Aeronautical and maritime spectrum pricing

Final report
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Indepen Consulting Ltd
Diespeker Wharf, 38 Graham Street, London N1 8JX
T +44 (0) 20 7324 1800 F +44 (0) 20 7253 4949 www.indepen.co.uk

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Executive Summary

Introduction

This is the Final Report for a study for Ofcom on applying administered incentive pricing (AIP) to spectrum allocated to aeronautical and maritime services. It follows recommendations from the Independent Audit of Spectrum Holdings[1] 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.

The purpose of this study is to develop concrete proposals for the extension of AIP to frequency bands allocated to aeronautical and maritime services. This study is required to

- Establish a priority list of frequency bands used by the aeronautical and maritime sectors for the initial application of AIP
- Establish whether legitimate non-market factors exist that might influence the application of AIP to relevant bands
- Establish if, and how, sharing will influence the level of AIP in relevant bands
- Develop pricing options and an optimal methodology for calculating costs and prices for relevant bands
- Identify AIP options that take account of unwanted emissions, such as those from radars into neighbouring bands
- Identify likely implementation issues and options for managing the introduction of AIP into relevant bands

In the course of the study we have undertaken interviews with industry and government representatives. Our analysis draws on the findings from these interviews and desk research and extends analysis of the approach to setting AIP developed in previous studies.[2]

Economic principles

When should AIP be applied?

When deciding which bands AIP should be applied to it is important to focus on opportunity cost. Where opportunity cost is thought to be zero for existing or potential alternative uses, then administrative costs alone should be recovered. Where a positive opportunity cost arises then AIP should in general be applied, since the (administrative) costs of applying AIP are modest and the benefits in terms of more efficient spectrum use may be significant.

It is important to note that this conclusion does not rely on the identification of specific opportunities to economise on spectrum use in the short or long term. Pricing will provide users with the incentive to make changes and share spectrum where appropriate and to lobby for relaxation of any constraints that might block change in the short or long term. Our analysis also suggests that AIP should apply to

[1] Cabinet Official Committee on UK Spectrum Strategy (UKSSC) in consultation with Ofcom, "Independent Audit of Spectrum Holdings", Government Response and Action Plan, March 2006. http://www.spectrumaudit.org.uk/220306.htm

[2] An Economic Study to Review Spectrum Pricing", Indepen, Aegis Systems and Warwick Business School, Ofcom, February 2004 http://www.indepen.co.uk/panda/docs/spectrum_pricing_review.pdf ; Indepen and Aegis. October 2005. "Study into the potential application of Administered Incentive Pricing to spectrum used for Terrestrial TV & Radio Broadcasting." http://www.ofcom.org.uk/consult/condocs/futurepricing/aipstudy.pdf

all spectrum where opportunity costs are non-zero. In other words there is no economic reason to give priority to one band over another, though there may be practical reasons to do so.

Spectrum has a non-zero opportunity cost if there are competing demands for the spectrum from either the existing or an alternative use now or in future. An important question is how one should think about opportunity costs when there is an existing constraint (e.g. caused by international harmonisation) on reassigning spectrum between alternative uses. Where it is possible the constraint might be weakened or removed (and this is typically the case), we argue that it is optimal to set a price for spectrum on both sides of the constraint which provides an incentive for all parties to move to the optimum i.e. the price that would apply without the constraint.

Should AIP be adjusted for externalities?

Indepen *et al* (2004)[3] concluded that setting prices of spectrum that promote efficiency entails setting prices equal to marginal opportunity costs. It was argued that this conclusion held in a situation where spectrum using services created positive or negative externalities. We have considered whether the application of AIP should depend on the presence of two kinds of externality in respect of use of spectrum by aeronautical and maritime services, namely

- Market externalities involving financial impacts in markets which are upstream or downstream from the market subject to the initial impact (these are sometimes termed pecuniary externalities)
- Non-market externalities such as greenhouse gas emissions, acoustic noise and radio interference which impact on consumer wellbeing and production, but not directly via the market through prices.

We conclude that neither market nor non-market externalities due to aeronautical and maritime activity constitute grounds for modifying spectrum prices based on opportunity cost estimates. Non-market externalities should in general be tackled directly via regulation or emissions pricing. The one exception to this general principle is where the production of an externality is related in a simple and non-varying way to the use of a particular input, for example, carbon dioxide emissions by aircraft are a linear function of fuel and therefore carbon inputs. In such instances it may be easier to measure the input (fuel) than measure the emission. The key question is whether or not spectrum inputs are directly and necessarily related to the production of externality. This is not the case, for example in relation to greenhouse gas emissions from aircraft, and so there are no grounds for modifying the price of radio spectrum to take account of the negative environmental impact of greenhouse gas emissions.

Administratively determined controls are generally sufficient to address radio interference externalities, except in relation to radar where under current regulation there could be material impact on use in adjacent bands because they involve pulses of very high power. This may justify application of AIP to these out of band emissions because in this instance the price is directly applied to the externality (i.e. out of band emissions).

Finally, we conclude that the level and application of AIP should not be determined by specific policy objectives in relation to the migration from one technology to another. Rather AIP should be based on opportunity cost alone.

[3] Op. cit.

Aeronautical spectrum use

The radio spectrum is used by the aeronautical community for a number of applications as follows:

- Communications between the ground and aircraft at MF, HF and VHF with supplementary satellite channels which have not been considered here.
- Ground based navigation aids across the whole spectrum, including beacons, systems that allow bearing and range to be measured, and landing systems. Again, these facilities are supplemented by satellite navigation systems.
- Ground based radars used to inform air traffic controllers and to monitor surface movement at airports operating in L-, S-, X- and Ku-band.
- Airborne systems including altimeters and weather radar

Use of some of this spectrum is internationally harmonised, in terms of frequency planning, of which a proportion is specifically identified for distress and safety purposes. In particular this includes the communications systems and the navigation aids. Secondary radar, which is a ground-air interactive system, is also closely specified. It is important to note that primary radars are not specified at a technical level. There are operational requirements in terms of detection resolution etc but how these are met in practice (i.e. the technical implementation) is not specified in international regulations.

The Civil Aviation Authority (CAA) issues Wireless Telegraphy Act licences for civil use of the spectrum allocated to aeronautical services on behalf of Ofcom. Intensive use of some systems across the European region means that international coordination is required. This coordination is achieved nationally using tools provided by Eurocontrol (and in the case of HF communications through ICAO).

Furthermore since many of the bands are shared with other users, in particular the Ministry of Defence (MoD), there is a mixture of apportionment and process to enable all users to be accommodated at a national level. In some cases it appears that there is no single “owner” of a band or spectrum segment as usage is so mixed.

Congestion

The main evidence for congestion is with respect to the VHF communications band where new assignments have to be coordinated through twice yearly regional planning meetings that attempt to accommodate new assignments by replanning existing assignments. While other systems do not generally require such regional replanning to accommodate new assignments a similar process is sometimes required at a national level. This indicates a lower level of congestion for these systems. This was confirmed in our meetings with aeronautical users.

Potential for more efficient spectrum use

In principle there are opportunities for more efficient use of the spectrum, either in terms of releasing spectrum for other use or for making additional capacity available, in the following areas:

- The application of new technologies to primary radars, in particular L- and S-band radars which would allow for the replanning of these bands and the release of spectrum (noting that the use of this spectrum by other services may, at least initially, be constrained by the continued use of radars in other countries). These new technologies also provide improved unwanted emission performance which at current performance levels has the potential to cause interference to spectrum users in adjacent bands. This area of spectrum management is completely in national control and can therefore be regarded as a nearer term possibility for change.

- Increased use of narrower band communications channels at VHF. The extended use of 8.33 kHz channels rather than 25 kHz channels and a migration to digital communications can be considered. All aircraft flying above 24,500 ft are fitted with 8.33 kHz radios and there is agreement to extend this requirement to aircraft flying above 19,500 ft from March 2007 with an implementation timetable extending to December 2010.[4] In addition, full expansion throughout remaining airspace is being considered and draft EC regulation to support this is being prepared within the Single European Skies programme. The full benefit is only likely to be obtained with a wider regional or international migration which will take time due to international regulatory processes.
- There is some duplication of functionality between the various navigation aids and this is currently being reviewed by Government. It is notable that there are two frequency bands designated for landing systems; ILS having its main band at VHF and MLS around 5 GHz. The latter was planned as an improved system many years ago but to date there has been virtually no take up even though equipment has been available for several years. Pricing could provide an incentive to rationalise this duplication of resources.
- Airborne systems by their very nature (i.e. use at high altitudes) have the potential to interfere with and be interfered with by other radio systems over very large areas, including trans-border situations. This makes compatibility issues difficult to manage. Nonetheless there is a case for ensuring that spectrum allocated to these systems is used in the most efficient manner.

Impact of AIP

AIP should not have an impact on aviation safety, rather safety constraints will be binding and any impacts in terms of reduced spectrum use will be economic (i.e. reduced traffic levels). Provided spectrum charges for air/ground systems are not linked to the carriage of airborne equipment, there should be no disincentive to commercial and private aircraft operators carrying radio equipment. However, there was a concern that imposing AIP might in practice compromise safety to an unacceptable degree by leading general aviation to dispense with carrying certain radio equipment. The correct policy response would be to revise the regulation to mandate general aviation to carry that equipment.

Most organisations involved in the aeronautical value chain are commercial entities and so where economies in spectrum use can be made we would expect there to be commercial incentives to economise on spectrum use. Contractual or regulatory arrangements limit the extent to which changes in cost can be passed on in the short term but these can be expected to be modified in the longer term to take account of changes in spectrum fees.

Maritime spectrum use

The radio spectrum is used by the maritime community for a number of applications as follows:

- Communications between ship and shore at MF, HF, VHF and satellite channels.
- Aids to navigation across the whole spectrum, including beacons, satellite navigation systems and differential global positioning system (DGPS) channels.
- Shore and ship based radars used to inform Vessel Traffic Services (VTS) and ships' masters. These operate at S- and X-band.

[4] http://www.eurocontrol.int/ses/gallery/content/public/docs/ru/SES_IOP_VCS_RUL_v2.0.pdf

- Distress and safety / search and rescue, widely based on specific frequencies associated with the applications listed in the bullets above but also specific frequencies for devices such as Emergency Position Indicating Radio Beacons (EPIRBs).

Use of some of this spectrum is internationally harmonised, in terms of frequency planning, of which a proportion is specifically identified for distress and safety purposes. In particular this includes the communications systems. Radars are only specified generally in frequency band terms which allows for some flexibility in implementation, although ship borne radars for larger vessels have to be type approved to international testing standards.

Assignments for shore based services are carried out on a national basis by Ofcom and ships' one-off lifetime licences cover ships' spectrum usage of all maritime radio systems.

The maritime radar bands are shared with the MoD and CAA and there is a national process to enable all users to be accommodated within the relevant frequency bands. In some cases it appears there is no single "owner" of a band or spectrum segment as usage is so mixed.

Congestion

The main evidence for congestion is with respect to the VHF communications band where it is becoming increasingly difficult to make new assignments to ports particularly around the English Channel and the South / South East coast of the UK. Based on interviews with maritime organisations we understand that such problems do not occur in other bands.

Potential for more efficient spectrum use

In principle there are opportunities for more efficient use of the spectrum in the following areas:

- The use of narrower band communications channels at VHF. Use of 12.5 kHz channels rather than 25 kHz channels and a migration to digital can be considered together with more extensive use of simplex channels rather than duplex channels. It appears that the move to simplex has already started. International harmonisation acts as a constraint to a certain degree but there is scope for national decisions to be made particularly since half of the VHF communications channels assigned by Ofcom are UK specific. While potential changes to the international channels are a long term prospect, changes to the national channels are not constrained in the same way.
- The application of new technologies to radars would provide improved unwanted emission performance which at current performance levels has the potential to cause interference to spectrum users in adjacent bands. At present this issue does not arise because radars operate in adjacent bands but this would change if the use of the adjacent bands changed. This area is completely in national control and can therefore be regarded as a nearer term possibility.
- Sector blanking for ground based radars could reduce the extent of on-shore transmissions, though the gains here could be limited by transitory emissions from ship borne radars in coastal waters and ports. Emissions in port could in principle be limited, for example, if there were regulatory controls forbidding ships to continue transmitting while in port.

Impact of AIP

Provided spectrum charges for ship/ground systems are not levied on the radio equipment on ships there should be no disincentive to commercial and private vessel operators carrying radio equipment. 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.

AIP could raise funding issues primarily for the Maritime and Coastguard Agency (MCA), which is an executive agency of the Department for Transport (DfT) and is primarily publicly funded. It would need to negotiate with the Department for Transport or make efficiency improvements to cover the costs of increased spectrum fees. Most other spectrum users are privately funded and would face commercial pressures from AIP to use spectrum more efficiently.

Approach to setting AIP

AIP is based on opportunity cost estimates which in turn depend on the marginal value of spectrum use for existing and potential alternative uses of the spectrum. To determine the appropriate level of AIP we have addressed the following issues

- How should AIP be set when the marginal benefits of spectrum to the existing and alternative uses differ considerably?
- What are the social costs and benefits of setting AIP too low versus too high when there is uncertainty about the best estimate of opportunity cost for a given band?
- Does the possible introduction of trading for spectrum used by the aeronautical and maritime sectors affect the application of AIP?
- How should AIP be refined over time in response to new information about demand, and technological and market developments?
- Should AIP be applied in the specific case of out of band radar emissions?
- How should AIP be applied in shared bands?

Allowing for multiple benefit estimates and uncertainty

Our approach to setting AIP represents a development of the approach in the Independent Audit in that we propose consideration of charges that may exceed a level "*slightly above the same service opportunity cost*" where the same service opportunity cost is zero, but the alternative service opportunity cost is positive (and potentially substantial). For example, where there are two estimates of marginal value, one significant and positive and the other zero, our starting point is to assume that opportunity cost at equilibrium is mid-way between the two. This initial judgement might be modified for three reasons.

- First, if it is thought that the application of AIP would lead to a significant release of spectrum from existing use and that consequently the equilibrium level of opportunity cost would be lower than the initial estimate.
- Second, if new services and applications are expected to introduce new demand for radio spectrum in the medium term, possibly in response to the initial release of spectrum due to the application of AIP, then this would suggest a somewhat higher level of opportunity cost and so a higher level of AIP than would otherwise be the case.
- Third, in using the best estimate of opportunity cost (taking account of the above considerations as a basis for setting AIP), account should be taken of the level of uncertainty in the opportunity cost estimate and the social losses of setting prices above or below the best estimate of opportunity cost. If the two competing demands have similar demand curves then there are grounds for a downward adjustment. However, where the competing use for the spectrum is likely to have high value the early application of AIP at or above the best estimate of opportunity cost may be appropriate to bring about the required reassignment of spectrum in a timely manner. A practical

example of this is the potential to economise on the use of spectrum by radar and to use such spectrum for mobile use.

Judgement is inevitably required in coming to a view about the relative slopes of spectrum demand and uncertainty concerning the opportunity cost estimate. In Chapter 5 and Appendix E we have provided a structured way of thinking about the problem that puts bounds on the adjustments one might make to the best estimates of opportunity cost. Based on this analysis we propose a rule of thumb that the best estimate of opportunity cost is reduced by between 20 and 40 per cent when setting AIP, with the reduction towards the top end of the range if uncertainty is high.

However, if there are strong *a priori* grounds for believing that the competing use is particularly valuable relative to the existing use with excess spectrum then no reduction should be applied to the best estimate of opportunity cost and AIP should be set mid-way between the two estimates of marginal benefit. Once appropriate allowance has been made for upside and downside risks, there are no grounds in terms of economic efficiency for phasing in AIP gradually or implementing AIP partially, though there may be practical reasons for doing so.

Impact of trading

If spectrum subject to AIP is also tradable in an efficient market, then the optimal level of AIP would be lower than without trading. This is because the costs of setting AIP on the low side would be reduced to the extent that trading results in movement towards an optimal allocation in any case. Trading of spectrum allocated to the aeronautical and maritime sectors is not yet permitted. If permitted, there are reasons to expect (based on international experience) that the market will be imperfect in the short term at least which argues against significantly reducing AIP.

Refinement of AIP over time

There are a number of sources of new information that might lead to the revision of AIP. First, the application of AIP will produce a response which may reveal new information. Second, auctions or trading may reveal information. Third, actual changes and changes in expectations in relation to technology and market developments will change the assessment of spectrum demand and supply over time, including new opportunities to utilise spectrum and the scope to economise on spectrum use in existing uses. All of these factors could affect the best estimate of AIP.

Out of band emissions

In relation to out of band (OOB) emissions by radars we agree with the Independent Audit that account should be taken of the spectrum used, which may restrict or deny use of adjacent spectrum. We have proposed that this should be done by applying absolute emission limits such that out of band emissions are at acceptable levels but that the assigned bandwidth is adjusted to define emissions more accurately. This is a considerable departure from the current situation and it may be necessary to adopt a transitional approach in which existing masks are used and AIP would be applied to both the existing assigned bandwidth and the unwanted emissions outside the band.

In addition to the impact of radar OOB emissions there is also the question of radar receiver sensitivity potentially constraining other services from using the spectrum. Consideration does not need to be given to sensitivity to adjacent band users as this would merely support poor receiver selectivity and in any event it should be the responsibility of the radar frequency assignment manager to provide sufficient protection by moving away from the band edge.

With regard to in-band sensitivity, which has the potential to restrict or deny use of the spectrum by other users, (both radar and, potentially, other radio systems), a case can be made for charging relative to the area in which use to other users is restricted or denied arising from in-band radar sensitivity. However, the issue of specifying receiver sensitivity through regulation, whether direct or indirect, is a much wider issue than that simply pertaining to radars. It relates to the current debate surrounding the technical parameters related to the receive aspect of Spectrum Usage Rights (SURs) and Recognised Spectrum Access (RSA). A coherent policy regarding the protection of receivers and the implication of a receiver's inherent performance needs to be determined before regulatory tools (SURs, RSA, AIP) specifically directed at receivers are put in place. Further work and debate is required in this area.

Shared bands

Many of the bands under consideration are shared between civil and military aeronautical and maritime users. For those shared bands that are not managed by Ofcom the approach favoured by the Independent Audit was to designate a single entity as the "band manager" liable for payments of AIP for that band. It is not yet clear whether this approach is legally feasible - if it were some ground rules for the apportionment of AIP within the band to existing licensees would need to be developed. In this instance we recommend that these charges are set on a cost pass through basis. This means that the AIP values determined by Ofcom would set a cap on what could be charged to existing licensees or for reservations of spectrum for a particular sector. In the event that AIP is recovered directly by Ofcom from users, the apportionment of AIP should reflect the constraint or denial of use created by the particular sectors and users.

In some situations (for example mobile only use) it may not possible to charge the user of the spectrum directly, because the spectrum use is not licensed; or direct charging may have weak incentive properties or be administratively inefficient. In these instances, other, possibly indirect, approaches should be considered, for example charges to the relevant government departments/agencies/regulators who may absorb or pass on the charges to end users.

AIP estimates

In bands where there are competing demands for the spectrum AIP should be set at the best estimate of the opportunity cost for the band – this will generally lie between the opportunity cost in the existing use and the highest value alternative potential use. In order to derive opportunity cost estimates for a given frequency band we have

- Determined whether the band is congested in the current use and if so calculated the marginal benefit of spectrum in that use. The opportunity cost estimates calculated are based on the resource cost of employing a more spectrally efficient technology to deliver the current level of service or functionality – in previous studies this has been termed the "least cost alternative" approach.
- Identified potential alternative uses of the band and assembled existing opportunity cost estimates for those uses from previous reports, namely Indepen *et al* (2004) and Indepen-Aegis (2005).
- Drawn on studies on radars undertaken for Ofcom which give an indication of the costs of improving the spectral efficiency of existing radars.

Tables 1 and 2 show our conclusions on the bands to which AIP should be applied (AIP should not apply to bands not listed) and our recommended nationwide annual per MHz AIP estimates. These estimates are indicative. Given the uncertainties in deriving the estimates some rounding of similar values may be appropriate.

What stands out in Table 1 is the high value for the communications band. This is a consequence of the considerable congestion in the band and the fact that aeronautical users do not have any alternative but to invest significant sums in more efficient equipment if future demand is to be accommodated. A similar but less marked situation applies in the case of maritime bands (see Table 2), though here we anticipate that AIP would only be applied where congestion is found - primarily around the English Channel and the south coast of England.

Table 1 AIP for congested aeronautical bands[5]

Frequency Band (MHz)		Aeronautical Usage	AIP estimate
From	To		
108	118	108-112 MHz ILS (localiser) 108-118 MHz VOR & GBAS	£217k/MHz
118	137	VHF Communications	£610k/MHz
328.6	335.4	ILS (Glide Path)	£217k/MHz
590	598	Ground Radar (50cm)	£275k/MHz
960	1215	DME, Secondary radar (1030/1090 MHz)	£252k/MHz
1215	1350	Primary radar	£252k/MHz
2700	3100	Primary radar	£252k/MHz
4200	4400	Radio Altimeters	£42.5k/MHz
5000	5150	MLS	£42.5k/MHz
5350	5470	Airborne Weather Radars	£42.5k/MHz
9000	9500	Ground movement and airborne radar	£34k/MHz
13250	13400	Doppler navigation aids	£25.5k/MHz
15400	15700	Ground movement radar	£25.5k/MHz

[5] A band is congested if there is excess demand from either the existing use or an alternative use now or in the future.

Table 2 AIP for congested maritime bands

Frequency Band (MHz)		Maritime Use	AIP estimate
From	To		
156*	163*	Coastal station (UK) radio International maritime distress, calling and safety Coastal and inshore search and rescue; DGPS channels, AIS channels	£372k/MHz
2900	3100	Radar (10cm) - in and out of band emissions, RACONs	£252k/MHz
9200	9500	Radar - in and out of band emissions, RACONs, Search and Rescue Transponders	£34k/MHz

* Only some channels in these bands are used by the maritime community

Implementation

In Chapter 7 we describe the steps that would need to be implemented to develop AIP estimates for the band and users with individual assignments in the frequency bands identified in Tables 1 and 2. The key parameters that need to be calculated are the bandwidth and population in the geographic area where use is restricted or denied to other users. We discuss issues in doing this for each aeronautical and maritime bands where AIP might be applied. Specific examples of the proposed approach are given to illustrate the method.

We also recommend priorities for applying AIP and these are summarised in Table 3.

Table 3 Priorities for Implementation of AIP

Priority	Frequency bands	Reasons
High	590—598 MHz (if not auctioned) 960-1350 MHz 2700-3100 MHz 118-137 MHz 156-163 MHz*	High demand from own and/or alternative use.
Medium	108-118 MHz 328.6-335.4 MHz 5000-5150 MHz 9000-9500 MHz 15400-15700 MHz	Existing use not congested. Potential for alternative use but demand not as high as in the high priority category.
Low	4200-4400 MHz 5350-5470 MHz 13250-13400 MHz	All airborne uses and there is limited scope for releasing spectrum in UK

* Only some channels in this band are used for maritime communications.

In order to implement our recommendations Ofcom will need to agree a number of detailed issues with representatives of aeronautical, maritime and military users. In particular it will be necessary to

- Determine how decisions about use of shared bands are made and the basis on which individual users are charged
- Identify more precisely areas of congestion for maritime communications with reference to information held by Ofcom on the ease of making assignments in different locations
- Agree a national price per MHz by band in light of our recommendations, possibly informed by spectrum auctions that may occur in the next year or so.
- Determine the approach to out of band emissions for radars, taking account of the options given in Chapter 5/ Appendix F
- Undertake the implied quantification of impacts for each radar frequency band and for aeronautical and maritime radars separately including determining the approach to calculating the bandwidth and geographic area over which spectrum use is restricted or denied to other users – models or measurement

In addition, we have a noted a number of areas where further work is required including

- Establishing definitive data on the use of spectrum in aeronautical and maritime bands. In the course of this study we received conflicting data on the extent and nature of use in different bands.
- Estimating the extent of spectrum use in the UK restricted or denied by radars operating on passing ships
- Estimating the extent of spectrum use in the UK that would be restricted or denied by use of mobile equipment on aircraft operating outside UK airspace
- Considering whether radar receiver sensitivity should be determined through regulation as part of a wider policy review regarding the protection of receivers in relation to SURs and RSA.

In conclusion, our experience gained from examining current use and management of bands allocated to aeronautical and maritime services suggests that there is considerable potential for more intensive use of these bands and that careful application of AIP would provide the necessary incentives to achieve this outcome.

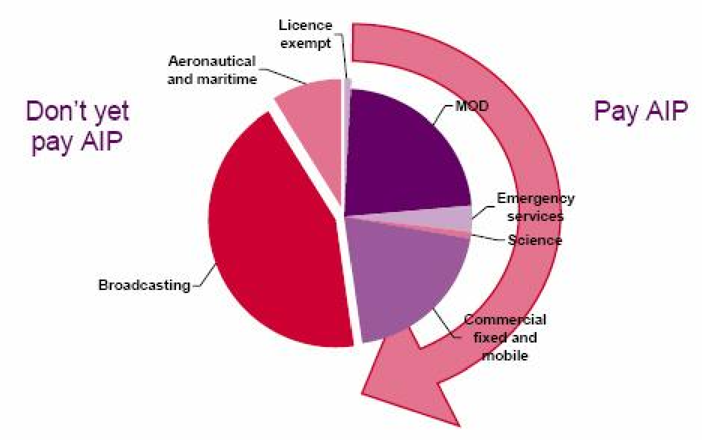
1 Introduction

This is the Final Report for a study for Ofcom on applying administered incentive pricing (AIP) to spectrum allocated to aeronautical and maritime services.

AIP was introduced in 1998 under the Wireless Telegraphy Act with the objective of promoting greater efficiency in the use of spectrum. The prices set were based on the estimated own use opportunity cost using a method developed by Smith-NERA in 1996.[6]

AIP is now applied to most congested frequency bands in the UK[7] other than bands used by terrestrial broadcasting and aeronautical and maritime services. AIP is paid by many commercial users of spectrum and some government and public agencies. Ofcom summarised developments in terms of the application of AIP below 1 GHz as shown in Figure 1.1 (the size of the segments is proportional to the spectrum occupied by the service).[8]

Figure 1.1 Evolution of AIP for spectrum below 1 GHz



Source: Ofcom. July 2006. "Future pricing of spectrum used for terrestrial broadcasting"

The aeronautical and maritime sectors are allocated a significant amount of spectrum by the ITU in a range of frequency bands (see Figure 1.2)[9] and it is therefore important that these users have incentives to use spectrum efficiently. AIP is one mechanism for providing such an incentive. Trading is another and we take account of the interaction between trading and AIP in our analysis.

