and protection criteria of radiodetermination radars in the 2900-3100 MHz band

[3] Procedures for determining the potential for interference between radars operating in the radiodetermination service and systems in other services

[4] Characteristics of and protection criteria for terrestrial radars operating in the radiodetermination service in the frequency band 8 500-10 500 MHz

X-Band only and because they have to be visible to airborne search and rescue services need to operate over 9.2 - 9.5 GHz, rather than just the marine X-Band (9.3 - 9.5 GHz).

At X-Band, line-of-sight operation becomes even more optical-like, if anything helping to ease bandsharing options. Short range communications from portable or small fixed equipment are quite feasible but also longer-range microwave links may also become a pressing requirement. A 50 wavelength antenna at X-Band giving a beamwidth of about 1.5° has a diameter of 1.5 metres - making X-Band superficially attractive for such links. At relatively heavy rainfall of 25 mm/hour, the attenuation of the link would be about 0.5 dB/km[1]. If the microwave link budget is determined assuming worst case rain, it may be necessary to transmit lower powers when in clear conditions to limit interference to radars.

It is also feasible at X-Band to have larger fixed-link antennas that exhibit very low sidelobes that further reduce interference possibilities. As with S-Band, under certain atmospheric effects ducting can occur, and therefore there may be similar possibilities for long range interference effects.

4.4 Long term future of Spectrum Liberalisation

Ever since the earliest days of radiocommunications, spectrum has always been in short supply. This has led to technical innovation in two separate ways: by increasing the available spectrum through developments in transmitting and receiving devices; and by innovation in spectrum-efficient modulation techniques. This innovation will continue, but as frequency of operation increases the atmospheric and rain attenuation generally becomes far worse, putting an effective limit on the use of the upper frequencies. For instance, in the range 200 - 400 GHz the atmospheric attenuation alone is high, varying from about 5 to 40 dB/km. Between about 75 to100 GHz there is an atmospheric window that has about 0.5 dB/km attenuation, which could potentially be used. Rain is the real problem, however. For instance, at about 75 GHz there is 10dB/km attenuation at 25mm/hour rainfall, getting worse at higher frequencies. This will not prevent use of the higher frequencies but it significantly limits the type of application that can make use of them, despite their inherent capability to provide very narrow beams, with compact antennas and to be able to cater for high signal bandwidths.

Even with increased use of fibre-optic links, undoubtedly in the future to every home and business, the pressure on the useable spectrum will inevitably rise. This will continue to put pressure on:

- Increased bandsharing
- Using more effective modulations
- Limiting peak powers

---

[1] “Electronic warfare and radar systems engineering handbook”, NAWCWPNS RP 8347, Naval Air Systems Command, Washington.

Clearly, marine radar will not be immune to this trend. Importantly, the use of pulse compression from solid-state transmitters has potential benefits in an increasingly congested future for the following reasons:

- Its use of the spectrum can be better controlled than a magnetron-based radar system
- Its peak power is lower,
- Its correlation processes can reduce the effects of interferers

Also, in using such systems, radar performance can be significantly improved, giving the possibility of sub-clutter visibility and more reliable systems because they can be 100% solid-state. As previously stated, it is likely that most new radars will use this technology within 10 years.

The pressure on spectrum will grow and therefore ITU will be heavily involved. The pressure from the UK for spectrum liberalisation is likely to extend to the whole of the EU. However, on a global basis this is perhaps unlikely in the short to medium term, as many countries are locked into command and control hierarchies and would not support market forces leading the way. In a more limited aspect this has been evident in the way that many national members of the International Hydrographic Organisation have viewed the increasing commercialisation of the United Kingdom Hydrographic Office.

This makes it difficult to see how the use of AIP in the marine radar bands within the UK will markedly influence international requirements. Bandsharing principles within these bands should be regulated by the ITU. The UK should influence EU countries and other like-minded nations to get suitable changes made at ITU, which in the future could include radical changes to marine radar modulation requirements. In this way both safety and the efficient use of spectrum can be maintained.

4.5 Action Summary

The actions defined in Section 4.2 above are summarised here in a logical completion time sequence, although activities can proceed in parallel:

- Establish human element safety margins (4.2.1)
- Examine the effects of interference on the detectability of small targets in clutter (4.2.3)
- Examine the implications of recently revised ITU Recommendations (4.2.7)
- Examine the effects of ducting on safety (4.2.5)
- Examine the effects of interference on coherent (NT) radars (4.2.4)
- Establish definitive acceptable interference levels (4.2.2)
- Determine the effects on safety if increased sharing of the marine radar bands with other radars is implemented (re-farming) (4.2.6)