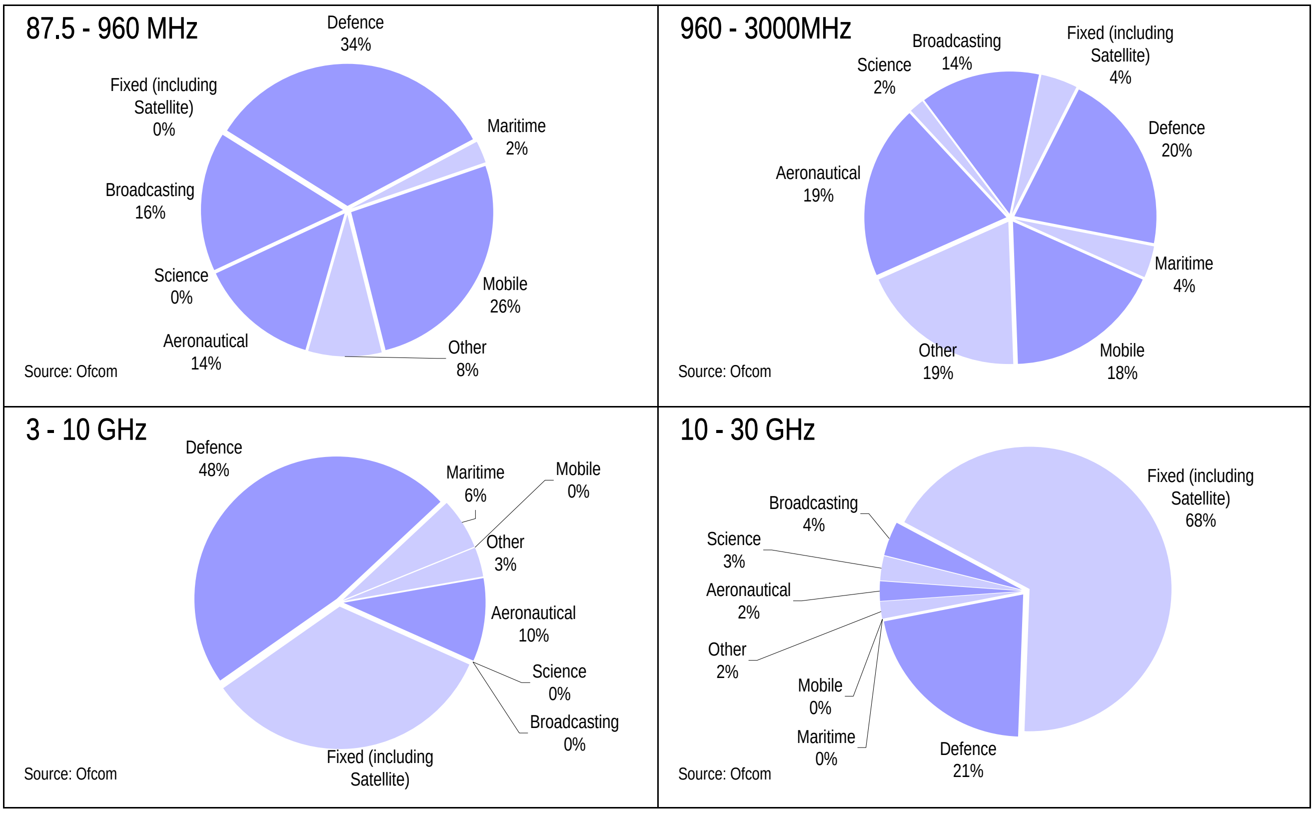
[6] Study into the Use of Spectrum Pricing, NERA and Smith System Engineering, Radiocommunications Agency, April 1996.

[7] Except where an auction has been used to assign rights of use.

[8] Ofcom. July 2006. "Future pricing of spectrum used for terrestrial broadcasting." http://www.ofcom.org.uk/consult/condocs/futurepricing/summary/

[9] This data may overstate actual spectrum occupied where there is secondary use of some bands and other opportunities for sharing between different uses.

Figure 1.2 Allocations to main uses in bands 87 MHz-30 GHz



This study on the application of AIP to spectrum allocated to aeronautical and maritime services follows proposals initially made in the Cave Review (2002).[10] Specific proposals for pricing in relation to aeronautical and maritime services were then given in Indepen *et al* (2004) which extended the Smith-NERA methodology to consider the value of the next best alternative use.[11] The Independent Audit (2005) investigated this area in more detail and made a number of relevant recommendations which the Government Response to the Audit (2006) has endorsed.[12] The recommendations of the Independent Audit are reproduced in Appendix A.

In response to the Independent Audit the Government stated that:[13]

> *"The Government agrees with the Audit that administrative incentive pricing (AIP) remains an important tool for promoting efficient use, that it should be applied more consistently, and should more accurately reflect the market value of the spectrum."*

In particular, the Government supported the Independent Audit recommendations for considering the application of incentive pricing to use of spectrum by aeronautical radars, VHF communications and possibly navigation aids and to use of spectrum by maritime navigation aids (radar), VHF radio and

[10] Review of Radio Spectrum Management", Professor Martin Cave, DTI and HM Treasury, March 2002. http://www.ofcom.org.uk/static/archive/ra/spectrum-review/2002review/1_whole_job.pdf

[11] An Economic Study to Review Spectrum Pricing", Indepen, Aegis Systems and Warwick Business School, Ofcom, February 2004 http://www.indepen.co.uk/panda/docs/spectrum_pricing_review.pdf

[12] Cabinet Official Committee on UK Spectrum Strategy (UKSSC) in consultation with Ofcom, "Independent Audit of Spectrum Holdings", Government Response and Action Plan, March 2006. http://www.spectrumaudit.org.uk/220306.htm

[13] Cabinet Official Committee on UK Spectrum Strategy (UKSSC) in consultation with Ofcom. *Ibid.* p.4

differential global positioning system (DGPS), subject to the results of public consultation and an impact assessment.[14]

The purpose of this study is to develop concrete proposals for the extension of AIP to frequency bands used by the aeronautical and maritime sectors. This study is required to

- Establish a priority list of frequency bands used by the aeronautical and maritime sectors for the initial application of AIP
- Establish whether legitimate non-market factors exist that might influence the application of AIP to relevant bands
- Establish if, and how, sharing will influence the level of AIP in relevant bands
- Develop pricing options and an optimal methodology for calculating costs and prices for relevant bands
- Identify AIP options that take account of unwanted emissions, such as those from radars into neighbouring bands
- Identify likely implementation issues and options for managing the introduction of AIP into relevant bands

In developing the methodology to address these questions we have built on the Indepen-Aegis (2005) methodology developed in relation to broadcasting which drew on own and alternative use estimates of marginal benefit, and considered the question of whether the positive externality associated with public broadcasting represents grounds for modifying the level of AIP. (The study concluded it did not.)[15] In this study the Indepen-Aegis methodology is further extended to explicitly consider the uncertainty associated with an estimate of opportunity cost, and the potential costs of setting AIP too high versus too low, in coming to a judgement about the appropriate level of AIP.

In the course of the study we have undertaken interviews with representatives of the aeronautical and maritime industries[16] and we would like to thank them for their contribution. While our analysis draws on the findings from these interviews and desk research the views expressed are our responsibility alone.

The structure of the remainder of this report is as follows.

- Chapter 2 discusses the economic principles governing spectrum pricing.
- Chapters 3 and 4 address respectively aeronautical and maritime demand for spectrum. Topics covered include international constraints, technology developments, spectrum demand and current arrangements for licensing and charging for spectrum access. Appendices B-D contain supporting material.
- Chapter 5 discusses how to set AIP given opportunity cost estimates and taking account of the shared nature of many bands allocated to aeronautical and maritime uses. Detailed support is given in Appendices E and F.

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[14] Recommendations 6.1, 6.6,-6.9 and 7.1-7.3, http://www.spectrumaudit.org.uk/final.htm

[15] Indepen and Aegis. October 2005. “Study into the potential application of Administered Incentive Pricing to spectrum used for Terrestrial TV & Radio Broadcasting.” http://www.ofcom.org.uk/consult/condocs/futurepricing/aipstudy.pdf

[16] Airport Operators’ Association, BAA, the Bandsharing Forum, British Ports Association, the Chamber of Shipping, the CAA, Eurocontrol, the MCA, Ministry of Defence, NATS, Ofcom, Port of London Authority, Trinity House and a member of the Independent Audit team

- Chapter 6 presents opportunity cost and AIP estimates and supporting material is given in Appendix G.
- Chapter 7 addresses implementation issues.

2 Economic Principles

2.1 Introduction

AIP is a means of promoting efficient spectrum use in the short and long term. Other mechanisms include administrative decisions, auctions of new or released spectrum and spectrum trading. The principle behind applying market mechanisms – auctions, trading and pricing – is that by reflecting the "opportunity cost" (i.e. the cost to alternative uses and users of being denied access to spectrum due to spectrum scarcity) directly on users of spectrum they will have both the information and motivation to economise on existing spectrum use and on future demands for additional spectrum to an optimal extent. Incentives are optimal in the sense that they are likely to maximise economic and social welfare.[17]

Ofcom notes that the case for AIP does not rest on the existence or identification of an immediate opportunity to economise on spectrum use:[18]

> *"It is important to understand in this context that Ofcom's primary purpose in applying AIP is not, in general, to achieve any specific short-term change in the use of spectrum. Rather, our aim is to ensure that the holders of spectrum fully recognise the costs that their use imposes on society by holding spectrum (or seeking to acquire additional spectrum), when making decisions. We fully appreciate that many holders of spectrum are not in a position to make rapid changes to their use of spectrum in response to the application of AIP, but note that in practically every case the holders of spectrum have opportunities to change their use of spectrum in the longer term, albeit in some cases the longer term may be many years away. The use of AIP is, in our view, justified by the benefits that should materialise in the longer term, as better decisions are made in light of increased awareness and appreciation of the value of spectrum – better decisions that should lead to more efficient use of the spectrum." Paragraph 1.9*

Three types of decisions could be made in the light of increased awareness and appreciation of the value of spectrum, namely:

- better decisions over the use of spectrum given existing regulatory constraints (including international harmonisation) on spectrum use
- better decisions in terms of the release or acquisition of spectrum
- better decisions over the harmonisation of international bands for aeronautical and maritime use.

The case for applying market based approaches, including AIP, does not rest on anticipating the changes that could occur in response to incentives. Indeed one reason AIP is applied is because we do not know with any certainty how users will respond to opportunity cost based pricing. However, responses might include one or more of those listed in Box 2.1. While the application of AIP should not be conditional on the magnitude of anticipated demand response, the level of AIP applied might be influenced by the anticipated response if this is likely to materially affect the estimate of opportunity cost.

[17] This is consistent with requirements under the Wireless Telegraphy Act 1998 para 2(2) to promote "efficient use and management of the electromagnetic spectrum" and "any economic benefits arising from the use of wireless telegraphy".

[18] Ofcom. July 2006. "Future pricing of spectrum used for terrestrial broadcasting." http://www.ofcom.org.uk/consult/condocs/futurepricing/summary/

Box 2.1: Possible responses to AIP

- Encourage UK users to promote earlier adoption of more spectrally efficient systems in Europe
- Encourage the release of assignments that are not required operationally
- Encourage sharing of spectrum with other users/services
- Incentives to develop and/or deploy more spectrally efficient equipment more quickly, for example, solid state radar and digital radio for aircraft, and to develop new more stringent guidelines on out of band emissions for radars
- Closure of non-essential radar facilities
- Rationalisation of duplicate services where this is compatible with safety requirements
- A reduction in demand for new spectrum allocations sought internationally
- A reduction in final service demand due to higher costs

In this chapter we address the following questions

- When should AIP be applied?
- Should AIP be adjusted for externalities?
- Should AIP take account of technology choices?

2.2 When should AIP be applied?

AIP should be applied when spectrum inputs are scarce in the existing or an alternative use i.e. additional spectrum has a positive marginal benefit to the user and so a positive opportunity cost. [19] Spectrum has a non-zero opportunity cost over a given area (which may be part or all of the UK) if there are competing demands for the spectrum from either the existing or an alternative use now or in future. Anticipated future demand would imply some value to holding unused spectrum now in advance of future demand – in other words the opportunity cost today is non-zero if a positive opportunity cost in future is anticipated. An analogy is to consider a spectrum market, where anticipated future excess demand would imply a positive price, even if spectrum were not scarce today, provided spectrum could be held for future use.

The short term efficiency gains from applying AIP are likely to be greater the fewer the number of regulatory and technical constraints there are on users' ability to change their spectrum use in response to prices.[20] However, the application of prices in the market place is not conditional on responsiveness, and neither should pricing be conditional on the anticipated response in relation to the application of AIP. In the longer term, regulatory and technical constraints may change and so greater efficiency gains may be possible.

An important consideration in relation to the longer term response is how one should think about opportunity costs when there are significant existing constraints on reassigning spectrum between alternative uses (e.g. international constraints). One way to think about this problem is to consider

[19] See Recommendation 7.1, Independent Spectrum Review, March 2002.

[20] If there is no prospect of pricing influencing spectrum use in the short and long term then there would be more limited benefits from applying the policy, comprising for example a reduction in the "deadweight loss" from taxation. The deadweight loss from taxation arises because taxes introduce disincentives for work, savings and consumption that involve welfare costs for consumers. The opportunity to reduce the deadweight loss from taxation via revenues raised from spectrum pricing is therefore socially valuable in its own right, even in circumstances where there is no response to spectrum pricing.

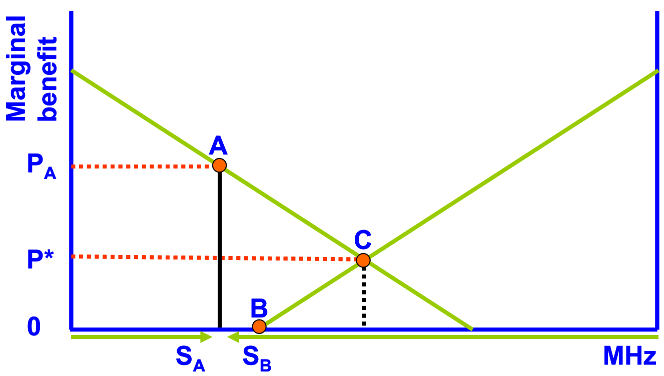
what would happen in a spectrum market with trading. If the constraint were binding in the short term, but with some probability that it would be relaxed in future, then the price of any trades will be different on either side of the constraint.

The situation is illustrated in Figure 2.1 for the simple example of two competing uses of a given spectrum band, and where there is scarcity in respect of use A and no scarcity of spectrum in relation to use B.[21] The constraint is given by the vertical line S_A, A. The optimum allocation of spectrum without the constraint is at point C.

In a liquid trading market the price/s in the presence of the constraint would reflect the probability that the constraint would be moved or removed in future. If the market expectation were that the constraint would be removed soon, then the single equilibrium price either side of the constraint would approximate P*. However, if the market expectation were that the constraint would be removed with a probability less than one then prices of traded spectrum will be as follows

- Trades to the right of the constraint will have a price that is somewhere in the range between zero and P*, depending on the assumption made about the probability that the constraint will be relaxed. If the probability is zero then the price is zero and if the probability is one then the price is P*.
- Trades to the left of the constraint will have a price between P* and P_A. If the probability is zero then the price is P_A and if the probability is one then the price is P*.

Figure 2.1 Marginal benefit from use of spectrum by uses A and B



The optimal price in the absence of the constraint would be P*. If the constraint is taken as given, then one might set prices corresponding to A ($P=P_A$) and B (P=0) for the two uses, but this provides weak incentives to shift the constraint, in particular there is no incentive for the existing use S_B to propose a reduction in their allocation.

However, from a social perspective, it may be appropriate for use B to face the opportunity cost of their current allocation without the constraint, and for use A to face the same constraint free opportunity cost. The reason for this is that it provides incentives to shift the constraint i.e. to allocate more spectrum to use A and less for use B. Potential inefficiencies with this approach are that use A may face too low an opportunity cost in the short-run, though trade between users within use A may

[21] Note that the results shown also apply for cases where there is scarcity of spectrum in use B.

alleviate any such inefficiency if trading is permitted[22] and use B may face too high a charge with the risk of leaving spectrum unused.

We suggest existing users should face the opportunity cost of spectrum assuming existing constraints can be moved or removed in the medium term. Otherwise they do not have an incentive to release spectrum they do not require, or to moderate their demands for additional spectrum. In addition, the application of AIP will in itself provide an incentive for users to lobby to remove the constraint and transparent opportunity cost estimates provide information for decision makers carrying out impact assessments. However, in circumstances where constraints are likely to be particularly difficult to change the risks of leaving spectrum unused may argue for setting prices on the low side initially.

The question of how multiple estimates of marginal benefit and constraints should be assessed is considered further in Chapter 5.

2.3 Should AIP be adjusted for externalities?

Indepen *et al* (2004) concluded that setting prices of spectrum that promote efficiency entails setting prices equal to marginal opportunity costs. It was argued that this conclusion held in a situation where spectrum using services created positive or negative externalities.

This position was supported by reference to the Diamond and Mirrlees (1971) result that in setting policy to maximise welfare in a second-best situation it is not desirable to tax (or subsidise) the use of inputs.[23] This result provides a powerful general argument against adjusting spectrum prices to take account of negative or positive externalities. This was further developed in Indepen-Aegis (2005) in relation to the application of AIP to broadcasting.[24]

There are two kinds of externality we need to consider here in respect of use of spectrum by aeronautical and maritime services

- Market externalities involving financial impacts in secondary markets which are downstream or upstream from the market subject to primary or initial impacts (sometimes termed pecuniary externalities)
- Non-market externalities such as greenhouse gas emissions, acoustic noise and radio interference which impact on consumer wellbeing and production, but not directly via market prices.

Below we conclude that market externalities due to aeronautical and maritime activity do not constitute grounds for modifying spectrum prices based on opportunity cost estimates. Non-market externalities should in general be tackled directly via regulation or emissions pricing. The one exception to this general principle is where the production of an externality is related in a simple and non-varying way to the use of a particular input, for example, carbon dioxide emissions by aircraft are a linear function of fuel and therefore carbon inputs. In such instances it may be easier to measure the input (fuel) than measure the emission. The key question is whether or not spectrum inputs are directly and necessarily related to the production of externality. Where this is not the case, for example in relation to greenhouse gas emissions from aircraft which relate directly and necessarily to fuel (and therefore carbon) inputs rather than radio spectrum inputs *per se,* there are grounds for modifying the price of the direct source of externality i.e. the price of fuel and not the price of radio spectrum.

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[22] Trading is permitted for most commercial uses of spectrum but a decision on whether spectrum used by aeronautical and maritime users can be traded is expected to be made in 2007.Ofcom, 2004 “Statement on Spectrum Trading”

[23] Peter Diamond and James Mirrlees. 1971. "Optimal taxation and public production 1: Production efficiency and 2: tax rules". *American Economic Review*, Volume 61.

[24] Indepen and Aegis. October 2005. “Study into the potential application of Administered Incentive Pricing to spectrum used for Terrestrial TV & Radio Broadcasting.”

Administratively determined controls are generally sufficient to address radio interference externalities, however, in relation to radar in particular, we conclude that the nature and potential impact on use in adjacent bands may justify application of AIP to out of band emissions. The main reason for this conclusion is that under current regulations the high power of radars means the impact on neighbouring bands is potentially material.

2.3.1 Market externalities

All economic activities have impacts on other parts of the economy since they involve inputs that might be used by, and outputs that may support, other economic activities. Aeronautical and maritime activities are no different in this regard from other activities. An example of a discussion of potential market (or pecuniary) externalities in relation to aviation is provided by the Air Transport Action Group report "The economic and social benefits of air transport".[25] This document discusses the direct and indirect GDP and employment associated with the aviation sector, the impact of the sector on productivity and its role in world trade.

There is academic literature that shows that such external economic impacts do not have any implications for optimal pricing since they involve secondary market impacts that occur through changes in quantities and prices in the market place, rather than via externalities (such as greenhouse gas emissions) that impact on production outside of market mechanisms. Only externalities involving impacts that are not priced (like that from pollution for example), might justify a departure from opportunity cost based pricing.

Baumol and Oates (1988) discuss the issue of pecuniary externalities in the context of environmental externalities and note that pecuniary externalities result from a change in the prices of some inputs or outputs in the economy, and that whilst such changes impact on the financial circumstances of others, they need not produce a misallocation of resources.[26] Baumol and Oates (1988) state that:

> *"[pecuniary externalities] do not constitute any change in the real efficiency of the productive process viewed as a means to transform inputs into utility levels of the members of the economy. Indeed, the price effects that constitute the pecuniary externalities are merely the normal competitive mechanism for the reallocation of resources in response to changes in demands or factor supplies."*

Cabinet Office guidance notes that macroeconomic or second-round effects:[27]

> *"…represent simply a re-distribution of resources within the economy, without any net overall economic effect."*

Boardman *et al* (2006) also discuss the limited set of circumstances in which market externalities are relevant to welfare analysis.[28] The overall conclusion is that in a wide range of circumstances market externalities are irrelevant to the optimality of the market equilibrium, and (unmodified) opportunity cost pricing will produce optimal results. This conclusion applies equally to AIP as it does to the system of market prices generally. We conclude that whilst market externalities could occur in the maritime and aeronautical sectors, no account should be taken of them in setting AIP.

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[25] ATAG. 2005. "The economic and social benefits of air transport." http://www.atag.org/files/Soceconomic-121116A.pdf

[26] Baumol and Oates. 1988. "The theory of environmental policy." Cambridge.

[27] Cabinet Office. http://www.cabinetoffice.gov.uk/regulation/ria/ria_guidance/index.asp
http://www.hm-treasury.gov.uk/economic_data_and_tools/greenbook/data_greenbook_index.cfm

[28] Boardman, Greenberg, Vining and Weimer. 2006. "Cost-benefit analysis – concepts and practice." Third Edition. Pearson Prentice Hall.

2.3.2 Non-market externalities

2.3.2.1 The general case

Aeronautical and maritime activities also involve non-market externalities in terms of polluting emissions, pollution arising from accidents and aural noise. These effects have impacts on other economic activity and welfare that are not mediated by market prices because of the absence of markets for these outputs. In general the most efficient way of dealing with material non-market externalities is to address them directly via regulation, taxes and tradable permits targeted at the externality itself.[29]

In a few instances a particular input is directly and necessarily related to the production of externality, for example, fuel and therefore carbon inputs are directly related to the production of carbon dioxide emission by aircraft and ships and there is no feasible means of changing the relationship between the input and the polluting output. In such instances measures targeted at the particular input are just as effective, and likely to involve lower transaction costs in terms of measurement, than measures targeted at the output of pollution.

Whilst radio spectrum inputs are used by the maritime and aeronautical sectors, they are not directly related to any of the externalities produced by these sectors (e.g. acoustic noise, air or water pollution), and changing the price of such inputs on grounds that economic activity in the sector involves externality would not be effective or efficient.[30]

The essence of the argument is that whilst it would in principle be possible to take account of (i.e. internalise) externalities in the aeronautical and maritime industry by adjusting input prices, potentially all input prices including spectrum prices would need to be adjusted with different adjustments for each source. This is not practical. To the extent that genuine externalities are addressed in the aeronautical and maritime sectors, they should be addressed directly using instruments targeted directly at the externality.

2.3.2.2 Radio transmissions

The use of radio transmitting equipment can involve direct externality in terms of the denial or restricted use in adjacent bands due to interference. Radio transmitters, particularly high powered transmitters including radars, produce unintended emissions which may affect use in other bands. As a general rule there are internationally agreed thresholds for out of band emissions that are applied to control emission levels rather than pricing. However, where such thresholds are exceptionally high – really only in the case of radars largely because of their pulsed nature – there is a case for applying pricing to encourage industry to move to tighter thresholds. The high power level of some radars, particularly aeronautical radars, means that, even where out of band emissions are within agreed

[29] Private negotiated solutions are infeasible due to transaction costs.

[30] Strictly it is in principle possible to address an externality by modifying the price of all inputs in an appropriate way. In particular, Holtermann (1976) found that "Where it is impossible to tax an externality directly, Pareto optimality can nevertheless be achieved by a set of taxes (subsidies) imposed on all of the other inputs and outputs of the agent creating the externality." Sally Holtermann. February 1976. "Alternative tax systems to correct for externalities, and the efficiency of paying compensation." *Economica*, Volume 43169. However, this is in practice infeasible given the information and practical constraints on achieving efficient outcomes via the modification of input prices. Holtermann notes that "*in general it is likely to be preferable on practical grounds to tax the externality directly whenever possible."* This conclusion is reinforced by more recent literature. For example, Helfand (1999) concluded "*The problems in distinguishing instruments among sources, combined with lack of information about firms' production functions (and thus how firms will respond to input instruments), make it difficult to calculate the level of pollution reduction, if any, which can be achieved from applying suboptimal input instruments.*"; and that "*separate input taxes need to be developed for all inputs that influence pollution and for each source of pollution".* Gloria Helfand. November 1999. "Controlling inputs to control pollution: when will it work?" *Association of Environmental and Resource Economists Newsletter*, Volume 19(2). Page 17. http://www.aere.org/newsletter/Newsletter_Nov99.pdf

international emission masks, significant impacts on spectrum that might be used by other services can occur (see Chapter 3).

Reflecting this situation, Recommendation 6.12 of the Independent Audit states that:

> *"Radar tends to produce significant levels of unwanted emissions which can adversely affect the intensity of use and hence value of other spectrum bands. The Audit considers that there is an economic case for taking account of these negative externalities through a system of penalties on radar users for the degradation they cause to spectrum use in other bands."*

Wider application of AIP to include out of band emissions above some threshold may be justified. AIP levels need not be modified, rather the level of AIP appropriate to other uses subject to radio interference could be applied to out of band emissions. This issue is considered further in Chapters 5 and 7.

2.4 Should AIP take account of technology choices?

The decision over whether to apply AIP, and the level of AIP, should be influenced by specific policy objectives in relation to the migration from one technology to another has been addressed by Ofcom and the Independent Audit. Ofcom set out a general principle along these lines:[31]

> *"…the application of AIP is not designed to achieve any particular change in spectrum use in either the short or long term, other than the general objective of securing optimal use. The application of AIP is one of the principal tools of Ofcom's market-led approach to spectrum management, which aims to leave many decisions about future spectrum use to the market. The purpose of AIP is to ensure that the market has the right signals about the opportunity costs of spectrum use, to ensure that the decisions taken are in the best interests of UK citizens and consumers."*

The Independent Audit touches on the role of AIP in promoting (or at least not retarding) particular technologies. In particular in Recommendation 6.8 it is stated that:

> *"The [microwave landing system] MLS allocation is currently underused and there may be a case for applying pricing to this spectrum on the same basis as ground-based radar sites. This is subject to a concern that disproportionate pricing on initial users should not discourage the adoption of an effective technology,"*

Spectrum pricing should reflect the opportunity cost of spectrum and spectrum use by alternative technologies, for example, instrument landing system (ILS) and MLS. Such an approach may introduce an incentive to replace a less spectrally efficient technology with a more spectrally efficient technology, but the goal of spectrum pricing is not to achieve a particular technology transition *per se*.

2.5 Conclusions

In terms of deciding to which bands AIP should be applied it is important to focus on opportunity cost. Where this is thought to be zero for existing or potential alternative uses, then administrative costs alone should be recovered. Where a positive opportunity cost arises then AIP should in general be applied, since the (administrative) costs of applying AIP are modest and the benefits in terms of more efficient spectrum use may be significant.

It is important to note that this conclusion does not rely on the identification of specific opportunities to economise on spectrum use in the short or long term. Pricing will provide users with the incentive to

[31] Ofcom. October 2006. "Future pricing of spectrum used for terrestrial broadcasting." Paragraph 3.11. http://www.ofcom.org.uk/consult/condocs/futurepricing/futurepricing.pdf

make changes where appropriate and to lobby for relaxation of any constraints that might block change in the short or medium term. Our analysis also suggests that AIP should apply to all spectrum where opportunity costs are non-zero. In other words there is no economic reason to give priority to one band over another, though there may be practical reasons to do so.

Spectrum has a non-zero opportunity cost if there are competing demands for the spectrum from either the existing or an alternative use now or in future. An important question is how one should think about opportunity costs when there is a significant existing constraint (e.g. caused by international harmonisation) on reassigning spectrum between alternative uses. In this circumstance we argue that it is efficient to set a price for spectrum on both sides of the constraint. This provides an incentive for all parties to move to the optimum i.e. the price that would apply without the constraint. While there is a risk that this could leave some spectrum unused if a zero price is applied then there is no incentive to move the constraint. Judgement is required concerning the balance of risks to determine the appropriate policy response.

We conclude that neither market nor non-market externalities due to aeronautical and maritime activity constitute grounds for modifying spectrum prices based on opportunity cost estimates. However, in relation to radar in particular, the nature and potential impact on use in adjacent bands may justify the application of AIP to out of band emissions.

Finally, we conclude that the level and application of AIP should not be determined by specific policy objectives in relation to the migration from one technology to another. Rather AIP should be based on opportunity cost alone.

3 Aeronautical Use of Spectrum

3.1 Air traffic service

Almost all of the aeronautical use of spectrum is for the provision of air traffic services (ATS) which includes flight information service, alerting service, air traffic advisory service, air traffic control service (area control service, approach control service or aerodrome control service) and the provision of navigational infrastructure. Thus it covers services to aircraft taking and not taking an air traffic control (ATC) service (e.g. those using navigation aids and distress services).

ATC is the provision and operation of a system for monitoring and controlling aircraft. This is carried out through a network of control centres, radars, navigational aids and other communication and data systems which support air traffic controllers who provide instructions to pilots both on the ground and in the air. The objective is primarily one of safety of navigation achieved through directing pilots and thereby obtaining appropriate separation between aircraft both horizontally and vertically. These distances vary according to circumstances, but aircraft flying along the airways under radar surveillance, for example, are kept five nautical miles apart horizontally or at least 1,000 feet vertically.

Airspace is either controlled or uncontrolled. In the former case controllers are responsible for separating the aircraft through the issue of instructions that pilots are required to follow. Controllers may also issue advisories (flight information) to assist pilots, who in any event have the final responsibility for the safety of a flight and in an emergency may deviate from ATC instructions. Pilots are required to file a flight plan for each journey containing details such as destination, route, timing and height.

Within the controlled airspace, a network of corridors has been established. These corridors, or airways, are usually ten miles wide and reach up to a height of 24,500 feet from a base of between 5,000 and 7,000 feet. They mainly link busy areas of airspace known as terminal control areas which are normally above major airports. At a lower level are the control zones which are established around each airport. The area above 24,500 feet is known as upper airspace.

ATC services are split between airport control and area (or en-route) control. Airport controllers are responsible for traffic on the airport surface and airborne aircraft within an agreed radius of the airport, up to an agreed height. Airport control can be the responsibility of one or both of an airport control tower and an airport control centre. Area controllers control the traffic between airports and may also control traffic in and out of airports where airport control facilities cannot be justified. En-route services provided from area control centres are handed over to another area control centre when an aircraft reaches the boundary between defined control areas which in many cases are delineated on a national basis.

Outside controlled airspace pilots take full responsibility for their own safety although they can ask for assistance. Military controllers, who work closely with their civilian colleagues to provide a fully integrated service to all users, offer an air traffic service to aircraft in uncontrolled airspace. Military personnel also provide services to aircraft crossing airways and for those flying above 24,500 feet. A priority task for them is aiding aircraft in distress.

Under a 15 year contract agreed with the Ministry of Defence (MoD) in early February 2006 National Air Traffic Services (NATS) will supply military air traffic controllers with operational support services including flight data processing, voice communications and primary and secondary radar. Military controllers already share NATS' control centres at Prestwick, West Drayton and Swanwick. Over time they will use the same flight data processing system, with UK airspace operated jointly as a single entity. NATS provides the en route air traffic management services to aircraft flying in United Kingdom and North Atlantic airspace.

3.2 Radio applications and systems

A significant number of radio based technologies are used to support ATS activities, both for the controllers on the ground and for the pilots. Broadly speaking these technologies are related to navigation and surveillance supporting all phases of aircraft movement (on ground, take off/landing, en route) with supporting communications channels allowing information to be transferred between parties on the ground and in the air.

Table 3.1 lists the range of systems used and their functions, it should be noted that not all aircraft are fitted with equipment able to utilise the various systems. In addition a number of satellite based systems are used for navigation[32] (Global Positioning System (GPS)), communications[33] and distress/safety, and private mobile radio channels are used for airport ground communications.

Table 3.1 The Main Aeronautical Systems using Radio Spectrum and their Functions

System	Function
Primary Radars	Detect the position of aircraft by means of reflected signals.
Secondary Radars	Detect the position, identity and altitude of (typically large) aircraft fitted with transponders and can exchange other digital information between aircraft and ground.
DME - Distance Measuring Equipment	Provides an aircraft's distance from a ground station.
NDB - Non Directional Beacons	A navigational aid for aircraft which broadcast signals from a known location. Being replaced by VORs and GPS.
VOR – VHF Omni-directional Radio Range	A navigation system which indicates the identity of the station and the direction (but not the range) the aircraft lies from the VOR station. Often co-located with a DME to allow a one- station fix.
VHF communications	Used for communication between aircraft and ground.
HF communications	Used for long-range ATC communications over the North Atlantic
Instrument Landing Systems (ILS)	Provides precise guidance to an aircraft approaching a runway.
Microwave Landing Systems (MLS)	A precision landing system with advantages over ILS - particularly its all weather performance.
Weather Radars	Ground and airborne radar used to locate precipitation its intensity, motion and type.
Radio altimeters	Airborne radar that allow the height of aircraft to be calculated
Doppler navigation aids	Airborne equipment is used to provide ground speed and drift angle information

Appendix B summarises the systems and technologies used broken down into the following categories: ground based radars; ground based navigation and landing systems; communications; and other systems on board aircraft. In terms of developments intended to achieve more efficient spectrum use it can be concluded that:

[32] But not as the primary means of navigating

[33] Mainly relating to passenger communications.

- For communications channels, there has been some movement towards narrower bandwidth analogue channels, and some movement in making use of data rather than voice for the transfer of information; however, there is scope for migration from analogue to digital, from 25 kHz to 8.33 kHz channels for aircraft flying below 24,500 ft[34] and from voice to data which should offer further efficiency savings.
- For primary radars which are largely based on older technologies that give rise to significant out-of-band emissions, a programme of replacement with more spectrally efficient solid state technology is already underway for some systems. Systems that are not part of this programme need encouragement to follow the same path.
- The original intention that MLS would replace ILS has not been realised so far. A significant amount of spectrum at 5 GHz that was made available for MLS is therefore sitting idle. There is a renewed interest in MLS as it increases airport capacity, particularly in bad weather. MLS has been implemented at Heathrow and a few other busy airports in Europe, but it remains to be seen whether this translates into widespread MLS implementation.
- Satellite based systems are capable of providing navigation, communications and safety/distress facilities and already do to a greater or lesser extent for the three facilities mentioned. There is however a certain wariness of the reliability of satellite based systems that relegates their role to a supplementary one and it cannot be expected that they will replace existing systems in the near to medium future.

Changes in the use of spectrum by the aeronautical industry take some time to be implemented in order to avoid loss of revenue from either taking aircraft out of operation or reducing the operational capability of airports. It is normal industry practice to give aircraft operators 7 years' notice of changes (as major refits happen every 6 years or less) which also allows for international compliance. We note that NATS' replacement of magnetron by solid state radars is planned to take 10 years.

3.3 International constraints

The allocation of blocks of spectrum to both aeronautical and maritime radio applications is made at an international level by the ITU (Article 5 of the Radio Regulations) and is taken into account in ITU-R recommendations, ETSI, ICAO (SARPS) and Eurocontrol and other specifications. At a macro level this to some extent manages interference, but in practice more detailed planning and coordination activities at an individual frequency level are needed to keep interference to acceptable levels. Coordination within the European Regional States also addresses these issues and is aimed at optimising use.

The information provided below has been gathered from the Radio Regulations and ICAO Standards and Recommended Practices (SARPS), also from discussions with Eurocontrol, the Civil Aviation Authority (CAA) and NATS.

[34] Use of 8.33 kHz is to be expanded to flight level (FL) 195 (19,500 ft) and above with effect from 15 March 2007.

3.3.1 Designation of frequencies planned within a framework

At the highest level aeronautical frequencies are addressed in the Radio Regulations as indicated in the table below.

ITU Radio Regulations		
Radiodetermination – Radio beacons 160 – 535 kHz	Article 28	Appendix 12 – Parameter values for coordination. No specific frequencies
Aeronautical services	Articles 35 to 45	Appendices 26 & 27 – MF/HF frequency plan and allotment areas.

Distress frequencies (addressed under maritime) are also of importance to the aeronautical community.

Also at an international level, the SARPS published by ICAO identify specific frequencies associated with many aeronautical radio systems as shown in the table below.

ICAO (SARPS Annex 10)	
Distress	RR frequencies identified
MF/HF Comms 2.8 – 22 MHz	RR frequency plan
VHF Comms 117.975 – 137 MHz	Allotment table distinguishing national and international blocks. Tables of specific frequencies with 100, 50, 25 and 8.33 kHz spacing. (although some channels might be designated as national blocks, they still require coordination internationally)
NDB 255 – 526.5 kHz	Identifies RR Appendix 12 coordination. Specific frequencies not identified.
ILS 75 MHz beacons 108 – 111.975 MHz 328.6 – 335.4 MHz	Specific frequencies and frequency pairings identified.
VOR 108 – 117.975 MHz	
DME 960 – 1215 MHz	
MLS 5030.4 – 5150 MHz	
SSR (& ACAS)	Specific frequencies at 1030 and 1090 MHz

From Vols I, IV and V

It is important to note that primary radars are not specified at a technical level. There are operational requirements in terms of detection resolution etc but how these are met in practice (i.e. the technical implementation) is not specified. Airborne aids such as altimeters, weather radar and Doppler speed/drift indicators have minimum operational performance specifications determined by the European Organisation for Civil Aviation Equipment and technical standards orders specified by the European Aviation Safety Agency.

3.3.2 Coordination and assignment of frequencies for operations

It remains the case that States are responsible for assigning operational frequencies. However, given the relatively low frequencies used (short range primary and other radars at X-band and above being exceptions) and the congestion, particularly in Europe, it is necessary that international coordination takes place. This coordination is essentially provided by ICAO and in the case of Europe supported by Eurocontrol.

For VHF Communications, Eurocontrol has developed a tool, SAFIRE, which is a repository for European aeronautical frequency assignments and associated tools to assess whether new frequency assignments can be made or not[35]. Personnel responsible for making frequency assignments in member States will be able to access the tools remotely. When an assignment is made other States have the opportunity to object. However, congestion is so great that often a new assignment requires other States to agree to shift their frequencies. Twice a year a block planning meeting is hosted by ICAO/Paris to resolve outstanding assignments that cannot be resolved using SAFIRE and through routine agreement between member States. Although the process of frequency assignment fundamentally follows the traditional “first-come, first-served” approach, in practice congestion is so great that assignments are made taking account of operational priorities.

More spectrally efficient channelisation based on 8.33 kHz has been introduced into the VHF Communications band. For example, ICAO has stipulated mandatory carriage of dual mode 25/8.33 kHz equipment for all aircraft wishing to fly above 24,500 ft in Europe. Further mandatory carriage is currently being considered for 19,500 ft and above with effect from March 2007 and is being considered for full expansion throughout remaining airspace; however, implementation of mandatory carriage typically takes several years to allow equipment to be fitted during normal refit cycles.

The mandatory carriage is crucial to the implementation of 8.33 kHz channelisation. An 8.33 kHz assignment can only be made in an airspace sector when all aircraft potentially entering the sector are fitted with the correct equipment. This means that ground station operators only have the flexibility to introduce more spectrally efficient communications technology above flight levels for which mandatory carriage has been stipulated.

3.4 Safety issues

An important question is whether charging for the use of radio spectrum used by aeronautical services would have any impact on safety, and if so what the right policy response would be. The aviation sector is subject to a range of regulatory requirements in terms of equipment, facilities and procedures that impose tight constraints on conduct and safety in the commercial sector in particular. This means that if safety is likely to be compromised by a lack of spectrum to support the current volume of airborne traffic, then procedures would be put in place to reduce traffic levels (i.e. limits on take-offs and landings) so that safety requirements could be met. In other words safety constraints are binding and the effect of insufficient access to spectrum would be an economic one, with airlines and airports experiencing reduced traffic levels.

However, general aviation aircraft utilise some equipment on a discretionary rather than a mandated basis. If spectrum charging discouraged such use it could have an impact on safety at the margin. However, we do not expect this concern to arise in practice. If, as is proposed in later chapters, AIP is recovered from charges applied to ground stations (and not airborne stations) then aviation users pay for the cost of spectrum through airport charges (which are often weight related) and so payments would not be linked to use of particular equipment. There would then be no disincentive from AIP for

[35] It is planned that this facility be made available to other countries around the world.

use of radio navigation facilities by general aviation. If, contrary to the conclusion above, there was a concern that imposing AIP might in practice compromise safety to an unacceptable degree by leading general aviation to dispense with carrying certain radio equipment, the correct policy response would be to revise the regulation to mandate general aviation to carry that equipment. Continuing to make spectrum available without charging AIP would not guarantee that the equipment would be carried and would, moreover, risk causing an economically inefficient allocation and use of spectrum.

3.5 Nature of use

Whether and how AIP is applied to spectrum used by civil aeronautical services is affected by

- The sharing of frequency bands between civil and military aeronautical and maritime use
- Whether the transmitting equipment in the band is ground based or airborne
- The extent of demand for frequencies in the band (i.e. congestion) from the current use and potential alternative uses. This is in turn affected by the sensitivity of radar receivers
- The scale of out of band emissions

In this section we describe these aspects of frequency use in bands used by civil aeronautical services. The conclusions from this analysis are summarised in Table 3.2.

3.5.1 Shared use

Table 3.2 shows that significant amounts of spectrum at VHF, 1GHz, 3 GHz, 5 GHz, 9 GHz and 15 GHz are allocated to aeronautical use, although in many of these bands civil aeronautical services share the spectrum with military services and, in some cases, maritime and other civil uses (e.g. satellite and amateurs). The relevance of this to spectrum pricing is that pricing for civil aeronautical services would only apply to the spectrum that they use and/or is reserved for their use – this might be the entire band (e.g. VHF communications) or individual assignments (e.g. in radar bands). This will, however, depend on the specific characteristics of the band and the nature and basis of any sharing.

In addition to the bands listed, aeronautical services make use of frequencies in private mobile radio and satellite bands. Aeronautical users are treated like any other user in those bands for the purposes of applying AIP and so we do not address aeronautical use in these bands.

3.5.2 Sharing between ground and airborne equipment

Column 3 of Table 3.2 indicates whether the aeronautical equipment using the specific frequency range is ground based or airborne. Ground based use is tied to specific frequencies within the bands. Airborne communications and secondary radar use also occurs on specific frequencies that are coordinated through ICAO in the case of MF/HF channels and regionally through Eurocontrol in the case of VHF channels, and by international treaty in the case of secondary radar.

By contrast airborne weather radars, altimeters and Doppler navigation aids may use frequencies anywhere in the allocated band and this use is not co-ordinated in any way i.e. specific frequencies are not assigned in the licence. In these cases the spectrum is effectively used on a commons basis.

Table 3.2 Nature of spectrum use in bands allocated to aeronautical services

Frequency Band (MHz)		Aeronautical Usage	Location of Use	Sharers in band	Potential alternative use	Congested in own use	Impacts on adjacent use
From	To						
0.255	0.5265	Non-directional beacon	Ground	None	Bcsting	No	No
2.85	22	HF Comms	Ground & airborne	None	Fixed, PMSE, bcsting, mobile	No	No
74.8	75.2	Marker beacons	Ground	None	None	No	No
108	118	108-112 MHz ILS (localiser) 108-118 MHz VOR & GBAS	Ground	None	PMR, PMSE	No	No
118	137	VHF Communications	Ground & airborne	None	PMR, PMSE	Yes	No*
328.6	335.4	ILS (Glide Path)	Ground	None	PMR, PMSE	No	No
406	406.1	EPIRBS/ELTs	Ground	Maritime	None	No	No
590	598	Ground Radar (50cm)	Ground	None	Broadcasting	No	Yes
960	1215	DME, Secondary radar (1030/1090 MHz)	Ground & airborne	Military	Mobile	No	No
1215	1350	Primary radar (L-band)	Ground	Military, amateur, satellite	Mobile	No	Yes
2700	3100	Primary radar (S-band)	Ground	Military, maritime	Mobile	No	Yes
4200	4400	Radio Altimeters	Airborne	None	Mobile/fixed	No	No
5000	5150	MLS	Ground	Satellite, military	Fixed/WiFi	No	No
5350	5470	Airborne Weather Radars	Airborne	Satellite	Fixed/WiFi	No	No

9000	9500	Ground movement and airborne radar (X-band)	Ground & airborne	Maritime, military	Fixed	No	Yes
13250	13400	Doppler navigation aids	Airborne	Military	Fixed	No	No
15400	15700	Ground movement radar (Ku-band)	Ground	Military	Fixed	No	Yes

* There is some small denial of use in the FM broadcasting band around Heathrow airport, however, this only denies access to very local radio stations and so has not been considered on *de minimus* grounds.

Notes: Aeronautical services also use PMR and satellite bands for communications but these bands are not allocated to aeronautical services and so are not considered here. Bands solely allocated to military aeronautical or maritime use are also not considered.

3.5.3 Competing demand

A key consideration in deciding whether to apply pricing to a particular frequency band and in determining the level of prices that might apply is whether there are competing demands for the band. Competing demands could arise from the existing use of the band or alternative uses which are currently excluded from access to the band. Column 6 of Table 3.2 summarises our conclusions in respect of congestion in the current use of aeronautical bands based on discussions with CAA and the Ministry of Defence.

We have found that only the VHF communications band is likely to become congested in future such that the lack of communications capacity could form a constraint on the level of air traffic. By contrast there is no growth in traffic for HF communications. Future congestion in the VHF communications band is expected to be addressed by one or more of:

- *Migration to narrow bandwidth channels (8.33kHz)*. All aircraft flying above 24,500ft are fitted with 8.33kHz radios and there is agreement to extend this requirement to aircraft flying above 19,500 ft from March 2007 with an implementation timetable extending to December 2010.[36] In addition, full expansion throughout remaining airspace is being considered and draft EC regulation to support this and the expansion to FL195 is being prepared within the Single European Skies programme.
- *Migration from analogue to digital communications*. This is expected to give an efficiency gain of up to 400% but digital communications are currently susceptible to interference from in-home cable TV systems and power line transmissions. These issues need to be solved before a migration to digital communications can be implemented.
- *Use of the 112-117.975 MHz band currently allocated to navigation aids (VOR)*. VOR are planned to be phased out in the 2015-2025 timeframe as part of the European Navigation Strategy.
- *Future Communications System*. Work is underway to identify the appropriate technology and spectrum to implement a future aeronautical communications system post 2020. This work is being undertaken in USA and Europe with a high degree of collaboration. L-band has been identified as potential candidate spectrum for this new system but it will be some time before a final decision is taken.

In bands allocated to navigation and radar applications there appears to be sufficient spectrum to meet anticipated demand. Indeed the MLS band is largely unused as are the higher radar bands, although in the case of the latter, propagation and implementation constraints mean that they cannot satisfy the operational requirements (i.e. range) provided by radars using L- and S-band.

The bands allocated to aeronautical services could in principle be used by other applications seeking additional spectrum. We have identified uses which currently face some degree of congestion within their current allocations and which are likely to find the bands under consideration attractive either because of their propagation characteristics or because there is equipment available in this and/or nearby bands. The possible alternative uses identified are shown in column 6 of Table 3.2.

3.5.4 Out of band emissions

Radio transmitters, particularly high powered transmitters including radars, produce unwanted emissions which may affect use in other bands due to interference. The very high power level of aeronautical radars, means that, even where these unwanted emissions are within agreed international emission masks, significant impacts on spectrum used by other services in adjacent

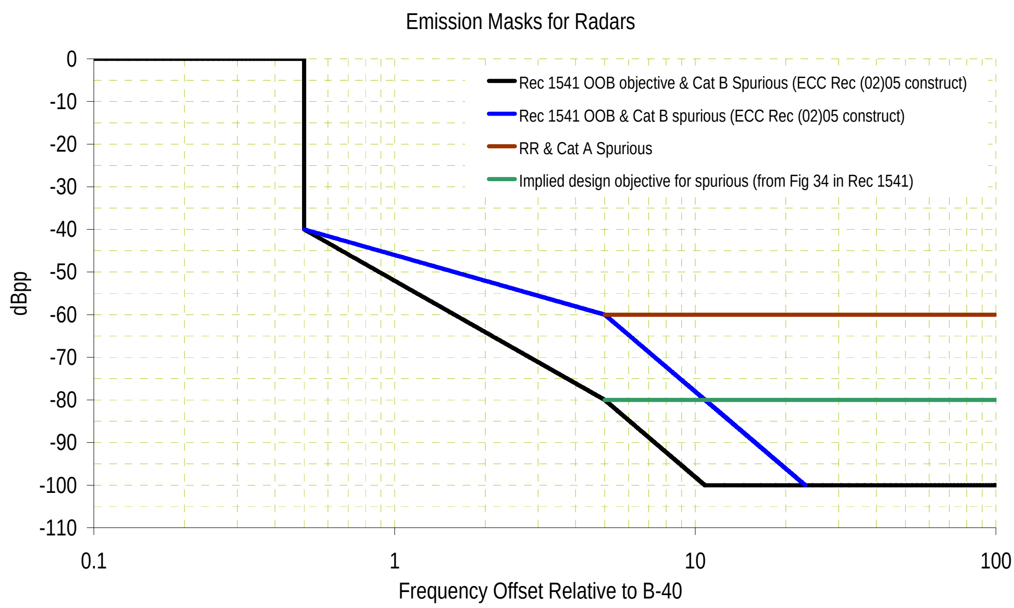
[36] http://www.eurocontrol.int/ses/gallery/content/public/docs/ru/SES_IOP_VCS_RUL_v2.0.pdf

bands may occur. We have reflected this situation in the final column of Table 3.2, where we identify radar bands that may impact adjacent bands.

To make the general point concrete we consider the case of an aeronautical S-band radar at 2710 MHz, which could potentially produce unwanted emissions that could potentially impact 3G and/or WiMAX networks in the 2500-2690 MHz band in the vicinity of the radar. The detailed analysis is given in Appendix C.

Radio regulations place limits on the power of spurious emissions relative to intended emissions, and actual unwanted emissions may be lower than those required by international standards. In particular, compliance with voluntary European recommendations and design objectives would imply lower emissions, as illustrated in Figure 3.1 which shows the various emission masks for radars.

Figure 3.1 Emission masks for radars



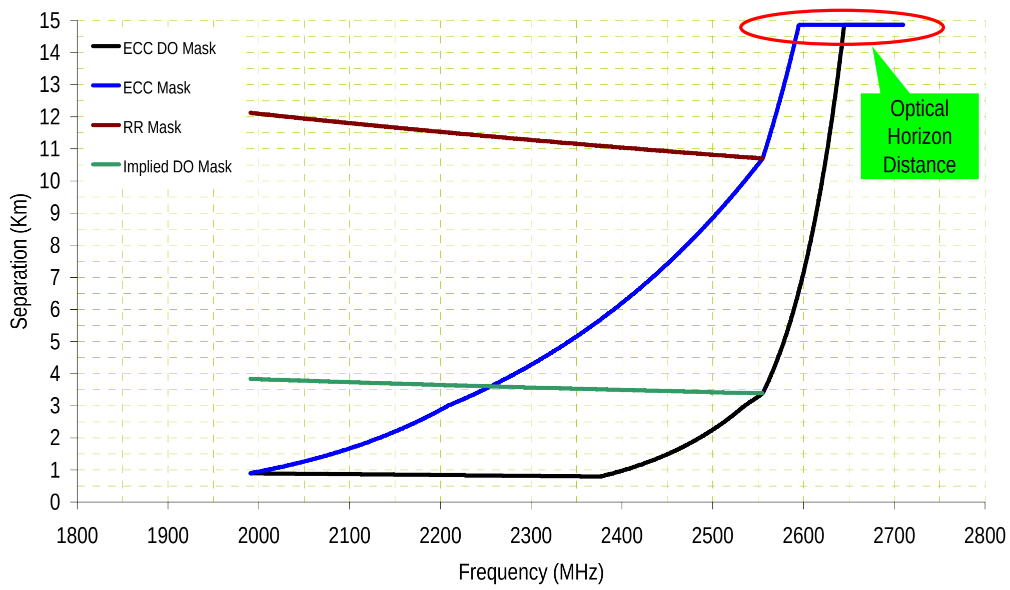
The high power level of aeronautical radars (up to 10 MW)[37] means that even with compliance with required or recommended emissions masks, significant impacts on use in the adjacent band may occur. To illustrate the potential impact of unwanted emissions we have calculated initial estimates of the separation distances between 3G or WiMAX systems and a 1 MW radar transmitter to avoid the 3G/WiMAX receivers seeing any radar signals (assuming standard noise tolerances for 3G hand held receivers). See Appendix C for the detailed analysis.

Figure 3.2 illustrates the results of the calculation in terms of separation distance as a function of frequency. Based on the radio regulations standard (designated “RR & Cat A Spurious” in Figure 3.1 and “RR Mask” in Figure 3.2), a separation distance of over 10 kilometres may be required to comply with mobile receiver standards for 3G and WiMAX equipment. It should be noted that in the band 2.5 to 2.69 GHz a significant separation distance may be required at the upper edge of the band, even with the optimised mask in place. In addition, the separation distances illustrated are based on the propagation conditions to mobile receivers. The elevated high gain antennas used at the base station

[37] These are transmitter power levels. Because of antenna gain the radiated power is higher than these levels.

could increase the separation distance required between systems at the lower half of the 2.5 to 2.69 GHz band.

Figure 3.2 Initial estimates of separation distances between 3G or WiMAX mobile stations and a 1 MW radar



It can be noted that the effect of radar on the 2.5 to 2.69 GHz band has been addressed in Ofcom's consultation document[38] relating to the proposed auction of this frequency band. The effect is analysed in further detail in an accompanying technical document[39]. The geographic areas affected by radar out-of-band emissions are broadly in line with our analysis but they also take account of terrain effects since specific radar sites are addressed.

The Ofcom analysis however goes a step further by considering the time domain. This looks at the relationship between the pulsed nature of radar emissions and the digital bits being used by potential victim systems (e.g. 3G and WiMAX), as well as considering that peak main beam radar emissions are rotated. It is postulated that the number of bits affected by a radar pulse is small and that error correction techniques in a victim system could mean that there may not be any significant impact on use of the band 2500-2690 MHz. Further information on this issue is expected to emerge as part of Ofcom's consultation process on the award of the band 2500-2690 MHz and it may be the case that conclusions regarding the application of AIP to radar out-of-band emissions might have to be modified to reflect the resulting analysis of the extent of the impact of radars on use of the band 2500-2690 MHz.

[38] Award of available spectrum: 2500 – 2690 MHz, 2101 – 2015 MHz and 2290 – 2300 MHz. Consultation Document - 11th December 2006.

http://www.ofcom.org.uk/consult/condocs/2ghzawards/2ghzawards.pdf

[39] Adjacent and In-Band Compatibility Assessment for 2500 – 2690 MHz. Technical Study / Research Document - 11th December 2006

http://www.ofcom.org.uk/consult/condocs/2ghzawards/technicalassessment/assessment.pdf

3.5.5 Radar receiver sensitivity

In addition to considering the impact of radars due to their high levels of out-of-band emissions, it is also necessary to consider the sensitivity of radar receivers and the need to protect them from interference.

There are two situations that need to be addressed:

- In-band sensitivity. Because of the different techniques used by radar systems it is difficult to generalise regarding the degree of protection radars require with respect to in-band emissions from other services. While there is a general rule of thumb expressed in terms of an I/N of -6 dB this criterion is not sufficient to address all situations particularly when one of the operational requirements relates to probability of detection. It can be recognised however that some radar receivers are very sensitive and this can be a significant constraint on other spectrum users if the radars are to be fully protected.
- Out-of-band sensitivity, which is directly related to the selectivity of the receiver. In principle this is of lesser concern from a regulatory point of view as it should be the responsibility of the radar operator to ensure that the receiver is not vulnerable to interference from spectrum users operating legitimately in adjacent frequency bands. Providing spectrum users in adjacent bands are operating in accordance with their licence terms and conditions it is not their responsibility to ensure that the radar receiver is protected. In the event that the radar receiver is vulnerable to these other spectrum users (i.e. has poor selectivity) it would be necessary for the radar frequency assignment to be moved away from the band edge.

The importance of radar receiver sensitivity and how it might constrain a UK strategy towards the radar bands can be related to spectrum release approaches that involve replanning (i.e. squeezing existing radars into a part of the existing allocation) and band sharing (i.e. new services operating in the same band allocation as the radars)[40].

If release of spectrum through replanning occurs then new services operating in the released spectrum will have to take account of radar systems operating in that part of the band in other countries as from a regulatory point of view these foreign radars will take precedence.

If release of spectrum is through band sharing then protocols for the new services that take account of appropriate radar sharing criteria will have to be developed. The mechanism for establishing these protocols is already in place in the UK in the form of the Public Safety Spectrum Test Group (PSSTG) a subgroup of the UK Spectrum Strategy Committee. It might be expected that protocols developed with respect to UK radar operations would also work with respect to radars in nearby countries although this need not necessarily be the case. As with the replanning case due regard will have to be given to radar systems operating in other countries as from a regulatory point of view these foreign radars will take precedence over other (non-radar) uses.

3.6 Scope for change

It is possible to distinguish five categories of use that enable us to identify the areas in which spectrum use might be made more efficient

- Internationally agreed frequencies for distress and safety (e.g. some communications channels and EPIRB frequencies). These use very little spectrum and their use of these frequencies cannot be changed easily.

[40] The term "band sharing" is used to describe sharing by more than one radio system within an allocation; appropriate geographic and frequency separation is required to ensure the different radio systems do not interfere with one another.

- Internationally agreed frequencies having little flexibility but which relate to other services. For example, secondary radar which uses two spot frequencies and which, as noted earlier, may have an indirect impact on the use of VHF channels depending on how much data can be carried by the SSR frequencies. However, this will be limited due to surveillance performance requirements and Data Link applications will also require VHF frequencies. These applications use little spectrum but in this case there is a potential substitution effect with respect to a congested application (VHF communications).
- Internationally agreed frequencies which have flexibility but which require coordination. Specific frequencies are identified for communications purposes (MF/HF/VHF) and for navigational aids (ILS/VOR/DME/MLS). Demand for MF/HF communications is relatively static whereas the demand for VHF communications channels increases steadily in a band that is already congested. This can be alleviated through the use of narrowband analogue or digital techniques. Navigational aids are less congested than VHF communications and new assignments can generally be accommodated with a judicious movement of frequencies within the regionally coordinated plan.
- Applications where frequencies are not internationally harmonised but operational requirements still have to be satisfied (e.g. primary radar). The constraints here are nearly absent. Plentiful spectrum coupled with an absence of incentives to use spectrum efficiently leads to inefficient technologies and relaxed spectrum planning.
- Applications providing supporting navigational aid (e.g. airborne weather radars, altimeters and Doppler speed / drift indicators). These are primarily airborne and because of the height at which the radio instruments are used the impact of use or change of use in one country can be apparent with respect to another country. For example, an aircraft at 10 km cruising height over Paris would be able to see London.[41]

Pricing is likely to have most effect in the short to medium term in those bands where there appears to be greatest flexibility in use or where there is the possibility of alternative aeronautical services using the spectrum (e.g. the use of MLS which is scarcely used instead of ILS which is heavily used).

Of all the possibilities outlined above it is also possible to distinguish between those changes that might be feasible in the short term (i.e. can be implemented nationally) and those that might occur given a longer timescale (i.e. requiring international agreement):

- In the shorter term the most likely possibilities for improved spectrum efficiency include the replanning of primary radar assignments and the implementation of radar technologies to release spectrum[42] and reduce out-of-band emission levels. As an alternative to replanning, spectrum release for other services could also be achieved through band sharing providing suitable protocols can be agreed.
- In the longer term narrowband technologies (analogue and/or digital) will need to be applied on a more widespread basis to alleviate congestion in the VHF communications band. In addition, rationalisation of the various navigation aids can be undertaken either to release spectrum or make effective use of existing allocations (e.g. the spectrum designated for MLS).
- Internationally agreed frequencies for distress and safety are less likely to change as are the frequencies associated with secondary radar.

[41] It can be noted that airborne radars operating in the mid-5 GHz band prevented a mobile service allocation (for Radio LANs) being made at WRC-03

[42] Noting that the use of any released spectrum by other services might, at least initially (i.e. without a similar approach being taken in other countries), be constrained by the continued use of radars in other countries.

3.7 Licensing and charging arrangements

In this section we describe current arrangements for licensing use of spectrum, the parties that might be affected by the application of AIP and the associated incentives for efficient spectrum use.

3.7.1 Licensing arrangements

The CAA's Directorate of Airspace Policy issues Wireless Telegraphy (WT) Act licences for the use of the aeronautical radio spectrum on behalf of Ofcom. WT Act licences[43] are generally issued to the operator of the radio equipment. Use of radio equipment on board aeroplanes is authorised by an aircraft licence which covers all aeronautical radio equipment carried and does not relate to the use of particular frequencies.[44] The fee charged is related to the weight of the aircraft.

Licences for ground stations authorise use of equipment at a particular site on specified frequencies and the fee charged is related to the number of frequencies used by each device.

WT Act licence fees are set by Ofcom and paid by licensees to the CAA who then passes on the payment to Ofcom. CAA's operating costs are recovered separately from Ofcom.

3.7.2 Mechanisms to recover AIP

Many airport operators, particularly the smaller ones, provide the air traffic service (ATS) at the airport themselves. They therefore operate the owned or leased air traffic service equipment, hold the WT Act licences and pay the fees. As airport ATS is at present not subject to direct price regulation[45], an airport that self-provides ATS is able to pass on any increased spectrum costs to aircraft operators, limited only by price competition with other airports and aircraft operators' overall ability to pay.

Most of the larger airports place competitive contracts for the provision of ATS with one of a few third party providers. ATS-related, spectrum-using equipment at these airports is generally (but not always) owned by the airport operator in order that they may more easily change ATS provider. It is however generally the ATS provider, as operator, that pays the WT Act fees.

These ATS contracts are usually for five or more years but the other terms are not public. Where the ATS supplier incurs spectrum fees, the ability to pass these on depends on the terms of the contract with the airport and on competitive considerations. In recent years ATS providers have been aware of the possibility of increases in spectrum costs and may have pass-through terms in their contracts with airports.

Generally airport ATS charges are included within the total charges made by airports to aircraft operators. Exceptionally, NATS currently charges aircraft operators directly (''direct charging'') for ATS at Manchester and all BAA airports except Southampton, although the contract with the airport operators limits what NATS can charge. However the Government has been considering whether to require NATS to charge the airport operator rather than the aircraft operator directly for ATS at the price regulated airports – namely Manchester and BAA's Heathrow, Gatwick and Stansted. This may be implemented from 2008/9 when the new price caps are implemented. The ATS charges would then fall within the five year price cap for these regulated airports, making recovery of any increase in WT Act Licence fees from the aircraft operators less likely within the current price control period. It is possible however that the CAA might introduce some mechanism for recovery by the airports, and

[43] References to "WT licences" should be understood as including, where appropriate, Recognised Spectrum Access (RSA). RSA is proposed to be introduced for Crown bodies, such as government departments and executive agencies, that do not require WT licences. RSA is analogous to a WT licence and is subject to the same principles in relation to charging.

[44] http://www.caa.co.uk/default.aspx?categoryid=8&pagetype=90&pageid=2

[45] The supply of NATS ATS services is not price regulated by CAA. However, ATS services at aerodromes will be subject to the SES Charging Regulation which may have ramifications for precisely how ATS providers recover AIP.

reimbursement of NATS, of any increase in a later price control period as is being considered for en route ATS (see below).

3.7.2.1 En route ATC

At present both NATS and the MoD own and operate equipment required to provide air traffic services in the UK and over part of the Atlantic Ocean and so pay the licence fees for the equipment that they operate.

NATS' price caps for En route and Oceanic Air traffic Services are set by the CAA for 5 year periods at a level judged sufficient to recover forecast efficient costs at a forecast volume of air traffic. These costs include the expected cost of spectrum use.

It is unclear whether NATS will be able to recover all or any of the extra spectrum costs which result from any new pricing arrangement. When the CAA set the price caps for the period 2006-10 they recognised that as a result of the possible introduction of spectrum pricing NATS might in the event incur higher costs in obtaining sufficient spectrum rights than the CAA had allowed.

In their final decision on the price review the CAA stated that[46]

"*For the avoidance of doubt, the opening RAB in CP3 would also take into account any adjustment made in respect of radio spectrum costs."*

However, the nature of adjustment the CAA would make is not specified here or in the earlier discussion of the issue in their firm proposals document. Here the CAA stated that[47]

"it will seek to identify any additional costs that NATS incurs during CP2 at the next price control review and would expect to treat efficient expenditure in a manner that is consistent with its duty not to make it unduly difficult for NERL to finance its relevant activities. "

The situation in respect of the treatment of additional spectrum costs will need to be resolved by the respective parties in parallel with the introduction of AIP.

Charges for domestic En route ATS are collected from aircraft operators by Eurocontrol's Central Route Charges Office on behalf of NATS. The charges levied on an aircraft are a function of the distance travelled in en-route airspace and the square root of the maximum take off weight of the aircraft. Some categories of flight, including military and small aircraft (under two tonnes or under 5.7 tonnes and flying under visual flight rules) are exempt from these charges. Charges for North Atlantic en route ATS are per flight.

The desirability of passing on charges to the end user depends upon which party has power to implement the necessary changes in spectrum use. If the charges cannot be passed on by the operator of the radio system the introduction of AIP would directly motivate them to implement more spectrally efficient technology. If however, the AIP charges are passed on in whole or part then the motivation relies on the price sensitivity of the end user and competition in the provision of services. If the end user (i.e. the air traveller) is price sensitive then the airlines as well as the ATS providers will have an incentive to keep spectrum charges low through the implementation of spectrally efficient technology. Clearly the strength of these incentives depends on the level of AIP.

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[46] Para 31, CAA : NATS Price Control Review 2006-2010 CAA Decision December 2005 http://www.caa.co.uk/docs/5/ergdocs/erg_ercp_natsdecision_dec05.pdf

[47] Para 14 CAA: NATS Price Control Review CAA's Firm Proposals 2006-2010, May 2005, http://www.caa.co.uk/docs/5/ergdocs/erg_ercp_natsfirmproposals.pdf

3.7.2.2 Aircraft

The owners of aircraft radio equipment are responsible for ensuring that the installation and use of the equipment is covered by a WT Act licence. However where this is part of an air/ground system subject to AIP, we have suggested that the AIP should be levied directly on the ground station rather than the aircraft though the aircraft operator will pay AIP indirectly through ATS charges. This could potentially cover systems such as VHF Communications, navigation, airborne weather radars and Secondary Surveillance Radar (SSR) systems.

The implementation of such systems on aircraft largely depends upon the requirements at the airport or ATC, but the airport operator can only move to more efficient systems if these are mandated for aircraft otherwise safety could be compromised. Backward compatibility to basic SSR operation is maintained by both aircraft and ground stations, and installation of more efficient Mode S equipment is enforced by regulatory mandate but may be voluntarily fitted ahead of regulatory changes.

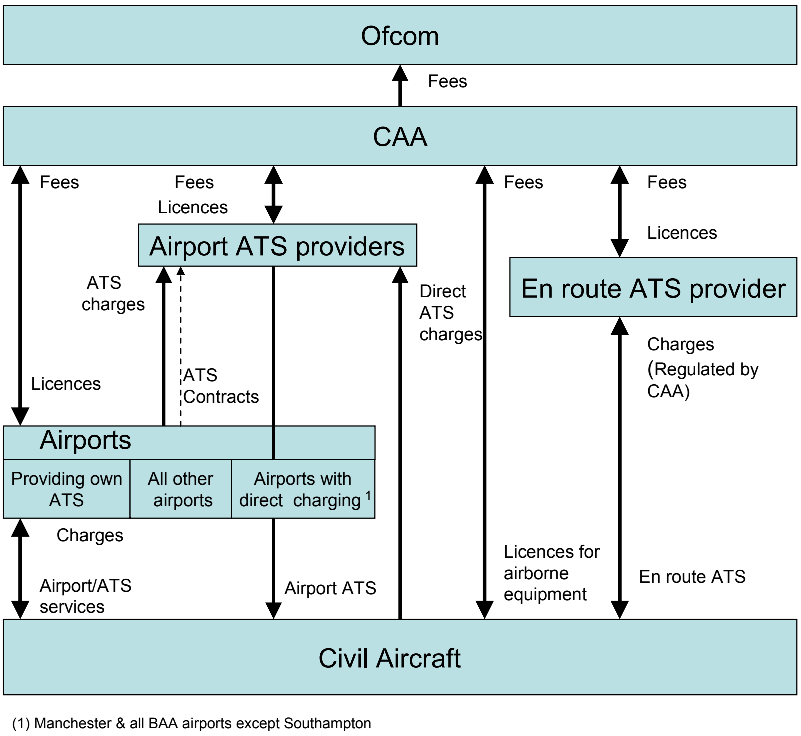
Changes to on-board equipment require the aircraft is taken out of service. Aircraft operators are understandably reluctant to take aircraft out of service more often than is required by their normal maintenance schedules. The timing of major maintenance depends on the type of aircraft and manufacturers instructions but occurs at least once every 6 years and sometimes more frequently. Hence changes to on-board equipment are likely to occur slowly without a strong financial incentive to do otherwise.

3.7.2.3 Summary

Figure 3.3 below shows the flow of spectrum-related charges between the main aeronautical related bodies.

In summary we find that those organisations that make decisions concerning investment in equipment to use radio spectrum will generally face spectrum related charges. The exceptions are the four price regulated airports (Manchester, and BAA's London airports) where NATS pays the spectrum fees and charges airlines directly. Although it is the airports that own or lease the equipment, NATS advise them on, and supply, the equipment. Given this it seems likely that incentives for efficient investment are preserved.

Figure 3.3 Main Aeronautical Revenue Flows Relating to Spectrum Access



Recovery of the costs of increased spectrum fees or investments that reduce use of spectrum may be delayed where either:

- a service provider using spectrum is regulated. This applies to NATS for En route ATC. Pass through could be delayed for a period of up to 5 years until commencement of the next price control period.
- airport ATS is provided under contract to airports.

This delay could provide a short term incentive to economise on spectrum use, though in both cases we would expect some explicit provision for spectrum costs to be built into future price controls/contracts should these costs prove to be material.

3.7.3 Incentives for efficient spectrum use

AIP would apply to holders of WT Act licences. If economies in spectrum use can be made at some point in the value chain we would expect commercial incentives to operate unless contractual or regulatory arrangements limit the extent to which changes in cost can be passed on.[48] Commercial incentives may not operate as strongly if organisations are publicly owned and funded, but for the most part organisations in the value chain (i.e. airports, aircraft owners and operators and air traffic control providers) are privately owned and financed. A possible exception might be where an airport is owned by local government. In this instance there may be objectives other than profit maximisation which could weaken the drive to reduce spectrum costs.

[48] A general result of the theory of tax (or charge) incidence is that the economic incidence of a tax is rarely the same as the legal incidence, and that changing the legal incidence may not change the economic incidence (imperfect competition does not necessarily change this conclusion). Harberger. 1962. "The incidence of the corporation income tax." *Journal of Political Economy*, 70. Tax incidence is also discussed extensively in public economics books, for example: Gareth Myles. 1995. Public economics. Cambridge University Press.

Further, under the terms of an existing contract with the airport an ATS provider may have negotiated the right to pass through some or all of the cost increases in spectrum to the airport. The strength of the short-term incentive to reduce spectrum use will then be less. The ATS provider is nonetheless likely to act to reduce its costs in order that it can bid competitively at the end of the contract term.

3.8 Conclusions

The conclusions from this Chapter are as follows

- The need for international co-ordination within the European region limits the scope for short term changes in the way aeronautical spectrum is used. However, in the longer term changes can be made. For example, the move to 8.33 kHz communications channels on a more widespread basis requires action at a European level while other spectrum management strategies can be implemented locally (e.g. adoption of MLS instead of ILS, the planning and implementation of primary radar).
- Frequencies for VHF communications are congested and this suggests AIP should be applied to this band. Other bands allocated to aeronautical services are not congested (and are not expected to become so) and so there could be potential to release spectrum for alternative services. In those bands where there is likely to be demand from other services there is a case for also applying AIP to these bands.
- In applying AIP the commons nature of some spectrum uses (e.g. weather radars, altimeters) and the scale of out of band emissions from radars both need to be taken into account.
- AIP should not have an impact on aviation safety, rather safety constraints will be binding and any impacts in terms of reduced spectrum use will be economic (i.e. reduced traffic levels). Provided spectrum charges for air and ground systems are levied on the ground station or in some other way that does not create an incentive not to carry radio equipment (e.g. are applied to the CAA), there should be no disincentive to commercial and private aircraft operators carrying equipment.
- WT Act licence fees are currently levied on equipment on aircraft (through a single annual payment linked to aircraft weight) and ground station equipment (based on the number of frequencies used). As such there is a weak relationship between fees paid and spectrum use denied to other services.
- Most organisations involved in the aeronautical value chain are commercial entities and so where economies in spectrum use can be made we would expect commercial incentives to operate. Contractual or regulatory arrangements limit the extent to which changes in cost can be passed on in the short term but these can be expected to be modified in the longer term to take account of changes in spectrum fees.

4 Maritime Use of Spectrum

4.1 Maritime safety and navigation services

The provision of safety of life, navigation, vessel traffic management, security, search and rescue and pollution containment capabilities at sea and on inland waterways gives rise to spectrum requirements for maritime radar (in several bands), communications, surveillance and navigation signals (e.g. from satellite and buoys at sea). Particular frequency bands are internationally allocated for these purposes (though often not on an exclusive basis). In addition maritime services use spectrum in other frequency bands, for example in private mobile radio and satellite bands. In this report we focus only on those frequencies/bands that are allocated specifically for maritime use along with more generally allocated bands (e.g. Radionavigation) that are extensively used by the maritime community.

Maritime services associated with safety of life and search and rescue are aggregated under the general umbrella of the Global Maritime Distress and Safety System (GMDSS). This is an international system which uses terrestrial and satellite technology and ship-board radio systems to ensure rapid, automated alerting of shore based communications and rescue authorities, in addition to ships in the immediate vicinity, in the event of a marine distress. It is intended to facilitate co-ordinated search and rescue operations with the minimum of delay.

In the UK the Maritime and Coastguard Agency (MCA) is responsible for implementing the Government's maritime safety policy. This includes coordinating search and rescue through HM Coastguard, ensuring that ships meet UK and international safety rules, through their survey and certification branches, and monitoring and preventing coastal water pollution, through the oil pollution response unit. There are approximately 1,000 coastguard officers stationed around the UK. There are 19 coastguard stations and 19 search and rescue centres.

Marine aids to navigation are operated by three light house authorities in the UK – Trinity House (covering England, Wales and the Channel Islands), the Northern Lighthouse Board (covering Scotland and the Isle of Man) and the Commissioners of Irish Lights (covering Northern Ireland and Eire).[49] These aids include lighthouses, beacons and buoys, Automatic Identification System for vessels (AIS) and the differential global positioning system (DGPS) stations which are used to provide corrections to GPS signals so as to improve the accuracy of information concerning a ship's location.

The MCA has overall responsibility for vessel traffic services but delegates responsibility for provision of these services (radar and communications) in and around ports to port authorities and on inland waterways to the British Waterways Board. The Port Marine Safety Code[50] provides a national standard for every aspect of port safety and applies to all harbour authorities. Harbour authorities must submit their plans for compliance with the Code to Government.

Only the busiest seaways in the world are controlled in a manner analogous to air traffic control for aircraft.[51] Around the UK only the Dover Strait is controlled on an advisory basis. The Channel Navigation Information Service (operated by the MCA) provides a coastal vessel traffic system comprising three radar sites and a vessel tracking system (radiocommunications and AIS) to monitor the flow of traffic in the south-west lane of the Traffic Separation Scheme and detect and report vessels contravening international regulations for collision prevention. Traffic, navigation and weather

[49] The requirements on these bodies derive from international regulation (the Safety of Life at Sea Convention) and functions and powers set out in Merchant Shipping Acts.

[50] http://www.dft.gov.uk/stellent/groups/dft_shipping/documents/page/dft_shipping_505324.hcsp

[51] Unlike the main commercial air traffic, commercial ships do not need to declare their destination where they commence their journey.

information is broadcast hourly to ships in the Dover Strait and elsewhere. Another role of CNIS is to receive mandatory reports from transiting vessels carrying dangerous goods.

In ports, vessel traffic services are not mandatory per se. It is a decision for the competent harbour authority (CHA) to make after formal risk assessment. However, if a VTS is operating it is mandatory for a vessel to participate in and comply with the rules of that VTS.[52] Port authorities and those managing inland waterways must demonstrate (to the MCA) that they meet the requirements of the Marine Safety Code and this typically only requires the provision of vessel traffic services in the busiest ports. At such ports the service may include one or more of

1. a traffic information service
2. a traffic organisation service
3. a navigational assistance service.

Ships carry on-board radar for navigation and radios for communications purposes. In general, the GMDSS is mandatory for all ships over 300 gross tonnes engaged on international voyages (including some fishing boats and small passenger vessels). Since January 2005 vessels above 300 gross tonnes must provide an Automatic Identification System which transmits (at VHF) information on the name and size of the vessel, its location, speed and direction of travel as well as other vessel and voyage related information. This information can be received by ships and coast stations and is used to enhance and cross check with the information presented by radar signals.

4.2 Radio applications and systems

Table 4.1 below summarises the main maritime uses of spectrum.

Many of these applications are required under the International Convention for the Safety of Life at Sea (SOLAS). In 1988, the SOLAS convention was amended to require ships subject to the Convention to fit equipment complying with the GMDSS. The GMDSS includes new and upgraded traditional radio systems capable of performing the following functions: alerting, locating, search and rescue coordination, maritime safety information broadcasts, general communications and bridge-to-bridge communications. The systems that form the GMDSS are Digital Selective Calling (DSC), satellite Emergency Position Indicating Radio Beacons (EPIRBs), the coastal maritime safety broadcast (NAVTEX), Inmarsat and Search and Rescue Radar Transponders (SARTs), and all supported by voice communications. More detail on these systems is given in Appendix D.

Changes in maritime technology occur slowly because in most cases this requires global agreement and equipment on all large vessels and in some cases all vessels (e.g. communications equipment) around the world to be changed so that safety objectives can be met. Ground based equipment such as radars typically has a life of around 15 years and this can also act as a brake on change. Recent developments include the requirement for all vessels over 300 gross tonnes to carry an Automatic Identification System (AIS), however, there are concerns relating to the security of AIS and the reliability of data supplied by ships as an input to AIS. Radar remains an essential aid to safe navigation and collision avoidance and will remain so for the foreseeable future. Carriage of AIS is not a requirement for small vessels. From 2008, newly built large vessels will have to install radar that can integrate AIS and all replacement radars will also have to be of this type.

[52] Statutory Instrument 2110 MS (Vessel traffic monitoring and reporting requirements) Regulations, 2004

Table 4.1 Maritime Spectrum Uses

Use	Description
Radar	Primary radar at 3 GHz (S-band) and 9 GHz (X-band). Radar stations on land are used to locate and track vessels in coastal and inland waterways. International Maritime Organisation (IMO) mandates carriage of X-band radars and S-band for larger vessels, although in the case of S-band it is at the discretion of the Administration. The UK does not offer exemptions to the carriage of S-band radar, unless the circumstances are exceptional. Many non-SOLAS vessels also carry radar, in particular leisure craft where X-band radar use is extensive.
Navigation	Certain categories of ship are required to carry an electronic position fixing system which is typically a Global Navigation Satellite System (GNSS) such as GPS, in addition to radar, and an automated identification system (AIS). The differential global positioning service uses remote broadcast sites to transmit correction signals on marine radio beacon frequencies to improve the accuracy and integrity of GPS-derived positions. In the UK, the use of DGPS is voluntary.
Communications	L band, VHF, MF, HF and the higher portion of the LF bands, and UHF onboard.
Life saving appliances	For example, VHF handheld radios and search and rescue radar transponders operating at 9 GHz, active radar target enhancers. An Emergency Position Indicating Radio Beacon (EPIRB) operating at 406 MHz is a carriage requirement for all Convention (passenger and cargo over 300 gross tonnes) ships.
Commercial vessel management	Using L-band MSS systems which also meet SOLAS requirements. Includes agreeing pilotage and access to waterways, ports and berths, managing cargo and passengers and provision of correspondence.

Other potential developments include

- An international initiative on e-navigation which is currently in its infancy. This may require enhanced satellite and VHF communications in addition to the Automatic Identification System (AIS).
- IMO has agreed the introduction of Long Range Identification and Tracking system (LRIT), which is based on satellite communications and allows a vessel to report its position and speed regularly.
- Use of GPS/GLONASS with terrestrial augmentation is seen as providing important navigation functionality so there is an interest in the capability to be provided by the forthcoming Galileo system
- Consideration of 12.5 kHz VHF channels to replace the current 25 kHz channels and more extensive use of simplex channels rather than duplex.

4.3 International constraints

The majority of maritime spectrum management is governed internationally, with Ofcom deciding national frequency allocations mainly for supporting infrastructure such as the distribution of radar imagery between coastguard and port stations. Ofcom also continues to be responsible for the assignment of individual frequencies to coast stations etc.

Table 4.2 below summarises the organisations relevant to maritime spectrum management. Two United Nations chartered organisations, the International Maritime Organisation (IMO) and

International Telecommunication Union (ITU), are responsible for defining and regulating maritime use of the frequency spectrum.

The allocation of blocks of spectrum to maritime radio applications is made at an international level by the ITU (Article 5 of the Radio Regulations). At a macro level this to some extent manages interference, but in practice more detailed planning and coordination activities at an individual frequency level are needed to keep interference to acceptable levels.

The information provided below has been gathered from the Radio Regulations and discussions with MCA and Ofcom.

Table 4.2 Organisations involved in maritime spectrum management

Organisation	Responsibility
ITU	A main body in relation to maritime spectrum use. Harmonised frequency allocations are agreed internationally through the ITU.
IMO	A main body in relation to maritime spectrum use. International mandatory carriage requirements derive from the IMO through the International Convention for the Safety of Life (SOLAS).
EU	Marine Equipment Directive (MED) which requires type approval of radiocommunication, radionavigation, life saving, fire fighting and marine pollution equipment.
CEPT/ETSI	Produces European recommendations on radiocommunication system performance that are sometimes different to those produced by the ITU (e,g. unwanted emissions)
MCA	Responsible for implementing international mandatory carriage requirements. Assists Ofcom in international negotiations. Ensures compliance with international standards (for example, through annual ship surveys and port control for UK and visiting ships). Issues various certificates for certain categories of ships.
General Lighthouse Authorities (GLAs)	Three UK lighthouse authorities responsible for marine aids to navigation including lighthouses, beacons and buoys and the differential global positioning system stations
Ofcom	Leads for the UK in international negotiations on maritime spectrum requirements. Responsible for issuing licences (ship and coastal).
Department for Transport	The central Government department responsible for the MCA. Involved with Ofcom/MCA in international negotiations.

4.3.1 Designation of frequencies planned within a framework

At the highest level maritime frequencies are addressed in the ITU Radio Regulations as indicated in the table below.

ITU Radio Regulations		
Radiodetermination – Radio beacons 283.5 – 315 kHz	Article 28	Appendix 12 – Parameter values for coordination. No specific frequencies
Distress and safety communications.	Articles 30 to 34 & 41	Appendix 13 (Non-GMDSS) and Appendix 15 (GMDSS). Specific frequencies identified.
Maritime services	Articles 46 to 59. Articles 51 & particularly 52 contain framework frequency plan and specific frequencies.	Appendices 17 & 25 – MF/HF frequency plan and allotment areas - also, frequencies added to plan. Appendix 18 – VHF frequency plan.

Source: Radio Regulations, International Telecommunication Union, Edition of 2004.

Distress and safety communications use internationally mandated channels as per Radio Regulation Appendices 13 and 15 noted in the table above.

Also, at an international level, the IMO publishes Performance Standards for Shipborne Radiocommunications and Navigation Equipment (consolidated edition of 2002). This publication requires that all ship borne radio and satellite communications equipment (MF, HF, VHF and Inmarsat), in addition to meeting the requirements of the Radio Regulations (see above), should comply with the performance standards identified in the publication. For all radios, frequencies are specified as are classes of emission, whereas for radars there is only mention of 3 GHz and 9 GHz as frequency bands. As the title implies, shore equipment is not addressed although by implication shore based radio equipment will have to interoperate and therefore frequencies / types of emission will be comparable.

4.3.2 Coordination and assignment of frequencies for operations

For coast stations there are three categories of VHF communications use[53] (usually designated CSR – Coastal Station Radio[54]):

- International – these channels (25 kHz duplex/simplex frequencies) are available for port operations and ship movement services. They are designated internationally and coast stations have to provide this service under international agreement.
- UK – these channels (a mix of 25 kHz simplex / duplex frequencies) are available as private commercial channels and are UK specific (i.e. they are not designated internationally).
- Marina – two 25 kHz UK simplex channels and one international 25 kHz duplex channel for use by sailing and yacht clubs, marinas or other similar organisations.

[53] In addition training schools and suppliers are licensed to use all maritime frequencies.

[54] Coastal Station Radio. Ofcom information booklet Of 18. Ref:Of.18/Fol.053_12/03.

Use of all of the above frequencies are subject to an Ofcom assignment process similar to that used for business radio and as such are associated with the Berlin Memorandum of Understanding regarding international coordination.

S-band and X-band radars operate both on shore at harbour and coast stations, and are shipborne. Both the on shore and ship borne radar installations operate on the same frequencies satisfactorily and there is no specific international coordination. However, as the radar frequency bands are shared with the MoD, there is a national coordination process that involves MCA, MoD and CAA.

Other navigation aids and distress / safety channels either operate within the framework of another application (e.g. radars or communications as discussed above) or are internationally designated. In these situations coordination is not necessary.

4.4 Safety issues

An important question is whether charging for the use of maritime radio spectrum would have any impact on safety, and if so what the right policy response would be.

Requirements to use radio equipment on commercial vessels are generally mandatory. This means that if safety is potentially compromised by lack of spectrum, then the effect will be economic i.e. traffic levels would be reduced.

As discussed above, harbour authorities are expected to comply with the Port Marine Safety Code and this means there is limited scope, if any, for ports to compromise safety in response to commercial pressures. If there were concern that imposition of AIP would lead to cost-cutting measures that compromised safety unacceptably, the remedy would be to tighten the Code or provide a direct subsidy. Providing an indirect subsidy in the form of discounted spectrum disguises the problem, leads to inefficient spectrum use and does not seem an appropriate or effective way to maintain safety standards.

Non-commercial vessels use radio equipment on a discretionary rather than a mandated basis. If spectrum charging discouraged such use it could have an impact on safety at the margin. However, we do not expect this concern to arise in practice either because these vessels do not make payments for the use of these systems (e.g. light dues) and/or the payments they do make (e.g. mooring fees) are not linked to their use of radio. In this regard it should be noted that WT Act licences for ships radios have been issued on a lifetime basis from December 2006 and if issued on-line are free. This policy will not be affected by decisions concerning the application of AIP to maritime bands. Again, if it was considered desirable that non-commercial/light vessels to have to carry radar, this would be better achieved by making it a regulatory requirement rather than by making spectrum available freely or excessive reductions.

4.5 Nature of use

The nature of spectrum use by maritime services shares many of the characteristics of spectrum use by aeronautical services in terms of the way it is shared and used and regulated on an international basis. Issues of out of band emissions from radars will also arise, but will not be as severe because maritime radars in the main have lower powers than aeronautical radars[55] and many are used out at sea. Our findings in respect of the nature of maritime spectrum use are summarised in Table 4.3.

[55] Typically 25 kW as opposed to nearly 1 MW, although some coastal radars will use transmitter power levels considerably greater than 25 kW.

Table 4.3 Nature of spectrum use in bands allocated to maritime services

Frequency Band (MHz)		Maritime Use	Location of Use	Sharers in band	Alternative uses	Congested in own use	Denies use in adjacent band
From	To						
0.283	0.315	Maritime Navigation	Ground	Aeronautical	None	No	No
0.415*	3.8*	Maritime Mobile	Ground	Aeronautical	Fixed/broadcast	No	No
0.415*	27.5*	International maritime distress, calling and safety Maritime mobile	Ground & ship borne	Aeronautical	Fixed	No	No
156*	163*	Coastal station (UK) radio International maritime distress, calling and safety Coastal and inshore search and rescue; DGPS channels, AIS channels	Ground & ship borne	Land search and rescue	PMR	Yes	No
121.45	121.55	EPIRBs (121.5 MHz)	Ship borne	Aeronautical emergency frequency	None	No	No
123.1	± 12.5 kHz	Search and rescue communications	Ground	Auxiliary aeronautical emergency frequency	None	No	No
132.65	± 12.5 kHz	Search and rescue communications (HMCG / helicopters)	Ground (& air)	None	PMR	No	No
242.95	243.05	EPIRBs (243 MHz)	Ship borne	None	None	No	No

406	406.1	EPIRBs (406.05 MHz)	Ship borne	Aeronautical	None	No	No
457*	468*	Communications (on ships)	Ship borne	None	PMR	No	No
2900	3100	Radar (10cm), RACONs	Ground & ship borne	Aeronautical & military	Mobile	No	Yes
9200	9500	Radar, RACONs, Search and Rescue Transponders	Ground & ship borne	Aeronautical & military	Fixed services	No	Yes

* Only some channels in these bands are used by the maritime community

Note: maritime services also use spectrum allocated to PMR and satellite. Bands allocated to maritime use by the MoD are not shown.

4.5.1 Shared use

Maritime spectrum use is often shared with other services (mainly military and aeronautical). In some cases the bands are managed by Ofcom and in others (e.g. radar) the MoD is the prime user and maritime users must submit requests for assignments to Ofcom for MoD clearance.

4.5.2 Shared ground and ship based use

As can be seen in Column 4 Table 4.3 maritime spectrum use in communications and radar bands is shared between ground and ship based equipment. The use of radar equipment on board ships is not co-ordinated and ships passing the UK may transmit signals that go some way inland. This equipment shares spectrum with land based radars on an uncoordinated basis.[56]

With respect to VHF communications channels it is generally the case that the equipment on ships is designed to operate across the whole band. Use of the ship's radio, whether to transmit or receive on a particular channel, will be determined by the designation of particular channels for particular purposes (Ship-to-shore, Ship-to-ship, Distress, Automatic Identification etc) and which channels nearby coast stations operate on. Each coast station in general will have been assigned one or more channels by Ofcom. The designation of specific channels to particular coast stations is known to seafarers through widely published documents.

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[57]. If this is the case then any spectrum pricing applied to the 9 GHz bands would be focussed on radar use.

4.5.3 Competing demand

Our assessment of congestion in respect of maritime use of spectrum is based on discussions with MCA, Ofcom and MoD and any indications that the sector is seeking additional spectrum and/or considering the adoption of more spectrally efficient technology. On this basis only the VHF communications band appears to suffer congestion in certain locations, particularly in busy shipping areas such as around the English Channel and along the South coast. We understand Ofcom experiences considerable difficulty making assignments in these areas and sometimes cannot meet requests from ports. The UK has proposed the possibility of moving from 25 kHz to 12.5 kHz channels in this band but 12.5 kHz channelling is not required in IMO performance standards and for international use would need support from other administrations. Based on our discussions with interested parties it appears that all other maritime bands – in particular the main radar and navigation bands - are not congested as new assignments are generally accommodated within existing allocations without difficulty.

While the majority of spectrum use by maritime services is located at sea or in coastal waters, maritime applications can restrict or deny some use of the relevant frequencies inland as a result of use on inland waterways, propagation of signals from vessels at sea and signals broadcast from coastal stations and ground radar. For example, coastal radars typically transmit a 360 degree signal and when ships are in port or close to shore their radars (S and X band) may be kept running at full power. Theoretically power levels could be directionally attenuated when close to shore so as not to

[56] Smaller land based maritime radar installations are often modified ship based radars.

[57] Restricted or denied spectrum refers to the amount of spectrum (i.e. bandwidth) use of which is denied to another service over a particular geographic area. The area is determined by the strength of the transmission and the susceptibility of the victim receiver.

restrict or deny spectrum use too far inland. Hence maritime use potentially denies spectrum access to other services. Potential alternative uses of bands currently allocated to maritime services are listed in Column 6 of Table 4.3.

4.5.4 Out of band emissions

The issue of radar out-of-band emissions has already been addressed under the aeronautical chapter of this report (see Section 3.5.4) with reference to more detailed considerations in Appendix C.

Old technology is also still extensively used by maritime radars, both land and ship based, and out-of-band emissions could potentially have an impact on spectrum users in adjacent bands in a similar way to that identified earlier in this report for aeronautical radars. However, the benefits of encouraging the implementation of better technology (such as the use of filter technology and waveform techniques where feasible) are not likely to be as great as for the aeronautical radars for three reasons:

- typical transmitter power levels for maritime radars are significantly lower than those used for aeronautical radars. It can be seen in Appendix C that for a typical 25 kW radar the exclusion distance (due to OOB emissions) at the edge of the band falls in the range 0.5 – 2 km[58] compared to a trans-horizon exclusion distance for the reference 1 MW aeronautical radar.
- most maritime radars operate in the X-band allocation, namely 9300 – 9500 MHz. Furthermore they effectively all operate on the same frequency near the centre of the band. Depending on the exact pulse length it is likely that both the necessary bandwidth and the related bandwidth occupied by an emission will fall within the 200 MHz bandwidth available, hence the small out-of-band exclusion distance referred to in the bullet above.
- in any event the frequency allocations either side of the 9300 – 9500 MHz maritime allocation are for radiolocation and will therefore also be populated by radars. If the same or similar radar technology is used in these adjacent bands there will be no effect on spectrum use due to maritime out-of-band emissions.

The implication of the above is that AIP charges could in the first instance be related to the whole of the 9300 – 9500 MHz band treated as in-band use with no additional charge for OOB use as the impact of OOB emissions outside this band is minimal, at least based on the current maritime co-frequency deployment.

Nevertheless, the principle of encouraging reduced levels of OOB emissions within the 9300 – 9500 MHz band through the use of "cleaner" technology could apply to maritime radars operating within the band if there were a need foreseen by whoever manages the band to release some of the spectrum for an alternative use.

4.5.5 Radar receiver sensitivity

As has already been discussed with respect to aeronautical radars, consideration also has to be given to radar receiver sensitivity as this characteristic has the potential to place a constraint on the release of spectrum for other users. In particular the impact of in-band sensitivity needs to be considered.

In the maritime case the opportunity for spectrum release from replanning is limited. However, there are opportunities for band sharing and it is here that in-band sensitivity may have an impact. In order to allow band sharing of any sort it is firstly necessary to agree a radar interference sensitivity criterion

[58] The use of pulses shorter that the 1 μsec reference would make the distance greater as the out-of-band emissions would extend further into the adjacent band.

(or criteria) which will determine what other radio services could share satisfactorily. Discussions are already underway within the PSSTG with a view to making this determination.

4.6 Scope for change

The Radio Regulations Appendix 18 VHF communications plan is based on 25 kHz channels. However it can be noted that the plan allows for the use of 12.5 kHz channels although there does not appear to be equipment generally available that supports 12.5 kHz channels. The plan also allows the use of simplex rather than duplex operations on some channels. So, while the framework is there for narrowband and greater simplex use there has been little or no movement in this direction at an international level, although it is understood that there is increasing use of two frequency simplex which is supported by all radios. Given that there is an international obligation to provide a service based on 25 kHz duplex channels it seems there is little opportunity to encourage more efficient use in the near term.

More flexibility is available for making more effective use of the UK VHF communications channels. These channels are not designated / planned at an international level so it is appropriate that national decisions be made about how to most effectively use them, although existing equipment may well constrain the speed of change.

A number of possibilities exist with respect to radar use, such as use of solid state/linear transmitters and different waveforms, and it will be seen that there are implications for the aeronautical radar replanning raised as a possibility earlier in this report. Maritime radars (both ground based and ship borne) satisfactorily operate on the same frequency in each of the two frequency bands (S-band and X-band). This means there is less opportunity for releasing spectrum through replanning the frequency assignments as is the case for aeronautical radars but there is still the opportunity to release spectrum for other users through band sharing providing suitable protocols can be agreed.

Sector blanking with respect to land based radar has been proposed as a means to reduce the impact of radars inland where their functionality is not generally required.[59] This could potentially allow for other use of the spectrum inland but this could be limited by other users in the band e.g. aeronautical radar. Sector blanking is already used in some locations, for example on the Thames River, to limit emissions into residential areas. Noting that the frequencies used by land based radar are also used by ship borne radar, it is likely that the benefits of sector blanking would be reduced along some parts of the coastline as the ship borne radar will themselves point inland. This is a particular problem in and around ports as we understand that ships may keep their S and X-band radars on even when docked. We understand that S-band radars are of reduced use to the ship when near land or in port, because insufficient resolution is provided[60] and so there could be a case for seeking to regulate their use in port. One possibility might be to reduce power when transmitting towards the shore so that the sterilisation effect is limited inland.

It has been suggested by in a study undertaken by QinetiQ et al (2004) for Ofcom that the aeronautical primary radar band 2700 – 3100 MHz could be replanned on the basis of the use of new technology.[61] Such a replanning exercise could release up to half of the spectrum. In making this proposal it is not apparent that the maritime use of the upper half of the band (i.e. 2900 – 3100 MHz)

[59] Independent Audit of Spectrum Holdings. Prof Martin Cave for HM Treasury. December 2005. http://www.spectrumaudit.org.uk/pdf/caveaudit.pdf

[60] These radars are mainly kept for use out at sea.

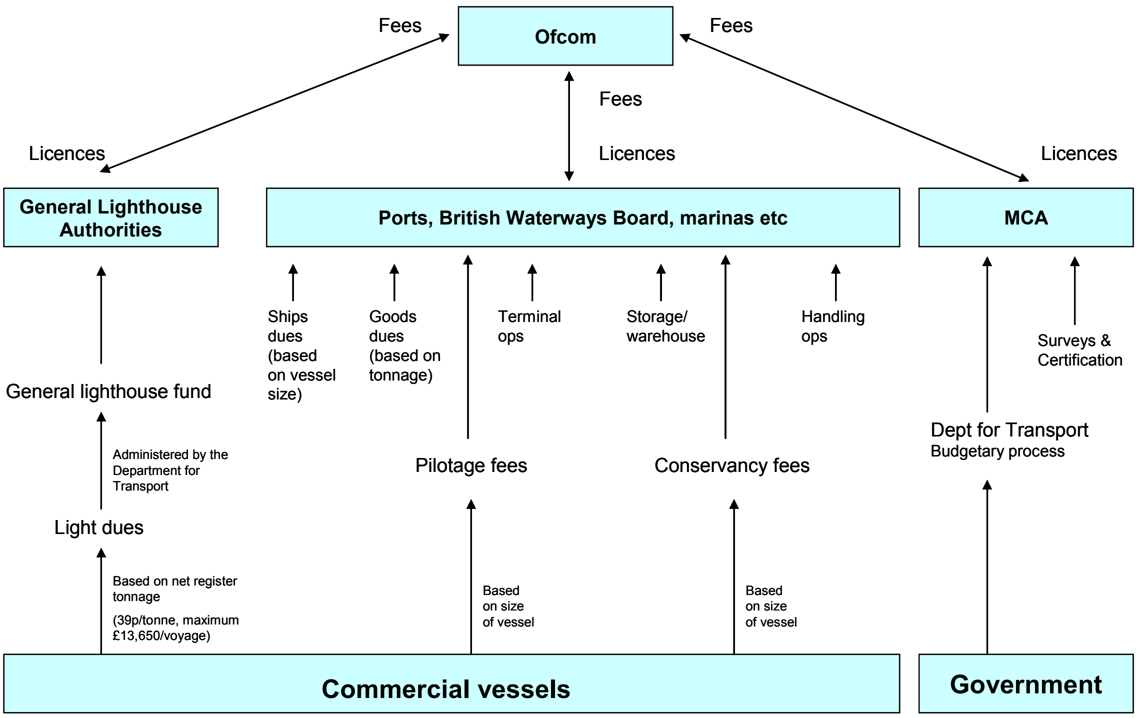
[61] A Study into techniques for improving radar spectrum utilisation (Project AY4490). QinetiQ, University College London, University of Bath & CCLRC Rutherford Appleton Laboratory. 19th April 2004. http://www.ofcom.org.uk/research/technology/spectrum_efficiency_scheme/ses2003-04/ay4490/ay4490_1.pdf

has been taken into account[62]. If the intention were to replan the aeronautical radar in the upper half of the band (i.e. 2900 – 3100 MHz, the same spectrum as that used by maritime radars) thereby releasing the lower half of the band, it would be necessary to undertake further work to determine the implications of these two communities and the MoD sharing.

4.7 Licensing and charging arrangements

Figure 4.1 below summarises the flow of funds and charging in respect of spectrum use in the maritime sector. It should be noted that some port authorities do not own ports facilities but rather supply piloting and navigation services to the port owners while others are vertically integrated. Licensing and payment arrangements are discussed further below.

Figure 4.1 Maritime sector funding and charging



4.7.1 Licensing

The table below summarises maritime licences issued by Ofcom under the WT Act. Ofcom issues ship's radio licences to and is responsible for the use of radio equipment on all ships registered in the UK, the Channel Island and the Isle of Man and all ships in UK territorial waters. However, there are clearly practical limits to the licensing of foreign ships in UK territorial waters. "Omnibus" licences are issued for all equipment on board a ship (as is the case for aircraft radios) and from December 2006 these will be lifetime licences with an administrative charge but free if applied for on-line. This means there will be no ready mechanism for applying annual AIP in this case.

Other licences are for the use of radio equipment at ground stations and the main licensees are the MCA, ports, fisheries, marinas/sailing organisations and the lighthouse authorities.

[62] Although it can be noted that maritime use is not large – a few coast radars and a larger number of lower power beacons / transponders.

Table 4.4 Wireless telegraphy act maritime licenses

Licence	Licensee	No stations	No assignments
Coastal station radio (UK)	MCA, others such as fisheries, Royal National Lifeboat Institution	771	1113
Coastal station radio (international)	Ports/MCA, Royal National Lifeboat Institution	755	1772
Coastal station radio (marina)	Marinas, sailing clubs	439	1303
Coastal station radio (training school)	Royal Yachting Association, colleges	163	All ships channels
Coastal station radio (Land SAR)	MCA, Royal National Lifeboat Institution	97	291
Maritime navigation aids (e.g. racons) and radar	Ports, MCA, lighthouse authorities	238	309
Maritime radio (suppliers and demonstration)	Commercial organisations	91	All ships channels
Differential Global Positioning System	Lighthouse authorities, commercial organisations	11	11
AIS	MCA, ports, lighthouses	79	201
Ship Radio	Vessel Radio licence covers all on-board radio equipment	64,500	n.a.
Ship Portable Radio	Vessel – assigned to pilots, delivery skippers and others. Applies to portable VHF ship radio equipment. Personal locator beacons, EPIRBs on any vessel.	not available	n.a.

Source: Ofcom

4.7.2 Mechanisms for recovering AIP

Many but not all of the organisations licensed to use maritime frequencies are either commercial entities or are operated as self funding trusts or corporations. In particular:

- Most ports in the UK operate on either a commercial basis or as private trusts and receive no systematic funding assistance from the government. A small number of ports are operated by local councils. Ports derive revenue from ships' dues or berthing and mooring fees (based on the size of the vessel); goods' dues (based on tonnage); handling operations (stevedoring revenues or fees paid by third-party stevedores); terminal operations; storage/warehousing; rental/estates; pilotage fees (based on size of vessel); and conservancy fees (based on size of vessel). However, the majority of port revenue is derived from pilotage and conservancy fees and, in some circumstances, additional facilities and services may be provided by external operators. The conservancy fees charged by ports generally fund the maintenance of the waterway, such that it is safe and navigable, and ensure that the port is fit for purpose.

- The constitution of the three lighthouse authorities differs somewhat. The Commissioners of Irish Lights and the Commissioners of Northern Lighthouses are corporate bodies set up under legislation, while Trinity House is a private corporation constituted by Royal Charter. The lighthouse authority functions undertaken by the three organisations are funded by the General Lighthouse Fund which is managed by the Department for Transport. The fund is financed by light dues which are paid by any commercial vessel entering UK ports.
- Vessels are operated by commercial organisations and/or individuals.

Any increase in spectrum fees paid by ports or the lighthouse authorities could in principle be passed on in the relevant fees charged to ships and/or absorbed (perhaps through more efficient spectrum use) if demand for berthing services was elastic. In this regard we note that ships may have a choice of where they berth. In practice for cargo destined for the UK, the shipping agent will take account of the total cost of transporting goods to their final destination i.e. both land and maritime transport costs and this can significantly limit the choice of the berthing port to a small number of UK locations. However, for large container vessels carrying cargoes that are distributed to a number of feeder ships for transport around Europe there is competition between the main ports in the UK and on Mainland Europe for their custom. Some concerns have been raised regarding the potential for fee increases to deter large vessels, in particular, from using ports in the UK. This would involve large vessels using other European ports and sending out smaller feeder ships to UK ports to avoid paying higher fees, which increase with vessel size. As discussed in Chapter 2, such market externalities should not affect decisions concerning the application of AIP.[63]

Concern has also been expressed regarding the possibility of losing ships from the UK register based on the assumption that AIP would be applied directly to UK registered ships. This would clearly be discriminatory but is academic as radio licences for ships are now issued on a lifetime basis and if issued on-line are free. It is therefore more appropriate to apply the incentive of AIP by charging for the use of spectrum at ports, where possible, the costs of which would be expected to be passed on to ships using those ports. This removes any potential discrimination against UK registered ships but gives rise to the different issue discussed in the previous paragraph.

The main publicly funded body in the sector is the MCA which as an executive Agency of the Department for Transport (DfT) obtains over 90% of its funding under a 3 year budget allocation from the DfT. Any increase in spectrum fees paid by MCA would need to be taken into account in discussion with the DfT.

4.7.3 Incentives for efficient spectrum use

AIP would apply to holders of WT Act licences. If economies in spectrum use can be made at some point in the value chain we would expect commercial incentives to operate unless contractual or regulatory arrangements limit the extent to which changes in cost can be passed on.[64] In the case of maritime services such effects are not likely to be material.

[63] We note it is also possible that some of these effects arise from a fee structure that is related to vessel size.

[64] A general result of the theory of tax (or charge) incidence is that the economic incidence of a tax is rarely the same as the legal incidence, and that changing the legal incidence may not change the economic incidence (imperfect competition does not necessarily change this conclusion). Harberger. 1962. "The incidence of the corporation income tax." *Journal of Political Economy*, 70. Tax incidence is also discussed extensively in public economics books, for example: Gareth Myles. 1995. Public economics. Cambridge University Press.

Commercial incentives may not operate as strongly if organisations are publicly owned and funded, but for the most part all organisations in the value chain (i.e. ports, ship owners and operators and navigation/communications providers) are privately financed and operated as either private entities or as private trusts. The main exceptions are the MCA and where a port is operated by local government there may be objectives other than profit maximisation which could weaken the drive to reduce spectrum costs.

4.8 Conclusions

The conclusions from this Chapter are as follows

- The mandatory and exactly specified nature of distress and safety frequencies means that it is unlikely that they could ever be changed. The situation in respect of other frequencies appears to allow for a degree of change in frequency usage but international constraints still have some impact.
- VHF communications channels are planned on the basis of 25 kHz channels and are a mixture of simplex and duplex links, increasingly the former. However, there are possibilities for reducing the bandwidth to 12.5 kHz. Opportunities for change in the short term are greater for UK rather than international channels.
- Congestion would only appear to be experienced in the VHF communications band at some locations. AIP should therefore be applied in these locations to encourage moves towards narrower channels and/or wider use of simplex channels.
- The case for pricing bands below 100 MHz and bands that are very small (such as the 283.5 – 315 kHz band) is not strong as demand from the current and alternative services in respect of these bands is likely to be low.
- 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, 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.
- AIP could raise funding and incentive issues primarily for the MCA as they are primarily publicly funded and so would need to negotiate with the Department for Transport or make efficiency improvements to cover the costs of increased spectrum fees. Most other spectrum users are privately funded and would face commercial pressures from AIP to use spectrum more efficiently.

5 How Should AIP be Set?

5.1 Introduction

In this Chapter we discuss the approach to deriving marginal benefit, opportunity cost estimates and translating these into AIP for use of spectrum by aeronautical and maritime spectrum. The following issues are addressed

1. How to set AIP when the marginal benefits of spectrum to the existing and alternative uses differ considerably
2. The social costs and benefits of setting AIP too low versus too high when there is uncertainty about the best estimate of opportunity cost for a given band
3. Iteration and refinement of AIP over time in response to new information about demand, and technological and market developments
4. Consideration of the potential implications of spectrum trading for the application of AIP
5. Applying AIP in the specific case of out of band radar emissions

Steps 1-2 above reflect the fact that there may be a number of estimates of marginal benefit for different uses at current allocations, and the value of opportunity cost at the optimum allocation of spectrum between uses (i.e. where marginal benefits are equated) will be unknown. AIP must be set based on available estimates of marginal benefit, using judgement over where the optimal price reflecting opportunity cost in equilibrium lies given likely supply and demand conditions (i.e. allowing for the response to AIP). A judgement over the level of uncertainty over the best estimate of opportunity cost is then required alongside a judgement over the costs and benefits of setting AIP too high versus too low.

These complexities arise because AIP is set administratively using centrally determined estimates of opportunity cost, and because AIP will be fixed for a period of time. In contrast, a market draws on decentralised information and expectations of future developments in a dynamic manner to “discover” a price that equates demand and supply over time. It is impossible to replicate this process administratively.

AIP can, and should, also be reset periodically (step 3 above) based on new estimates of marginal benefit and opportunity cost and reconsideration of the original judgements based on new information.

Step 4 is a check on the overall reasoning on the assumption that if permitted some trading may take place. To the extent that trading is effective and efficient then the benefits from AIP are reduced. The implications for the level of AIP are considered in our analysis.

Step 5 involves the somewhat separate consideration of whether AIP should be applied to out of band emissions. If the response to this were anticipated to be large this might lead to a different judgement over the level of AIP for adjacent bands in anticipation of the release of spectrum from aeronautical and maritime bands. The latter could lower the opportunity cost of spectrum in adjacent bands.

This Chapter concludes with a discussion of how to set AIP where there are multiple users of a band and where bands are shared between mobile users and ground stations and between mobile users.

5.2 Setting AIP with multiple marginal benefit estimates

A generalised approach to setting AIP using opportunity cost was presented in Indepen *et al* (2004) which involved considering marginal benefit estimates for the current and alternative uses of spectrum. If there is a use with a marginal benefit higher than the current use of the band, then the estimated opportunity cost lies between the two values, and the AIP is set towards the bottom end of the range of values in the first instance.

Our proposed approach represents a development of the above, and the approach proposed by the Independent Audit.[65] In particular the developments take account of instances where the marginal benefits of competing uses of spectrum differ considerably and setting AIP towards the bottom end of the range of values may not produce an optimal response (a circumstance we analyse explicitly and find implies higher optimal levels of AIP). In addition, we have proposed that in bands that have a within band marginal benefit of zero in the first instance, because there is currently no excess demand, it is possible that the opportunity cost is greater than zero if there is a possibility of excess demand from the same or other uses in future.

Focussing on the problem of interpreting multiple marginal benefit estimates it is useful to consider the basic problem, and then add complexity. Figure 5.1 shows two competing demands for a fixed quantity of spectrum (MHz) represented by the demand curves, with allocations S_A and S_B. The allocations are inefficient since use B has an allocation S_B beyond the point at which spectrum is more highly valued in this use than in use A which has an allocation S_A. The loss of social surplus with this allocation is represented by the shaded triangular area which corresponds to the extent to which the value under demand curve A exceeds the value under demand curve B.

Figure 5.2 shows the same two competing demands for spectrum, but now with the introduction of a price P* which equates to the value of use at the margin for A and B where the two demand curves intersect. This is the optimal price since it provides an incentive for use B to reduce demand, and therefore allows a reallocation of spectrum to use A up to the point where the area under the curves (total social surplus) is maximised. At the optimal position shown in Figure 5.2, the opportunity cost of spectrum is P* for each application – A and B.

Figure 5.1

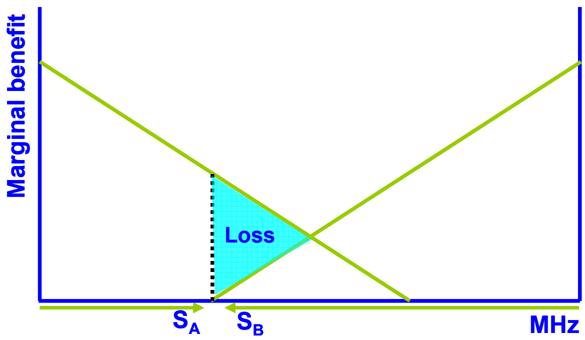
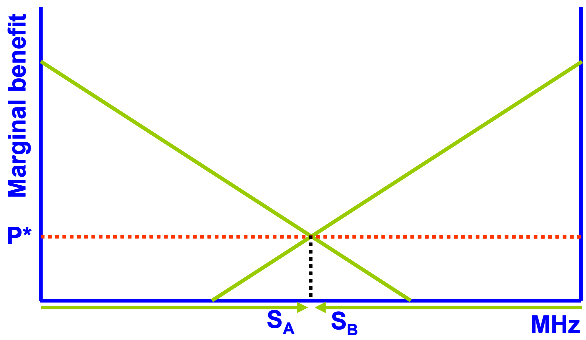


Figure 5.2



In practice the current allocation of spectrum between two uses A and B is unlikely to be optimal (i.e. at S_A, S_B) as historically allocations have been determined by a series of administrative decisions driven primarily by political and technical considerations rather than having regard to economic and

[65] It proposes that where the band could be used by an alternative service, then (Appendix E)

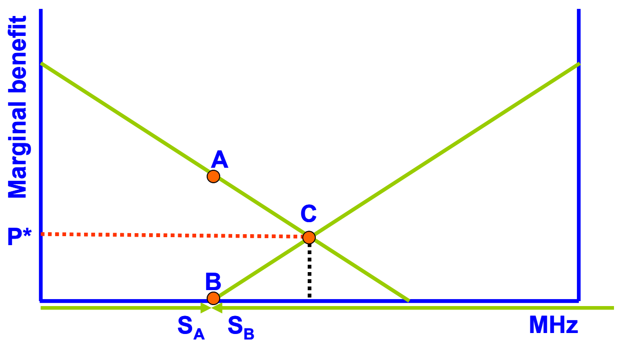
"initial AIP should be set slightly above the same service opportunity cost if there is an alternative use, or the same-service opportunity cost if it is judged that the same service is in fact the highest value use. This should be iterated over time."

social welfare. This means that observed estimates of marginal benefit for different uses are likely to differ.

Multiple estimates of marginal benefits may also arise because the different uses are constrained by, say, an international constraint on use. This situation was discussed in Chapter 2 where we concluded that prices should be set at the best estimate of opportunity cost assuming no constraint. The analysis below therefore assumes there are no constraints on spectrum allocations.

Figure 5.3 shows a situation where demand from use A is unmet but all demand from use B (at a zero price) is met within current allocations i.e. spectrum for use B is not congested and the own use marginal benefit is zero.[66] This situation applies for example in the frequency range 2.7-3.1 GHz where use A is mobile communications and use B is primary radar.

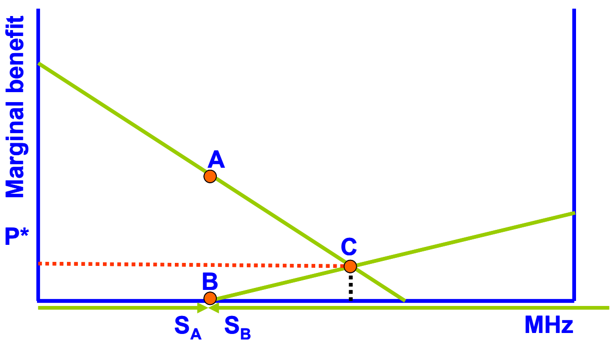
Figure 5.3



If estimates of marginal benefit at points A and B were available, and the two demand curves had equal slope as indicated, then the optimal price that equated the marginal benefit of the two competing uses would be half way between the two estimates. In this case setting AIP marginally above the lower of the two estimates (zero) would achieve little in terms of efficiency gains.

If the slopes of the demand curves differ, in particular if the marginal benefit S_B is relatively flat over some interval, then this corresponds to an assumption that a relatively large demand response to AIP is likely for use B (see Figure 5.4).

Figure 5-4



In this case the released spectrum will result in an equilibrium opportunity cost that lies between points A and B, but is closer to zero than the price at A. An important consideration in deciding the level of AIP is therefore to consider the anticipated response.

[66] The situation in which there is unmet demand for both services and a sub-optimal allocation could also apply.

It is important also to consider the fact that the situation shown in Figures 5.3 and 5.4 are static – it represents a snapshot in time. Over time, in particular if AIP is expected to result in the release of spectrum, new technologies and applications are likely to be developed and existing applications enhanced. A forward looking estimate of opportunity cost would take account of these possibilities which could lower or raise the best estimate of opportunity cost relative to P* (depending on whether their dominant impact was to increase technical spectrum efficiency or spectrum demand via new applications).

In reaching an overall conclusion a judgement is required taking account of the following considerations. First, what is the range of marginal benefit estimates? Second, how large a quantity response is anticipated? Third, is the release of spectrum likely to promote innovation and new demand in terms of an enhancement to an existing service or new entry?

As a rule of thumb, unless there are good grounds for thinking the second or third considerations will dominate, it may be reasonable to conclude that the central estimate of opportunity cost lies mid-way between within band and adjacent band estimate of marginal benefit.

Explicit consideration should nevertheless be given to the possibility that pricing will result in a significant demand response, or that new sources of demand will arise for released spectrum. If large reductions in existing demand and significant new sources of demand are likely to take time to materialise, however, a pragmatic assumption of an equilibrium mid-way between the two estimates of marginal benefit is a reasonable basis for deciding the initial level of AIP.

Two further possibilities should also be considered, namely circumstances in which an existing maritime or aeronautical use involves sufficient demand that optimal AIP would not result in any reduction in demand; and circumstances in which optimal AIP would result in the complete displacement of an existing maritime or aeronautical use by an alternative. The aeronautical communications band could represent an example of the former, whilst the UK specific aeronautical radar band at UHF (590-598 MHz) would likely be displaced by applications such as mobile TV or digital TV if priced efficiently (existing radar applications utilising old equipment could migrate into internationally harmonised bands). In both of these cases utilising an opportunity cost estimate mid-way between available marginal benefit estimates could be expected to produce an efficient outcome i.e. no modification of the general rule of thumb is required.

However, it is important to note that the best estimate of opportunity cost is not necessarily the optimal level at which to set AIP since the potential costs of upside and downside risk in setting AIP may imply an optimal price that departs from the best estimate of opportunity cost. These issues are considered in the next section. Anticipating the findings of this section, an efficient adjustment allowing for uncertainty in estimates and asymmetry in terms of the social costs of setting AIP too high versus too low partially offsets any error due to a failure to correctly account for asymmetry of demand curves in deciding a central estimate of opportunity cost.

5.3 Allowing for uncertainty and unintended consequences

Once a best estimate of opportunity cost has been made the question remains of what price to set for spectrum. Opportunity cost will have been estimated with a degree of uncertainty, and the true value that would precisely mimic a competitive market in spectrum will be unknown. It is then important to consider the possible loss of welfare from setting prices a little too high versus a little too low in deciding on the optimal level of AIP.

If the optimal price were known, then setting prices at 50 per cent of this level would deliver 75 per cent of the social benefits since the loss of efficiency from incorrect pricing increases as a triangular area (as in Figure 5.5) and this area is 25 per cent of the potential loss with prices at 50 per cent (with linear demand curves).[67] However, the optimal price is unknown, so the policy problem is what price should be set when uncertain estimates of opportunity cost and the demand curves are available, taking account of the possibility of alternative mistakes in setting prices i.e. spectrum use is denied if prices are set too high versus spectrum is not reallocated from low to high value uses if prices are set too low. If the cost of alternative mistakes is asymmetric, then the decision over pricing should be "biased" relative to the best estimate of opportunity cost in order to maximise expected social surplus.

For the case where two competing uses for spectrum have identical demand curves, Figure 5.5 illustrates the loss involved in setting prices a little too low (at P-). If the initial allocation of spectrum is to the right of the optimum, for example if all the spectrum is initially allocated to use A, then the price P- would move the allocation to use A back to S_A, allowing a reallocation of spectrum to use B.

Figure 5. 5

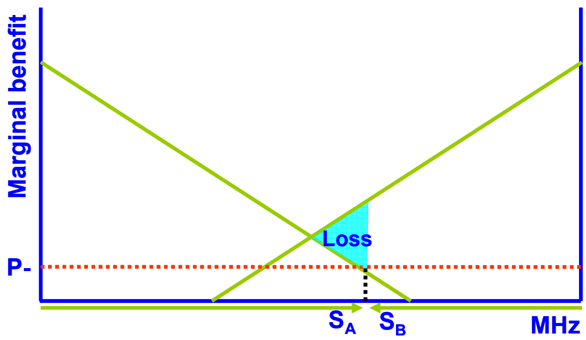
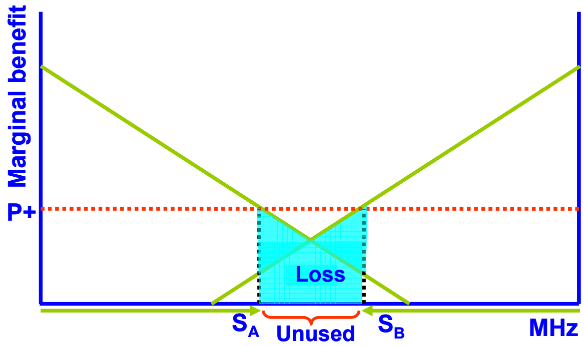


Figure 5. 6



While this still involves a loss of welfare relative to the optimum allocation, the loss is smaller than that associated with a price that exceeds the optimum and therefore results in unused spectrum – as shown in Figure 5.6 where spectrum users A and B reduce demand to the point where some spectrum remains idle, and a social loss corresponding to the shaded area under the two demand curves is incurred. In this case it would be appropriate to set the level of AIP below the best estimate of opportunity cost in order to maximise expected social surplus.

In practice the two demand curves for competing uses are likely to differ in slope. In particular, if a new potential use of spectrum places a relatively high value on spectrum (i.e. has a steep demand curve) relative to the existing use, then reducing the allocation to the lower valued use becomes a higher priority, and leaving some spectrum unused is less costly.

Figure 5-7 and Figure 5-8 illustrate the welfare losses with asymmetric demand curves when prices are set too high and too low respectively relative to the optimum.

[67] Social surplus is measured by the area under the two curves at market price P. The foregone benefit from setting prices too low increases according to the area of a triangular region of loss (as shown in Figure 5.5.). The loss of efficiency is therefore a quadratic function of the price and a price of 50 per cent of the optimal level involves a loss of $(50\%)^2$ or 25% - in other words an efficiency gain of 75 per cent.

Figure 5.7

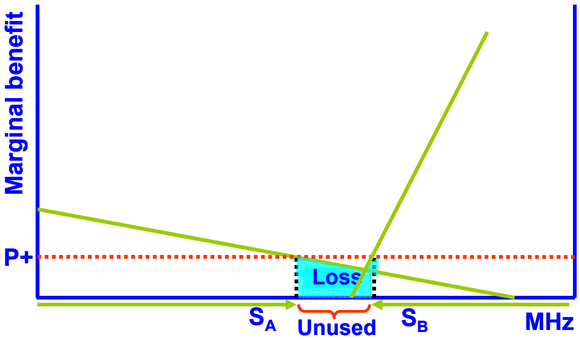
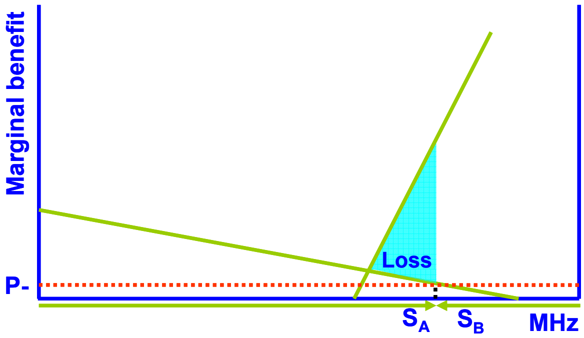


Figure 5.8



These figures illustrate that it is plausible that the losses from setting prices too low will exceed those from setting prices too high, if the slopes of the two demand curves are sufficiently different. It might then be optimal to set AIP based on the best estimate of opportunity cost, or even in principle to set prices slightly above the best estimate of opportunity cost. This reasoning is in the absence of trading. We discuss the impact of trading in the next section below.

We consider uncertainty and unintended consequences analytically in Appendix E, and present the key findings from our quantitative modelling below. As a first step, the losses illustrated in the above figures can be quantified as a function of price for any given set of linear demand curves.

Figure 5.9shows the relative loss of welfare as a function of price relative to the optimal price for symmetric linear demand curves (as shown in Figures 5.5 and 5.6), whilst Figure 5.10 shows the relative loss of welfare as a function of price relative to the optimal price for asymmetric linear demand curves with a relative slope of 1:5 as illustrated in Figure 5.7 and Figure 5.8 (note that Figure 5.10 continues beyond 200%, but this region is not shown).

Figure 5.9

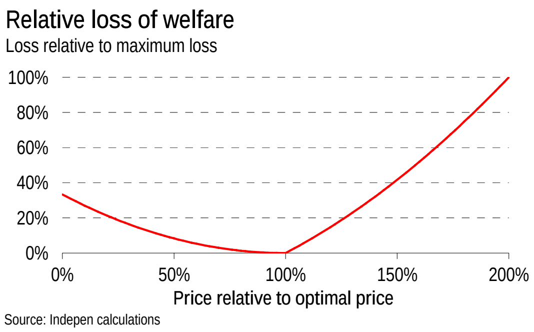
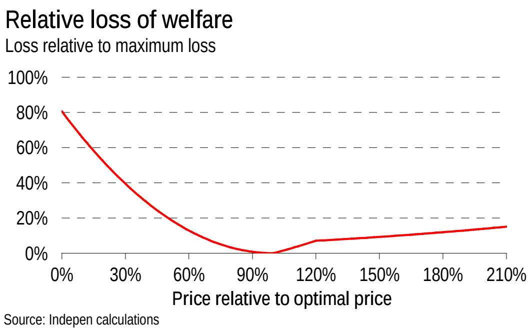


Figure 5.10



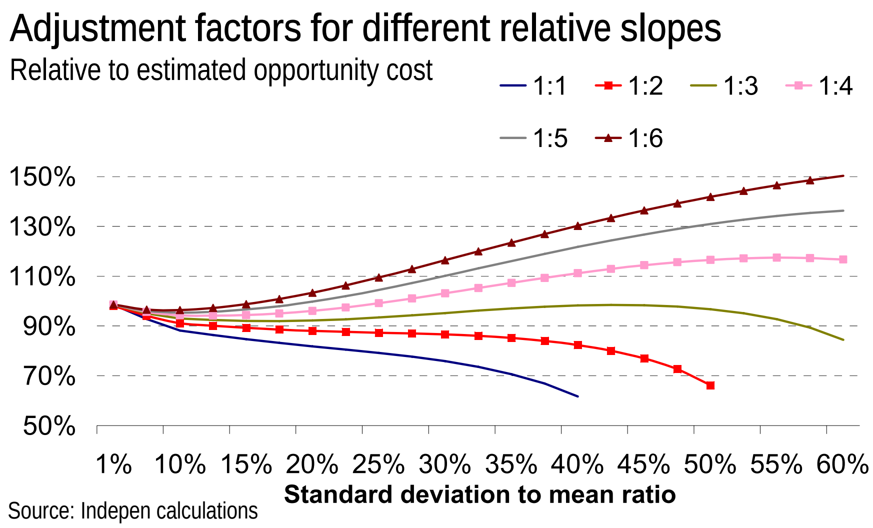
In Figure 5.9 the loss of welfare relative to the optimal price (indicated by 100%) is shown for prices below (less than 100%) and above (more than 100%) the optimum. Losses rise more rapidly for prices above the optimum. Likewise Figure 5.10 shows the same functional relationship, but this time for asymmetric demand curves.

In Appendix E we also set out calculations of the level of AIP which maximises expected social surplus given different demand curves and uncertainty in the opportunity cost estimates. The approach we adopt is to consider an uncertain estimate of cost alongside loss functions of the form shown in Figures 5.9and 5.10. Depending on the level of uncertainty, a minimum expected loss occurs with prices offset from the best estimate of opportunity cost, given that losses are steeper in one direction than the other.

Solving for a range of uncertainty over the estimate of opportunity cost, and a range of relative slopes of demand curves, yields the general result in terms of the optimal shift in price relative to the estimate of opportunity cost shown in Figure 5.11.

The horizontal axis shows the level of uncertainty in the opportunity cost estimate in terms of the ratio of the standard deviation to the mean (assuming the distribution of opportunity cost estimates is normal and truncated at zero). The vertical axis shows the increase or decrease in AIP relative to the opportunity cost estimate. Each of the curves shows the relationship between uncertainty and the price adjustment factor for a given ratio between the slopes of two linear demand curves. All the curves shown are for a situation in which the slope of the demand curve for the application with "too little" spectrum is greater than or equal to that for the application which currently has excess spectrum. This situation seems likely to apply to potential uses of S-band which is currently allocated to aeronautical and maritime radar for example.

Figure 5.11



Source: Indepen calculations

A number of points are apparent:

- As the level of uncertainty in the opportunity cost estimate falls to zero the required adjustment falls to zero i.e. if opportunity cost were known precisely then there is no risk of unintended consequences from setting AIP equal to the best estimate of opportunity cost and therefore no adjustment is required.
- For the bottom curve, for demand curves with equal slopes (1:1), the adjustment is always downwards and reaches a 21 per cent reduction in opportunity cost with a standard deviation to mean ratio of 25 per cent i.e. for a 95 per cent confidence interval[68] for opportunity cost in the range ±50 per cent.
- For demand curve slope ratios greater than around 1:4 the optimal adjustment is upward with sufficient levels of uncertainty (around a 30 per cent standard deviation to mean ratio) over the opportunity cost estimate. This reflects the fact that a more valuable use is denied spectrum, and

[68] That is within two standard deviations up and down from the mean. This assumes the values are normally distributed.

the cost of this circumstance persisting if prices are set too low can exceed the cost involved in setting prices too high and leaving some spectrum unused.

The conclusion from this analysis is that the optimal level of AIP may be higher or lower than the best available estimate of opportunity cost, and that a judgement is required over the level of uncertainty of the opportunity cost estimate and relative slopes of competing demand curves in coming to a view over what, if any, adjustment is appropriate.

If the competing demand has a steeper demand curve than demand in the existing use with excess spectrum, then the best estimate of opportunity cost would be less than half way between the two marginal benefit estimates. However, the optimal adjustment for uncertainty and asymmetry in losses is then smaller or even upward. The impact of a failure to correctly account for differences in slope of the demand curves in estimating opportunity cost would therefore be partially offset by a failure to take account for the interaction of differences in slope and uncertainty when calculating the optimal level of AIP. Figure 5.11 shows the range of adjustments for a range of values for the relative size of the slopes of the demand curves under consideration. Judgement is inevitably required in coming to a view about relative slopes and uncertainty. Our analysis provides a structured way of thinking about the problem and puts some bounds on the adjustments one might make to the best estimates of opportunity cost.

On balance we propose a rule of thumb that the best estimate of opportunity cost is reduced by between 20 and 40 per cent when setting AIP. This range is roughly given by assuming a relative slope in the range 1: to 1:2 and a standard deviation to mean ratio of 20% to 40%[69] (see Figure 5.11). However, if there are strong *a priori* grounds for believing that the competing use is particularly valuable relative to the existing use with excess spectrum then no reduction should be applied to the best estimate of opportunity cost and AIP should be set mid-way between the two estimates of marginal benefit. This might apply, for example, in the case of the radar bands at 2.7-3.4 GHz where the spectrum is well suited to use by mobile applications.

5.4 Impact of trading

With trading at least some of the inefficiency associated with incorrectly estimating opportunity cost might be eliminated via trade, but the social loss would remain if AIP were set too high. A more conservative approach to pricing is therefore appropriate with trading since the asymmetry of losses from setting prices a little too high versus a little too low is more pronounced than in the absence of trading.

The impact of possible future spectrum trading on the optimal level of AIP depends on assumptions about the efficiency of trading. In the limit, if trading and the incentives it provides to different institutions is a perfect substitute for spectrum pricing, then the optimal adjustment factors would converge towards -100% i.e. the downside risk of implementing pricing would be large relative to the anticipated negligible benefits above and beyond those achieved via trading. However, in the short term at least trading may not achieve the full potential efficiency if markets are thin and transaction costs are high (as users learn about the process). International experience so far suggests these outcomes are likely.[70] In addition for non-commercial agencies the potential to realise value from spectrum trading may be a less powerful incentive to economise on use than having to pay for spectrum and this also argues for trading and AIP to be regarded as complementary policies. By

[69] This equivalent to a 95 per cent confidence interval of between ±40 per cent and ±80 per cent.

[70] This experience is reviewed in Spectrum Policy Review, Ovum, Indepen Aegis for the Hong Kong Government, 2006 http://www.indepen.co.uk/panda/docs/spectrum_policy_review.pdf

introducing a direct cost for spectrum holdings, AIP is anticipated to introduce strong incentives for change in the use of publicly held spectrum.

Appendix E sets out the results of a recalculation of the optimal adjustment to the best estimate of opportunity cost allowing for uncertainty and the costs of errors, assuming 50 per cent trading efficiency. Partial trading reduces the downside cost of setting AIP too low, and therefore results in a downward movement in the magnitude of all of the adjustment curves. Hence, the introduction of trading for spectrum subject to AIP implies that greater conservatism in setting AIP is optimal. No decision has yet been made concerning the application of trading to spectrum allocated to aeronautical and maritime use, but if trading is anticipated then our analysis suggests conservatism in setting AIP.

5.5 Refinement of AIP over time

Once account is taken of differing estimates of opportunity cost and the potential costs of setting AIP too high versus too low, there would not appear to be any reason in terms of economic efficiency to phase in or to discount the estimated level of AIP. Once a best estimate of AIP is available it should be applied in our view.

Spectrum pricing has been signalled clearly since the Cave Review in 2002. AIP for aeronautical and maritime spectrum will not be introduced immediately following our analysis due to the need to consult, develop a final position on AIP, and go through the required administrative steps. From this perspective the application of AIP has been, and will be, far from immediate. This means we need to consider how AIP might be updated either to set initial levels or periodically over time in response to new information.

There are a number of sources of new information that might lead to the revision of AIP. First, the application of AIP will produce a response which may reveal new information. Second, auctions or trading may reveal information. Third, actual changes and changes in expectations in relation to technology and market developments will change the assessment of spectrum demand and supply over time, including new opportunities to utilise spectrum and the scope to economise on spectrum use in existing uses. All of these factors could affect the best estimate of AIP.

5.5.1 Response to AIP

The initial level of AIP is based on information and judgement, as discussed. However, the application of AIP will reveal information about supply and demand conditions which might lead to a revision of the original estimate of AIP. For example, if the application of AIP led to a larger than anticipated release of spectrum this might imply that AIP should be in reduced in future. Alternatively, released spectrum might turn out to be particularly valuable to alternative uses which might imply that AIP should be raised in future.

Since the process and timing whereby AIP is adjusted over time may alter the response to the initial level of AIP, the dynamic aspects of AIP should be considered alongside the question of the optimal initial level of AIP. If uncertainty over supply and demand conditions is particularly high, then early review of the level of AIP based on the market response may be appropriate. However, administrative requirements in terms of due process will constrain the ability to reset AIP in response to new information in a timely manner. It can take up to two years to revise AIP estimates, taking account of time for consultation and passing new statutory instruments.

5.5.2 Information from auctions and trading

Information from auctions could be used to set or modify AIP. If the ownership of bidding entities and entities paying AIP that may be revised based on auction proceeds overlaps, then their bidding behaviour could be altered to the extent that a change in AIP is anticipated. If only some bidders in the auction were also subject to AIP that might be revised as a result of the auction outcome, then the auction would not necessarily lead to an efficient allocation.

A related question is how information from, say, an auction should be interpreted. Bidders willingness to pay for spectrum may reflect the anticipated scope to price discriminate in the final service market, though this would not necessarily alter marginal willingness to pay for a factor input,[71] or market power in the final service market. If market power is derived from spectrum scarcity then the potential to earn rents in the final service market will be reflected in bids for spectrum. If market power derives from some other factor, then final demand and demand for spectrum may be lower than in a competitive equilibrium, and the price paid for spectrum correspondingly lower.[72]

Similarly when interpreting spectrum trading information in setting AIP, where overlapping ownership is involved, the price at which spectrum trades occur will include a discount for current and anticipated AIP in relation to the traded spectrum. In particular, if AIP were optimally set initially, spectrum may trade for modest prices. Under these circumstances trades at low prices would not be a signal that AIP should be reduced.

We conclude that spectrum auctions and trades will provide information that could be used as a basis for resetting AIP over time, though caution is required in interpreting market information if there is overlapping ownership between entities involved in auctions or trades and those subject to AIP.

5.6 Determining AIP charges for out of band emissions

We now consider how AIP might be applied in relation to impact on use in bands adjacent to radars. The first question considered is who should bear the cost of the externality in terms of AIP, since both the sensitivity of the receiving equipment and the out of band emissions contribute to impact on adjacent use. A related problem has been explored in the environmental literature, and the conclusion is that the organisation responsible for emissions should pay a fee on emissions which constitute an externality, and the user who is harmed then has the correct incentive to reduce their sensitivity because interference will then be at an optimal level. [73] This means the entity permitted to operate a radar (which is permitted under current regulation to operate with very high levels of out of band emissions) should pay the AIP.

The second question that needs to be addressed is how should charges for high levels of out of band emissions be set? Detailed discussion of this issue is given in Appendix F. Here we summarise our findings.

One option would be to apply AIP to the guard band implied by compliance with the various compulsory or voluntary radio masks in existence. For example compliance with current European voluntary recommendations, or the more stringent voluntary European design objective, rather than

[71] Price discrimination can be beneficial in terms of overall welfare, and a widely applied rule of thumb is that it is likely to be beneficial when it results in increased overall output. The aim of price discrimination by producers is to extract infra-marginal consumer surplus, and this need not necessarily involve a distortion of the marginal product of a factor input at the margin, which determines willingness to pay for the input. John Vickers. 1998. “When is discrimination undue?” Regulating Utilities: Understanding the Issues. IEA, Reading 48.

[72] A monopoly will pay the marginal revenue product of an input rather than the marginal value product which applies in competitive markets. However, the marginal revenue product is necessarily lower than the marginal value product. For proof, see Gravelle and Rees. 1994. “Microeconomics – Solutions Manual and Workbook”, page 149.

[73] Baumol and Oates. 1988. “The theory of environmental policy.” Cambridge. Chapter 3.

the current ITU recommendations[74] would then imply lower AIP payments (because less spectrum would be used) for out of band emissions.

Applying AIP to out of band emissions on this basis would promote a number of potentially desirable responses in terms of the optimal use of radio spectrum:

- Adoption of equipment complying with existing more stringent voluntary emissions masks.
- Promotion of new more stringent voluntary masks – provided the administration of AIP were sufficiently responsive to recognise the change.
- Operation at frequencies further from the edge of band/at lower power, if out of band equipment were more sensitive to interference than within band equipment or opportunity cost were discontinuous.

Although basing AIP on emission standards is an effective and practical way of encouraging the use of more spectrally efficient technology, it does not encourage the use of lower transmitter peak powers since each mask is relative to peak power. We have therefore also considered options involving absolute emission limits at the edge of radar bands.

Figure 5.12 illustrates four options in schematic form. There is a trade-off between the amount of spectrum that would need to be assigned within the radar band and the impact on adjacent users. The four options have been illustrated in terms of an emission mask associated with a single radar (some options being relative and some absolute). These forms of constraint can be readily translated into field strength levels or power flux density levels that are currently the more favoured way of expressing Spectrum Usage Rights (SURs).

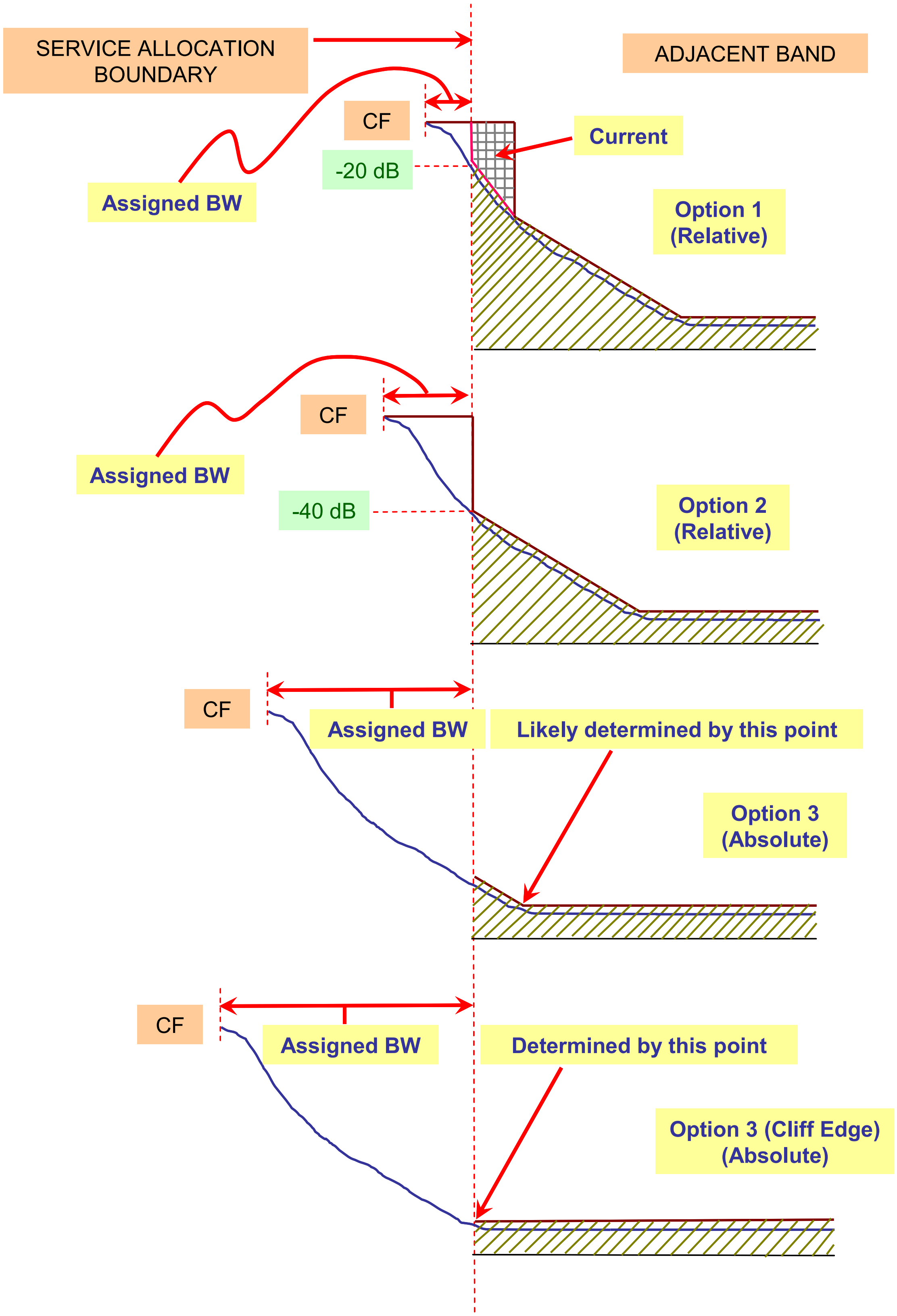
Option 1 effectively represents the current situation in practice but does at least formalise the power level in the additionally occupied domain rather than assuming that the level is the same as the main transmission. Unwanted emission levels are imprecise as they remain relative to the main emission level. In practice this option is unlikely to have an impact on improving spectrum usage.

Option 2 effectively places the additionally occupied domain[75] within the service allocation of the spectrum user generating unwanted emissions in this domain. With reference to Figure 5.12 this moves the vertical part of the mask so that it coincides with the service allocation boundary. This provides additional protection to the spectrum user in the adjacent band. The onus is on the radar user to provide this additional protection at the expense of using more bandwidth within their service allocation. However, unwanted emission levels once again are imprecise as they remain relative to the main emission level.

[74] The recommendations on out of band emissions are non-binding. Regulations on spurious emissions are binding.

[75] The "additionally occupied domain" exists between the -20 dB point, which defines the necessary bandwidth, and the -40 dB point which is where the definition of out-of-band emissions starts.

Figure 5.12 Impact of spectrum mask options



Note: CF = Centre frequency

Option 3 removes the uncertainty for an adjacent band user that arises from the fact that radar masks are currently specified in relative terms. As is always the case in specifying spectrum usage rights in absolute levels there is the pure option of specifying a single level that has to be met by any unwanted emission (cliff edge option), or a sloping level (for OOB emissions) followed a flat level (more akin to current masks but in absolute terms). The latter implies at least some impact on adjacent band users while the former, depending on the level at which it is set, rather less impact. The former would also generally encourage narrowband rather than wideband assignments at the allocation edge leading to a potential improvement in spectrum efficiency.

In the light of the general move towards technology neutral spectrum usage rights, the preferred solution is for a single absolute out of allocation level to be specified (i.e. the cliff edge option). This level then effectively defines[76] the necessary bandwidth of a transmission (which has to reside within the service allocation). All other things being equal this means that a high power radar will have a larger necessary bandwidth than a low power one and the impact of both will be the same on adjacent spectrum users. This is contrary to the existing situation where a high power and a low power radar would have the same necessary bandwidth but would have a different impact on adjacent band users.

A transitional approach could use existing masks (see schematic at the top of Figure 5.12) but in this instance AIP would be related to both the in-band assigned bandwidth and the impact of unwanted emissions outside the band. This could be refined to accommodate the ill-defined region between the -20 dB and -40 dB points by either including it as part of the main transmission (i.e. basing the assigned bandwidth on the -40 dB (occupied) bandwidth rather than the -20 dB (necessary) bandwidth), or by extending the unwanted emission mask upwards towards the main transmission as currently defined (i.e. from the -40 dB point to the -20 dB point).

In setting the level of AIP the approach described in previous sections of deriving a best estimate of opportunity cost and taking account of uncertainty would be applied.

5.7 Pricing high receive sensitivity

In addition to the impact of radar OOB emissions there is also the question of radar receiver sensitivity potentially constraining other services from using the spectrum.

It is not felt that consideration need be given to sensitivity to adjacent band users as this would merely support poor receiver selectivity and in any event it should be the responsibility of the radar frequency assignment manager to provide sufficient protection by moving away from the band edge.

With regard to in-band sensitivity, this has the potential to restrict use of the spectrum for other users - either radars or other radio systems. In the case where radar users effectively occupy a whole frequency band the incentive to reduce the impact of sensitivity already exists through the potential rewards from allowing band sharing with other users.

However, when considering radars individually a case can be made for charging relative to the area in which use to other users is restricted or denied arising from in-band radar sensitivity. However, the issue of specifying receiver sensitivity through regulation, whether direct or indirect, is a much wider issue than that simply pertaining to radars. This issue relates to the current debate surrounding the technical parameters relating to the receive aspect of Spectrum Usage Rights and Recognised Spectrum Access. It is important therefore that a coherent policy regarding the protection of receivers and the implication of a receiver's inherent performance is determined before regulatory tools (SURs,

[76] Noting that this will make the definition of necessary bandwidth different to that in the Radio Regulations.

RSA, AIP) specifically directed at receivers are put in place. Further work and debate is required in this area.

5.8 Pricing in shared bands

The purpose of AIP is to face the users of spectrum with its opportunity cost and so AIP should be applied to those who "use" spectrum. In practice it is usually only possible to apply AIP to those entities that are licensed or otherwise authorised (e.g. Crown bodies) to use the spectrum. For the purposes of the discussion below we assume that Crown users pay on a comparable basis to licensed users.

In most of the aeronautical and maritime bands there is some degree of sharing between users of the spectrum. In this section we consider how in principle AIP should be applied in the following situations

- when bands are shared between two or more different types of user; for example military and civil maritime and aeronautical users
- where spectrum is shared between mobile transmitters and ground stations
- when spectrum is shared between mobile transmitters

Implementation issues are considered further in Chapter 7.

In this section we conclude that

- in shared military/civil bands a single military or civil band manager should be identified and be responsible for AIP. AIP charged to existing licensees should be set on a cost pass though basis. If this is not legally or practically feasible then Ofcom should perform this role apportioning AIP between different users in the band on the basis of the constraint they impose on other users.
- as a matter of principle AIP should apply to both fixed and mobile use of spectrum by aeronautical and maritime users, but that in practice AIP can only be applied using available licensing instruments (for example, through the ground station licence where mobiles and ground stations share spectrum or through the vessel radio licence in the case of aircraft) or, in the case of public sector use, by agreement with Ofcom.

5.8.1 Shared military/civil bands

As noted in Chapters 3 and 4 some aeronautical and maritime bands are allocated to and planned by either the MoD or the civil authority[77], and others are jointly managed.

The spectrum assigned to different users and the constraints on the use of that spectrum need to be defined more clearly. The key point for the application of AIP is that rights of access to specific frequencies in a given location are clearly assigned to a single entity - this is then the entity that is charged AIP. Unused or underused spectrum may be leased or on-sold to third parties, but the processes for achieving this have still to be developed.

In practice two cases need to be considered

- Bands managed by the MoD: MoD should pay AIP for the whole band. This gives an incentive to release spectrum – either through trading or returning unused frequencies to Ofcom. AIP will need to be on-charged to other users of the bands based on their licensed use. In the event this is not

[77] Ofcom is the civil radio licensing authority; for radio licensing decisions relating to aeronautical and maritime safety of navigation Ofcom is advised by the relevant civil authorities (the CAA and MCA); this is particularly so with aeronautical where the CAA has a central role in the assignment of frequencies in aeronautical bands.

legally or practically possible the MoD should pay for the whole band less any existing assignments which would be recovered directly by Ofcom.

- Bands managed by Ofcom: Direct users should only pay for the spectrum they are assigned. The remaining frequencies would be available for other users/uses. In the case where use of the band is reserved for either the aeronautical or the maritime sector it may be that the regulatory body would be charged for this reservation.

The sums paid will depend not only on the level of the AIP but also on the amount of spectrum occupied by existing licensees. If licensees have national assignments then the payment will equal the AIP value (which is expressed as £/MHz for a national assignment) multiplied by the bandwidth occupied. If licensees have localised assignments then the sum paid will equal the AIP x bandwidth occupied x a measure of the fraction of the UK area restricted or denied (or fraction of the population that lives in such an area). We elaborate on how this might be done in some specific cases in Chapter 7.

It may be that the civil aeronautical or maritime sector may wish to reserve spectrum in bands managed by Ofcom or the MOD, in order to cater for future growth in demand. Such reservations should be subject to AIP.

5.8.2 Bands shared between fixed ground stations and mobile equipment

In bands shared between ground stations and mobile users spectrum use by ground stations is co-ordinated, based on specific frequency assignments, whereas spectrum use by mobile equipment is not co-ordinated. Frequencies used by mobile equipment (on-board aircraft or vessels) are either determined by location (e.g. specific communications channels at airports or ports) or international regulation (e.g. international assignments for distress channels and SSR, ships radars sharing with fixed radars).

The situation has some similarities to that for cellular telephony networks where the transmitters (i.e. ground stations) are licensed but not the mobiles and use of spectrum by the latter is not co-ordinated. In this case AIP is paid by the transmission operator for all the spectrum occupied. However mobile radio equipment on aircraft is licensed, and so in principle AIP could be applied to the mobile,[78] but this is not the case for ships' licences which will be issued on a lifetime basis (at zero cost if licensed on-line) from December 2006. The practical application of AIP for communications bands and use of spectrum for radars is considered below.

5.8.2.1 Communications bands

As mentioned above, for communications bands the situation has some similarities to that for mobile telephony where network operators as well as their customers could be said to use the spectrum (although unlike aeronautical and maritime users, mobile phone users cannot communicate directly between each other i.e. bypassing the operator.) In the mobile telephony case AIP is applied to the operators and not their customers so that transaction costs are kept to a minimum and the incentive is applied most directly. Similar considerations apply in the case of aeronautical and maritime use of spectrum for communications purposes.

For ships communications Ofcom manages the band and can only charge licensees on the basis of the assignments made to the ground station. While this omits use of spectrum by ship to ship communications, there is little that can be done about this.

[78] Though we understand Ofcom is reviewing licensing options for equipment on UK registered aircraft so this situation could change in future and applying AIP directly for foreign-registered aircraft is problematic.

In the case of aeronautical communications there is a choice between 1) charging the ground station operator AIP for all use of the communications bands and 2) splitting the charge between the ground station and the airborne stations. We suggest that the operator of the ground stations communicating with the craft should face the opportunity cost of all of the communications spectrum used. The reasons for this are that

- Transaction costs are minimised. There are many fewer communications operators than there are craft and issues of how the payment should be divided between different craft do not need to be addressed.
- This more directly focuses incentives for efficient use of the spectrum directly on those entities that are in the best position to change the way the spectrum is used, namely ATCs in the case of air transport and the ports/marinas/search and rescue operators in the case of maritime transport.
- It is feasible administratively. For maritime Ofcom only applies AIP to specific assignments. For aeronautical, CAA is responsible for frequency allocation in the communications bands (although Ofcom formally issues WT Act licences) and so could possibly be charged for the full amount of use. CAA could then apportion the total charge across the ground stations based on the frequency use restricted or denied.[79]

5.8.2.2 Use of spectrum for radar operating on mobile craft

The main examples here are maritime radar on ships, secondary aeronautical radar and aircraft radars operating in bands at 9 GHz

Maritime radar on ships (at 2.9-3.1 GHz and 9-9.5 GHz) and aircraft radar at 9 GHz access spectrum allocated to this service and ground based radars but this use is not co-ordinated between users i.e. the spectrum is used on a commons basis. Aircraft/ships whose radio equipment is licensed in the UK could in principle be charged for use of this spectrum, though the basis for setting charges would be somewhat arbitrary and the move to issue lifetime ships radio licences means that there would be no ready administrative mechanism for collecting annual fees in this case. In addition some use of the spectrum is by aircraft/ships licensed in other countries and these users would fall outside the system. These practical difficulties argue against applying AIP directly to ships/aircraft radar.

Furthermore the fact that aircraft/ships radars use the same frequencies as ground based radars means that in many instances charges to ground based radars would be sufficient to recover the opportunity cost of use by the aeronautical/maritime sector. This then leaves the issue that there is no charge applied to some use by ships/aircraft in locations away from the coverage areas of ground based radars. The extent of this use is not known and furthermore there is no practical way of directly charging users. As discussed further in Chapter 7, it may be that charges for this spectrum use will need to be levied on the industry as a whole via the relevant government agencies.

The case of secondary aeronautical radar is somewhat different. Secondary radar involves transmissions from ground stations to the aircraft and a return signal from the on-board device and passive monitoring by on-board radar of signals from neighbouring on-board radars. The transmissions use specific internationally harmonised frequencies. Use of the spectrum (by ground stations and aircraft) is on a commons basis in the sense that this use is not co-ordinated, though some users are licensed – namely the ground station and at present airborne equipment for aircraft registered in the UK (but not other aircraft). The issue that needs to be addressed is should these licensed users face the opportunity cost of their use of spectrum?

[79] We understand there are a number of legal issues to be resolved before this mechanism could be put in place.

In principle the answer is yes, because these users potentially restrict use for other applications. However, there are good practical reasons for focussing the opportunity cost on use of the spectrum by the ground station. Firstly the ground station is licensed and will continue to be so for the foreseeable future whereas Ofcom is reviewing licensing arrangements for airborne equipment. Secondly, administration costs are lower if it is applied to a small number of ground station operators because there are fewer entities to charge. Thirdly the basis for charging ground stations is much clearer (frequency use over a given geographic area) than for aircraft for which there is no readily available measure of spectrum use. Fourthly charges to the ground station will be paid by both foreign and UK registered aircraft and so appear fairer than those applied only to UK-registered aircraft.

5.8.3 Mobile only bands

Applications that fall into this category comprise airborne weather radars, radio altimeters and Doppler navigations aids also on aircraft. In all three cases use of spectrum is not co-ordinated; there is no measure of use by each licensee; and many users are not licensed in the UK (but they fly over the UK and restrict or deny spectrum use here). In all these cases frequencies are effectively used on a commons basis. These can be thought of as a "private" commons in which the aeronautical/maritime services are allocated the band and access to the band is limited to only aeronautical/maritime users. At present Ofcom does not apply AIP in other commons bands as it is generally not practical to do so. Users cannot be identified because they are not licensed, the transaction costs associated with licensing use would be very high, because of the large number of users and there is no single entity that is responsible for access to licence exempt bands that might be licensed and charged AIP. [80]

In principle airlines as a collective should face the opportunity cost of this spectrum use in order to promote adoption of efficient technology. As a practical matter this could be done by levying the charge on CAA and requiring CAA to recover the charge.[81] CAA might be able to recover the charge through the aircraft licence fee, fees charged for WT licences issued to ground based equipment or fees charged to NATS for its en-route licence (assuming this is legally possible). There are potentially issues with all three approaches.

- If costs were recovered through the aircraft radio licence, then aircraft are likely to pay by weight i.e. on a basis unrelated to spectrum use. The fee would only be recovered from UK registered aircraft and these airlines could be at a competitive disadvantage relative to airlines registered elsewhere. The extent of this disadvantage will depend on the scale of AIP. We also note that UK registered aircraft would have an artificial incentive to register elsewhere.
- If costs were recovered through an uplift to the AIP for ground based radars then all aircraft using spectrum above the UK would pay for it through en route and landing charges. This option addresses the competitive and other downsides of levying charges through the aircraft licence and would strengthen the incentive on ATCs to lobby for change in spectrum use. However, it is rather indirect and to have an effect on airlines' behaviour they would need some assurance from the ATCs that the value of any spectrum savings made by the airlines would be passed on to them.
- If costs were recovered through charges levied on NATS for its en-route air traffic control licence then these could be passed on to all aircraft using en-route airspace, subject to the price caps

[80] There are private commons in the US. The 2 GHz Unlicensed Personal Communications Services (S-PCS) was the first U.S. private spectrum commons but had limited success until the technical restrictions were relaxed recently. The 700 MHz "Guardband Managers" band was created in the U.S. as part of its digital dividend plan to serve as a buffer around a new public safety band. The regional licensees of this band have tremendous flexibility, effectively acting as a spectrum management authority in authorising usage of this band subject to interference constraints on the neighbouring public safety band. One such band manager is Access Spectrum - see www.accessspectrum.com

[81] Allocation of the charge between civil and military users may also be necessary.

applied to these charges. The price caps are set five yearly and so any pass through to aircraft is likely to be subject to a delay, at least initially.

On balance if AIP is applied it would seem preferable to do this through charges for ground based equipment, though this is a matter to be decided in discussion between the CAA and Ofcom. If AIP is applied then (as discussed in Chapter 3) the impact of use of mobile equipment on aircraft flying outside UK airspace would need to be taken into account in estimating the spectrum use restricted or denied in the UK.

The final option to be considered is not to charge AIP at all in these bands. This would avoid the administrative costs of calculating the appropriate level of fee to charge for this spectrum but there would be less pressure for efficient spectrum use. While ideally AIP would be charged, we consider this area to be of lower priority than others because of the practical issues involved.

5.9 Conclusions

5.9.1 Approach to setting AIP

Our approach to setting AIP is a development of that in the Independent Audit in that we propose consideration of charges that may exceed a level "*slightly above the same service opportunity cost*" where the same service opportunity cost is zero, but the alternative service opportunity cost is positive (and potentially substantial).

For example, where there are two estimates of marginal benefit, one significant and positive and the other zero, our starting point is to assume that opportunity cost is mid-way between the two. This initial judgement might be modified for three reasons.

First, if it is thought that the application of AIP would lead to a significant release of spectrum from existing use and that consequently the equilibrium level of opportunity cost would be lower than the initial estimate. In this case AIP should be set below the mid-point.

Second, if new services and applications are expected to introduce new demand for radio spectrum in the medium term, possibly in response to the initial release of spectrum due to the application of AIP. If new uses of spectrum are thought probable then this would either suggest a somewhat higher level of opportunity cost and so a higher level of AIP than would otherwise be the case.

Third, in using the best estimate of opportunity cost (taking account of the above considerations as a basis for setting AIP), account should be taken of the level of uncertainty in the opportunity cost estimate and the social losses of setting prices above or below the best estimate of opportunity cost. If the two competing demands have similar demand curves then there are grounds for applying a downward adjustment. However, where the competing use for aeronautical and maritime spectrum is likely to have high value the early application of AIP at or above the best estimate of opportunity cost may be appropriate to bring about the required reassignment of spectrum in a timely manner. A practical example of this is the potential to economise on the use of spectrum by radar and to use such spectrum for mobile use.

Judgement is inevitably required in coming to a view about any reductions or premia applied. Our analysis provides a structured way of thinking about the problem and puts some bounds on the adjustments one might make to the best estimates of opportunity cost. We propose a rule of thumb that the best estimate of opportunity cost is reduced by between 20 and 40 per cent when setting AIP. However, if there are strong *a priori* grounds for believing that the competing use is particularly valuable relative to the existing use with excess spectrum then no reduction should be applied to the best estimate of opportunity cost and AIP should be set mid-way between the two estimates of marginal benefit.

5.9.2 Impact of trading

We note that an efficient liquid spectrum trading market would reduce the optimal level of AIP, since the costs of alternative errors in setting AIP would change with prices that are too low involving less efficiency cost to the extent that trading results in movement towards an optimal allocation in any case. However, trading is a future option and is not anticipated to involve high levels of liquidity. In addition, there are sound grounds for considering that non-commercial agencies may be more responsive to actual pricing (a cost) than to the opportunity to sell spectrum in order to “profit”.

5.9.3 Refinement over time

There are a number of sources of new information that might lead to the revision of AIP. First, the application of AIP will produce a response which may reveal new information. Second, auctions or trading may reveal information. Third, actual changes and changes in expectations in relation to technology and market developments will change the assessment of spectrum demand and supply over time, including new opportunities to utilise spectrum and the scope to economise on spectrum use in existing uses. All of these factors could affect the best estimate of AIP.

5.9.4 Out of band emissions

In relation to out of band emissions by radar we agree with the Independent Audit that account should be taken of the externality for other adjacent users. We have proposed that this should be done by applying absolute emission limits such that out of band emissions are at acceptable levels but that the bandwidth assigned to individual radar is adjusted to accommodate this outcome. This is a considerable departure from the current situation and it may be necessary to adopt a transitional approach in which existing masks are used and AIP would be applied to both the existing assigned bandwidth and the unwanted emissions outside the band.

5.9.5 Mobile use in shared bands

In respect of shared spectrum or mobile only use it is often not possible to charge the user of the spectrum directly, because spectrum use is not licensed. Rather indirect approaches must be used involving charges levied on WT licences for ground stations or the relevant government agencies/regulators who may be able to pass on the charges in other licence fees.

6 AIP Estimates

6.1 Introduction

This chapter considers which frequency bands AIP should be applied to, presents marginal benefit estimates for the main frequency bands allocated for aeronautical and maritime use and discusses how these values might be used to set AIP for the bands in question. It is important to recognise that the values presented are best estimates based on available evidence. As additional evidence of marginal benefits becomes available (e.g. as a result of auctions) the AIP estimates could be updated.

Where there are two estimates of marginal benefit for a frequency band (corresponding to two different uses of the band) the best estimate of opportunity cost for the band will generally lie between the marginal benefit in the existing use and in the highest value alternative potential use. In order to derive best estimates of opportunity cost for a given frequency band we have

- Determined whether the band is congested in the current use and if so calculated the marginal benefit of spectrum at the current spectrum allocation to that use. The marginal benefit estimates calculated are based on the resource cost of employing a more spectrally efficient technology to deliver the current level of service or functionality – in previous studies this has been termed the "least cost alternative" approach.
- Identified potential alternative uses of the band and assembled existing marginal benefit estimates for those uses from previous reports, namely Indepen *et al* (2004) and Indepen-Aegis (2005).
- Drawn on studies on radars undertaken for Ofcom which give an indication of the costs of improving the spectral efficiency of existing radars. This information can be used to indicate whether AIP at calculated levels is likely to have an impact on spectrum use by radars.

In 2006 there were two spectrum auctions in the UK which provide some limited market evidence of the value of spectrum in specific bands. The relevance of this information and price information that will become available from future auctions is discussed below.

At present best estimates of opportunity cost at existing allocations differ considerably from band to band, depending on the technologies and services that may operate in each band. This issue was raised in the Independent Audit which noted the "excessive differential between the pricing of fixed and mobile services, especially below 3 GHz" (p32) and that "a longer term move to a spectrum value curve would address this problem" (p34). We have partially addressed this issue through our choice of potential alternative uses of the bands, by assuming that technology and service restrictions on bands will be reduced in future. In particular we assume that for frequencies below 4 GHz a range of mobile technologies delivering converged communications services will be possible. Above 4 GHz only fixed services will be technically feasible for some time to come. We have assumed that fixed terrestrial broadcast services will continue to be limited to those frequency ranges which are allocated to the service internationally (i.e. the current limited radio frequency capabilities of receivers continues), though these frequencies might also be used by a range of fixed and mobile applications.

6.2 Where should AIP be applied?

As a general rule AIP should be applied where there are competing demands for spectrum and where it is practical. The extent of congestion in bands allocated for aeronautical and maritime use was discussed in Chapters 3 and 4. Most bands below 16 GHz were identified as being potentially congested in some locations, either as a result of demand from own use or a potential alternative use of the band.

In practice the extent of demand for spectrum below 100 MHz from alternative uses is likely to be low because of the long propagation distances, small amounts of bandwidth available and large antenna size required. Furthermore, Ofcom has decided not to apply AIP to broadcasting in the HF frequencies.[82] We therefore recommend that AIP is not applied to frequencies used by aeronautical and maritime services below 100 MHz.

The main practical complication in bands above 100 MHz concerns shared use of the spectrum. It was concluded in Chapter 5 that

- In bands used for communications purposes ground station charges should be set assuming they recover AIP for all aeronautical/maritime communications use of the relevant bands
- In bands used for aeronautical weather radars, altimeters and Doppler navigation aids AIP should be recovered through WT Act charges set in respect of ground stations
- Charges for use of spectrum by ships radars are either not necessary because they are recouped through charges on fixed radars locations where such radars operate or might be it levied on the industry as a whole via the relevant government agencies.

Tables 3.2 and 4.3 summarise our conclusions on the aeronautical and maritime bands (respectively) to which AIP should be applied. It should be noted that our recommendations extend pricing to several more bands than those recommended in Appendix A of the Independent Audit.

The Independent Audit suggested that pricing in the 960-1215 MHz band and the 5 GHz MLS band be linked to the outcome of the review of navigation aids and landing systems. However, our arguments for applying AIP in these bands do not rest on showing the potential for rationalising navigation systems. Rather it is potential demand from alternative services that means these bands should be subject to AIP.

The Independent Audit also suggested that the opportunity cost of spectrum in bands where there are airborne only uses was zero. However, use in these bands precludes their use by other services (e.g. fixed services) and so AIP should in principle be applied. This provides incentives to release spectrum not required, moderate future spectrum demands and lobby to remove regulatory constraints on spectrum use.

6.3 Marginal benefit estimates for potential alternative uses

The alternative uses we need to consider for the purposes of setting AIP and for which there are existing marginal benefit estimates (at existing allocations) are as follows:

- Radio and TV broadcasting
- PMR
- Public mobile services
- Fixed links

The values estimated by Indepen *et al* (2004) and in Indepen-Aegis (2005) for these services in various bands are shown in Table 6.3 together with a description of the method of calculation. The values for spectrum used by mobile and fixed services have been calculated as the change in input costs that would occur if an average user was denied (given) access to a small amount of spectrum.

[82] Ofcom. July 2006. "Future pricing of spectrum used for terrestrial broadcasting." http://www.ofcom.org.uk/consult/condocs/futurepricing/summary/

The additional cost (cost saving) depends on the application and is calculated as the estimated minimum cost of the alternative actions facing the user. In principle, these alternatives may include

- Investing in more/less network infrastructure to achieve the same quantity and quality of output with less/more spectrum
- Adopting narrower bandwidth equipment
- Switching to an alternative band
- Switching to an alternative service (e.g. a public service rather than private communications)
- Switching to an alternative technology (e.g. fibre or leased line rather than fixed radio link).

This referred to as the "least cost alternative" approach. The actual AIP applied by Ofcom is typically around half the opportunity cost values shown in Table 6.1. We return to this issue in Chapter 7.

Table 6.1 Marginal benefit estimates from previous studies and auction results

	£k/ MHz for a national channel	Method of calculation	Source
Public mobile (900 and 1800 MHz)	840	Least cost alternative	Indepen et al (2004)
PMR (VHF and UHF)	620	Least cost alternative	Indepen et al (2004)
Fixed links	95	Least cost alternative	Indepen et al (2004)
UHF TV	500	Market value of traded multiplex capacity	Indepen-Aegis (2005)
412-414 MHz	45	Annualised auction value[83]	Auction – 2006[84]
1781.7-1785/1876.7-1880 MHz	85	Annualised auction value	Auction – 2006[85]

Auctions of spectrum at 400 MHz and at 1800 MHz in 2006 also provide spectrum valuations. However in both cases there are significant limitations on the use of the bands which will have reduced their value relative to other bands allocated to PMR and public mobile services. In the case of the 400 MHz band limitations on the use of the band due to MoD use in an adjacent to the band. In the case of the 1800 MHz band, the frequencies are shared between 12 users and there are relatively tight power limits on the band as compared with, for example, bands assigned to public mobile operators.

Further auctions of spectrum at UHF, 1.5 GHz and 2.6 GHz will be held over the next 2-3 years and will provide further information concerning the opportunity cost of spectrum for mobile applications. In the short term the auction values are likely to provide an upper bound on the value of adjacent or other substitute spectrum that might be released from bands currently allocated to aeronautical or maritime use. This is because the supply of additional spectrum could lead to a fall in opportunity cost in the

[83] The value was computed as the annualised value over the initial term of the licence and assuming a 10% discount rate.

[84] http://www.ofcom.org.uk/radiocomms/spectrumawards/completedawards/award_412/

[85] http://www.ofcom.org.uk/radiocomms/spectrumawards/completedawards/award_1781/

absence of any new applications being developed to use any spectrum released as a result of AIP. In the longer term the release of spectrum could stimulate the development of new applications and demand could rise and with it the opportunity cost of the spectrum.

6.4 Marginal benefit in own use

Discussions with spectrum users and managers suggest that only the communications bands used by aeronautical and maritime use are expected to be congested over the foreseeable future. This means that the own use opportunity costs in other bands are therefore zero over the medium term. The calculations given below focus on the communications bands as these are the only bands which are congested (in some locations at least) in the current use. We have also used publicly available information to estimate the costs of improving the spectral efficiency of existing radars.

6.4.1 Aeronautical communications bands

Our approach to determining the marginal value for the VHF band is based on the cost of moving from 25 kHz bandwidth technology to 8.33 kHz, for flight sectors below 24,500ft, as this would seem to be the most practical way in which spectrum efficiency could be enhanced in the near term.

Eurocontrol has estimated the potential financial costs and spectrum benefits of moving from FL245 to FL 195 for 8.33 kHz communications on a European basis. [86] This allows calculation of the average cost of releasing additional channels for VHF communications. The fact that countries have agreed to move to FL 195 suggests implicitly that the benefits of this action exceed the costs and so the average cost estimates produced could be said to give a lower bound on the marginal benefit from the release of additional VHF communications spectrum.

In practice most of the spectrum dividend comes from the release of frequencies in France, the UK and Italy as these countries have the majority of sectors in which planes fly between FL245 and FL195. Eurocontrol has estimated that if the UK and France convert thirty nine 25 kHz assignments to 8.33 kHz operation this will yield an additional fifty assignments (central estimate) across Europe, implying that one 25 kHz assignment will yield on average 2.3 8.33 kHz assignments.[87] The Eurocontrol estimates do not include a further possible fifteen conversions in Italy.

The direct refitting costs to aircraft and the costs to air navigation service providers estimated by Eurocontrol are summarised in Table 6.2. These costs exclude any aircraft downtime costs or costs of refitting ground stations and so probably understate the full economic costs of the conversion. It should be noted that about half the costs shown are associated with refitting military aircraft as to date these aircraft have been exempted from converting to 8.33 kHz above FL245.

[86] http://www.eurocontrol.int/ses/gallery/content/public/docs/ru/SES_IOP_VCS_JMA_v2.0.pdf

[87] Calculated as (39+50)/39.

Table 6.2 Estimates of the costs of implementing 8.33 kHz channels from FL245 to FL195 (€000s)

	Low	Medium	High
Commercial air transport	8050	10350	13800
Business & general aviation	6900	9200	11500
State aircraft (i.e. military aircraft)	19500	26000	32500
Air navigation service providers	1970	2560	4515
Other costs (flight plan handling modifications, project management, safety awareness training etc)	1610	1950	2180
Total costs	**38030**	**50060**	**64495**

Source: Eurocontrol (2006), Justification material for the draft implementing rule on air-ground voice channel spacing.

Taking medium estimates from Table 6.2 and assuming (conservatively) conversion of frequencies in Italy releases around a further 15 channels, then we have a total cost of around €50m and a spectrum dividend of 1.35 MHz as a result of 54 conversions each of 25kHz[88] Converting the cost to an annualised value per MHz (assuming one off costs are depreciated over 15 years and a 10% discount rate) gives a value of €4.42m/MHz or £2.95m/MHz.

Excluding the cost of refitting military aircraft, which is lumpy because of the exemption from FL245 requirements, would roughly halve this value (£1.41m/MHz). The implied value of spectrum is still significantly more than the value in the next best alternative use, namely PMR. This could suggest that spectrum should be reallocated from PMR to aeronautical communications or that the aeronautical sector should consider the reallocation of more lightly used spectrum in the 108-118 MHz band to communications.

6.4.2 Maritime communications band (156-163 MHz)

The options for reducing congestion in the maritime communications band are to move to narrower bandwidth equipment and/or make greater use of simplex channels. Moving from 25 kHz to 12.5 kHz channels together with digitisation was under consideration by ITU/CEPT/ETSI and the maritime industry as a potential long term solution to congestion problems, though initiatives in this area are being treated somewhat cautiously and overall with only isolated support.

For the purposes of the calculations given below we assume that

- The industry moves to 12.5 kHz bandwidth for the UK channels releasing around 1 MHz (about half the 2.2 MHz in the 156-163 MHz band used for UK channels) and in time to 12.5 kHz bandwidth for international channels releasing about a further 1 MHz (about half of the 2.8 MHz in the 156-163 MHz band used for international channels)
- All other countries move to narrower bandwidth communications, so that any ships entering UK ports are suitably equipped and problems of interference with neighbouring countries using different channelisation do not occur.

[88] 39 conversions in the UK and France, and 15 in Italy.

- When the industry moves to narrower bandwidths manufacturers produce equipment at prices comparable to current prices for 25 kHz maritime radios i.e. £125-250 for a portable and £150-450 for a fixed radio.[89]
- Users would need to replace their radios and this would involve a refit cost of £100/radio – generally all that should be required is removing one (small) unit and putting another one in its place.
- On average the stock of radios is half way through its 15 year life.

We assume that there are at present in the region of 64,500 ships licensed in the UK and approximately 4,500 assignments for around 2,000 coastal stations most of which would need to re-equip[90]. (It should be noted that some vessels and Coast stations may have more than one radio whilst conversely, some Coast stations may have one radio serving two or more assignments). Further assuming an average new radio cost of £200 and a refit cost of £100, this implies a total one-off cost for the industry of around £21m implying an annualised cost of £0.618m/MHz assuming 2x2 MHz of spectrum is released. This is virtually identical to the marginal benefit estimate for PMR reported in Table 6.3.

6.4.3 Primary aeronautical radars

The main objective in this section is to calculate the cost of reducing the spectrum used (in and out of band) by aeronautical radars in order to inform views about the level of AIP required to change behaviour. Reports by QinetiQ et al (2004)[91] and BAe Systems (2006)[92] address ways of improving the spectral efficiency of existing magnetron aeronautical radars. The options examined include:

- The use of filter technology (fixed frequency inductive-iris band-pass filters) to reduce the bandwidth occupied to the necessary bandwidth
- The use of different waveform techniques by the systems within a band to ensure minimum interference between radar systems
- The use of filter technology and waveform techniques combined
- The use of ultra narrow band (continuous wave) transmissions which only use 10% of the spectrum required by pulsed radars.

The technology required for ultra narrow band (continuous wave) transmissions is not likely to be available for another 15 years and so we have focussed on the other three options. These options have the effect of reducing in-band and out of band emissions and so potentially release spectrum within radar bands and allow greater use of adjacent bands. The details are given in Appendix F.

The results suggest that significant amounts of spectrum could be released at L, S and Ku band by applying new waveforms and filters to magnetron radars and replanning the bands. In all cases spectrum is only released if all radars in the band (civil and military) are modified and in the case of S band the presence of maritime radars was not taken into account, although as noted earlier maritime usage is not large. The latter would reduce the spectrum dividend but in many cases geographical

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[89] http://www.icomamerica.com/

[90] Data supplied by Ofcom.

[91] Project AY4490 – A study into techniques for improving radar spectrum utilisation. QINETIQ/S&E/SPS/CR040434/1.1, 19th April 2004. http://www.ofcom.org.uk/research/technology/spectrum_efficiency_scheme/ses2003-04/ay4490/

[92] Study into spectrally efficient radar systems in the L and S bands. BAE Systems et al. SP-A21524-18304-RPT Issue 001. May 2006. http://www.ofcom.org.uk/research/technology/overview/ese/sers/

separation will make sharing of frequencies possible and so it still seems likely a significant block of spectrum could be released[93].

The cost estimates shown in Table 6.3 comprise the equipment and downtime costs of adopting new waveforms and filters. Downtime costs – assumed to be £100k per day and 10 days/radar – dominate the total cost estimates. We understand that these downtime costs were provided to Qinetiq by the aeronautical industry but we have been unable to determine a precise basis for these estimates.

NATS has already converted some of their radars to solid state operation and so the cost estimates are probably overstated. In addition there is no estimate of possible savings in spectrum in adjacent bands from reduced out of band emissions which suggests the costs/MHz values given in Table 6.3 should be regarded as maximum values. Subject to the caveats noted about downtime costs the estimates in Table 6.3 suggest a maximum cost per MHz of around £20,000- 80,000/MHz assuming a 15 year depreciation period and 10% discount rate. We note this is significantly below the marginal benefit estimates for alternative uses of the spectrum reported in Table 6.3 and suggests therefore that substantial amounts of spectrum could be released if AIP was applied to frequency bands used by aeronautical radars.

Table 6.3 Costs of reducing radar emissions by applying new waveforms and filters

	L Band (1.24-1.35 GHz)	S-Band (2.7-3.1 GHz)	Ku-Band (15.4-15.7 GHz)
Cost	£11.7m	£43.2-128.2m[94]	£0.8m
Spectrum Released	70 MHz	200 MHz	200 MHz
OOB impact	Positive but not quantified	Positive but not quantified	Positive but not quantified
One –off cost/MHz	Max £0.17m/MHz	Max £0.22- 0.64m/MHz	Max £0.004m/MHz
Annualised cost/MHz (assuming 10% discount rate 15 year discount period)	Max £0.02m/MHz	Max £0.03-0.08m/MHz	Max £0.0005m/MHz

Source: Qinetiq (2004), Indepen analysis

The Qinetiq report from which the numbers reported above were derived examined aeronautical radar. However, application of new waveforms and filters would also have the potential to reduce (in and out of band) emissions from maritime radars. There could be benefit in extending the Qinetiq analysis to examine this issue.

6.5 Deriving AIP

Given the marginal benefit estimates reported above, at what level should AIP be set? The analysis in Chapter 5 suggested that in most circumstances to derive AIP we should start by assuming that AIP is half way between the estimates of marginal benefit for the current use and the highest value alternative use and then modify this value up or down depending on whether

[93] Noting that the use of any released spectrum by other services might, at least initially (i.e. without a similar approach being taken in other countries), be constrained by the continued use of radars in other countries.

[94] The low end of the range is the cost for civil radars only. The high end includes military radars assuming the cost per radar is the same as for civil radars. Some NATS radars may already have this capability and so costs are overstated. Also costs of military radar conversion may be less than those for conversion of civil radars if there is less cost of downtime.

- the application of AIP would lead to a significant release of spectrum from existing use – reduce the AIP level
- new services and applications are expected to introduce new demand for radio spectrum in the medium term, possibly in response to the initial release of spectrum due to the application of AIP – increase the AIP level
- there is high or low uncertainty concerning the opportunity cost estimate and the social losses from setting prices above or below the best estimate of opportunity cost. If the two competing demands have similar demand curves then there are grounds for a downward adjustment. However, where the competing use for aeronautical or maritime spectrum is likely to have high value the early application of AIP at or above the best estimate of opportunity cost may be appropriate.

We proposed a rule of thumb that

a the best estimate of opportunity cost is adjusted downward by between 20 and 40 per cent when setting AIP, depending on a judgement over the level of uncertainty in the estimate – the more uncertain the value the higher the adjustment,

b if there are strong *a priori* grounds for believing that the competing use is particularly valuable relative to the existing use with excess spectrum then no adjustment should be made to the best estimate of opportunity cost and AIP should be set mid-way between the two estimates of marginal benefit.

Below we apply this rule of thumb to derive AIP estimates for each of the frequency bands identified as potential candidates for AIP (see Tables 6.1 and 6.2 respectively). The results are summarised in Tables 6.6 and 6.7 given below.

6.5.1 Aeronautical bands

108-118 MHz

There is excess demand for use of this band from PMR and PMR equipment could readily use the band. There is not excess demand from the existing use by ILS and navigation systems. It is possible that the band might be used in future by aeronautical communications but no decisions have been made about this. We assume therefore that the marginal benefit in the own use is zero and in the alternative use in £620k/MHz (the value for PMR). We take a value mid-way between these two values as the best estimate of opportunity cost and make a 30% downward adjustment on the grounds that there is moderate uncertainty about the slope of the demand curves. This gives a value of £217k/MHz.

118-137 MHz

There is excess demand for use of this band from PMR and PMR equipment could readily use the band. The opportunity cost estimate for PMR is £620k/MHz. There is also excess demand from aeronautical communications services and we have estimated that the marginal benefit from use of the spectrum for aeronautical communications is in the range of £1.41-2.95m/MHz.

There is very high uncertainty concerning this estimate and so we suggest setting AIP in this band with a 40% downward adjustment on the mid-point between £620k/MHz and £1.41m/MHz i.e. at £610k/MHz.

328.6-335.4 MHz

There is excess demand for use of this band from PMR and PMR equipment could readily use the band. The opportunity cost estimate for PMR is £620k/MHz. There is not excess demand from ILS in this band, implying a zero marginal benefit in this application. We take a value mid-way between these two values as the best estimate of opportunity cost and adjust this downward by 30% on the grounds that there is moderate uncertainty about the slope of the demand curves. This gives a value of £217k/MHz.

590-598 MHz

In addition to the current use of this frequency range by aeronautical radar, there is significant interest in this frequency range for new mobile applications, including mobile TV. Ofcom has announced that it will seek to auction this frequency range in the second half of 2008 together with the other spectrum released as part of digital switchover.[95] If this occurs then AIP will not be necessary, however, if the spectrum is not auctioned in the timescales Ofcom anticipates then AIP should be applied.

At present the best estimate of opportunity cost is given by the mid-point between the marginal benefit to radar and that for digital TV services.[96] We do not know the marginal benefit of the spectrum for aeronautical radar, but have taken an average value of £50k/MHz computed for primary radar in the 2.7 GHz band. The mid-point estimate is then £275k/MHz. We do not suggest reducing this value as release of this spectrum is likely to result in additional demand for the spectrum from new applications such as mobile TV.

960-1215 MHz, 1215-1350 MHz and 2700-3100 MHz

There does not appear to be excess demand for these frequency bands spectrum from aeronautical applications and so the marginal benefit in the own use is zero.

These frequency ranges are well suited to use by mobile services, because of their range, in-building penetration and non-line of sight reception. The frequency bands sit above and between frequency ranges that are internationally harmonised for use by mobile services. The estimated marginal benefit of additional spectrum for existing mobile services (i.e. £840k/MHz) is likely to be much higher than the marginal benefit from use of this band. This is because initially at least the band will not be harmonised for use by public mobile services (unlike the bands used by existing public mobile services). Lack of harmonisation will limit the market for services – possibly because of lack of roaming features and higher equipment costs – and so reduce the value of the spectrum.

Furthermore significant amounts of additional spectrum that could be used to deploy mobile services will be auctioned in next year (in the 2-3GHz frequency range) This adds further uncertainty to the potential value of the spectrum in these frequency ranges for mobile applications. We therefore suggest AIP is set applying a 40% downward adjustment to the mid-point between zero and the marginal benefit for public mobile services i.e. 420k/MHz reduced by 40% giving a value of £252k/MHz.

Bands from 4200MHz to 15700 MHz

There does not appear to be excess demand for these frequency bands spectrum from aeronautical applications and so the marginal benefit in the own use is zero.

[95] "Digital Dividend Review", Ofcom, December 2006, http://www.ofcom.org.uk/consult/condocs/ddr/

[96] While there are other potential uses of the spectrum e.g. mobile TV and mobile broadband the value of the spectrum to these is highly uncertain.

The potential alternative uses are fixed applications and there is a single marginal benefit value for all bands up to 16 GHz - namely the fixed link value of £85k/MHz. Other possibly higher value applications such as PMSE and WIFi (at 5GHz) and in time future mobile services such 4G could potentially use bands below 6 GHz and so we have not applied any adjustment to derive an AIP value at the mid-point between the two available marginal benefit values i.e. at £42.5k/MHz.

For bands over 6 GHz demand will be primarily from fixed link applications and arguably the demand from these applications (and possibly others) becomes more uncertain the higher frequency range under consideration – partly because propagation distances shorten and there are more available substitute bands. We have therefore applied a 20% downward adjustment for bands in the range 6-10 GHz and a 40% adjustment above 10GHz to give AIP values of £34k/MHz and £25.5k/MHz respectively.

6.5.2 Maritime

156-163 MHz

There is excess demand for use of this band from PMR and PMR equipment could readily use the band. The opportunity cost estimate for PMR is £620/MHz. There is also excess demand from maritime communications in some locations and we have estimated that the marginal benefit from use of the spectrum for maritime communications is £618k/MHz. There is considerable uncertainty concerning the latter value (because the numbers of radios that need to be replaced and the cost of new radios and refits is uncertain) and this suggests setting a value at the mid-point between the two marginal benefit estimates and then applying a 40% downward adjustment i.e. giving an AIP value of £371k/MHz.

2900-3100 MHz

The reasoning here is that same as that given above for the 2700-3100 MHz band and so we suggest an AIP value of £252k/MHz.

9000-9500 MHz

The reasoning here is that same as that given above (4200 – 15700 MHz) and so for this band we suggest an AIP value of £34k/MHz.

6.5.3 Summary

Tables 6.6 and 6.7 summarise the conclusions given above for AIP estimates for the aeronautical and maritime bands respectively. These estimates are indicative. Given the uncertainties in deriving the estimates some rounding of similar values may be appropriate.

What stands out in Table 6.4 is the high value for the communications band. This is a consequence of the considerable congestion in the band and the fact that aeronautical users do not have any alternative but to invest significant sums in more efficient equipment if future demand is to be accommodated. Our analysis suggests however there is a good case for allocating more spectrum for communications purposes to aeronautical services.

Table 6.4 AIP estimates for congested aeronautical bands

Frequency Band (MHz)		Aeronautical Usage	AIP estimate
From	**To**		
108	118	108-112 MHz ILS (localiser) 108-118 MHz VOR & GBAS	£217k/MHz
118	137	VHF Communications	£610k/MHz
328.6	335.4	ILS (Glide Path)	£217k/MHz
590	598	Ground Radar (50cm)	£275k/MHz
960	1215	DME, Secondary radar (1030/1090 MHz)	£252k/MHz
1215	1350	Primary radar	£252k/MHz
2700	3100	Primary radar	£252k/MHz
4200	4400	Radio Altimeters	£42.5k/MHz
5000	5150	MLS	£42.5k/MHz
5350	5470	Airborne Weather Radars	£42.5k/MHz
9000	9500	Ground movement and airborne radar	£34k/MHz
13250	13400	Doppler navigation aids	£25.5k/MHz
15400	15700	Ground movement radar	£25.5k/MHz

A similar but less marked situation applies in the case of maritime bands (see Table 6.5), though here we anticipate that AIP would focus on the limited number of locations in which congestion is found - primarily around the Dover Channel and some of the south coast of England.[97]

[97] This could be done by applying a modifier in the fee algorithm that reflects the geographical distribution of congestion, as is done for PMR for example. See "Modifications to Spectrum Pricing", Ofcom, January 2007.

Table 6.5 AIP estimates for congested maritime bands

Frequency Band (MHz)		Maritime Use	AIP estimate
From	**To**		
156*	163*	Coastal station (UK) radio International maritime distress, calling and safety Coastal and inshore search and rescue; DGPS channels, AIS channels	£372k/MHz
2900	3100	Radar (10cm) - in and out of band emissions, RACONs	£252k/MHz
9200	9500	Radar - in and out of band emissions, RACONs, Search and Rescue Transponders	£34k/MHz

* Only some channels in these bands are used by the maritime community

7 Implementation

7.1 Introduction

In this Chapter we provide recommendations on how charges might be set for different users in different bands given the national AIP estimates given in Chapter 6. In doing this we have taken into account approaches used by Ofcom for other frequency bands and in defining spectrum usage rights.

The sections below present a band by band discussion of how AIP should be set for national and localised users. The approach is illustrated with *hypothetical* numerical examples which are intended to demonstrate the approach and are not necessarily to reflect the real world situation. These examples are followed by an assessment of the priority of different bands for applying AIP, taking account of the demand for the bands in question, the nature of international constraints and the size of the frequency allocations under consideration. Next we bring together the conclusions given throughout this report on which entities might be charged AIP. Both the setting of AIP and its application to specific users/uses of spectrum are complex in many areas and are subject to on-going discussions between Ofcom and the affected parties as to how best to focus the incentives offered by AIP in a fair and effective way.

The Chapter concludes by noting a number of areas in which further work is required if our recommendations are to be implemented.

The analysis assumes that

- A single entity, possibly representing several entities, has responsibility for each frequency band and in those cases where this entity is not Ofcom it is charged the AIP for the entire band in the first instance.
- As recommended in Chapter 5, that entity is required to set charges for other existing users in the bands based on an agreed methodology for setting AIP for localised use.
- AIP paid by a given user depends on the spectrum use restricted or denied to others, which in turn depends on the bandwidth occupied and the affected area (i.e. a function of transmit power and receiver sensitivity).
- National AIP values are apportioned between localised users based on the share of the UK population in the area affected by the user. This approach is consistent with that adopted by Ofcom for PMR.[98] It is based on the assumption that economic activity is greater in areas of high population density and this leads to a higher opportunity cost of the spectrum in these areas.
- Where the bandwidth occupied or impacted areas of two or more users overlap, a simple rule is devised for calculating the share of the overlapping bandwidth/share of population attributed to each user e.g. each user is attributed a 1/Nth share when N is the number of overlapping users [99]
- For aeronautical applications that may restrict terrestrial applications, the relevant area over which this use is restricted or denied is the maximum area affected between zero and 100 feet above the ground.

Finally, we note that if existing licensees wish to secure pre-emptive rights over currently unused spectrum they will need to pay for these rights. Payments would need to reflect the nature of the

[98] Modifications to Spectrum Pricing, Consultation, Ofcom, 6 July 2006 http://www.ofcom.org.uk/consult/condocs/pricing06/

[99] As a practical matter we envisage this calculation being done at most once a year.

rights reserved and could be based on the associated AIP cost; however, detailed consideration of the approach to setting these charges is beyond the scope of this study.

7.2 Radar bands

This section presents the approach for setting AIP in the following radar bands: 1215-1350 MHz, 2700-3100 MHz, 9000-9500 MHz and 15400-15700 MHz. The recommended approach is illustrated for S band radars (2700-3100 MHz) but the same principles apply to the other bands.

Two specific issues arise in the maritime radar bands. The first concerns the use of radars on board ships and the associated coastal strips and land around ports that may have restricted use for other radio services. It is not practical to take account of this use in setting AIP for the maritime community because of the absence of any objective measures of such radar use. Also the fact that ground and ship borne radars share a common set of frequencies (e.g. all 9 GHz radars operate around the centre frequency in the band) means that AIP charged to ground based radars will often implicitly pay for on-board use. We therefore suggest that AIP is only applied to ground based radars and not to use of radars on ships. Secondly the common use of frequencies means that bandwidth overlaps need to be taken into account as well as overlaps in affected geographic areas.

In terms of alternative use within this coastal strip it may well be the case that private systems could operate quite satisfactorily under current conditions whereas public systems probably would not. In order to increase the possibilities for alternative use AIP has to be directed towards reducing the impact of radar from passing ships. There is no clear solution to this except to note that some form of international agreement limiting the extent of such emissions would be required. The move to such an agreement might be encouraged if AIP could be directed at the right UK institution – possibly the Department for Transport or the MCA.

Pricing for in-band and out of band emissions are addressed separately below. The total AIP payable by a given radar will be the sum of the in-band and out of band charge. The calculations depend on assumptions concerning the in and out of band emission limits. The reader should refer to the discussion of this issue in Chapter 5 and Appendix F.

7.2.1 In-band emissions

For in band emissions the steps in the calculation of AIP for a specific radar are as follows

i The AIP charged for a given radar is a linear function of the bandwidth occupied and the fraction of the UK population in the affected areas. This requires that the bandwidth occupied and the affected areas be defined

a The definition of the bandwidth occupied (BO) depends on whether the in-band emission limit is defined as -20 dB or -40 dB below the peak power level at the centre frequency or at an absolute emission level. We have suggested in Appendix F that operators should declare which of these limits they are working to and pay AIP accordingly. Out of band emissions could be calculated through measurement or using relevant ITU-R Recommendations (see Appendix C)

b The affected area (A) can be calculated using standard propagation models and making an appropriate assumption regarding the sensitivity of a victim receiver. Overlaps with all existing radars (civil and military) would need to be taken into account. Once this is done the identified area would need to be mapped on to population grid squares and the sum of the shares of the UK population in the relevant grid squares calculated (POPSHARE). Note that in the case of maritime radars some of the affected areas will be over the sea and no AIP will be paid on this use if there is no population in these areas (this will generally be the case, unless populated islands fall in the affected area).

AIP charge for in-band emissions for a given radar then equals P x BO x POPSHARE.

Indicative values for a reference[100] S band radar at Heathrow airport are as follows.

P= £252k/MHz

BO (-20dB) = 6.4 MHz

BO (-40 dB) = 31 MHz

A= 50,000 sq km[101]

POPSHARE = assume 30% even though the area relative to the whole of the UK is less than this because the area around Heathrow airport is very densely populated

In this case AIP paid would equal £483.9k based on the -20 dB bandwidth. A higher payment might be required if out of band emissions significantly constrain spectrum use in neighbouring bands.

7.2.2 Out of band emissions

The extent of out of band emissions depends on the emission limits for radars that apply at the band edge. The legacy of existing radars may mean that it is necessary to start with the limits that currently apply. If over time radars migrate away from the band edge in response to the incentives provided by AIP then it may be possible for alternative out of band emission limits to be declared – preferably at an absolute level that is low enough not to cause problems in the adjacent band. In this more ideal circumstance no AIP relating to out-of-band emissions would apply.

The steps in the calculation are as follows.

i Define the additional bandwidth (A-BW) deemed to be occupied as a result of out of band emissions. Nominate the extent of unwanted emissions falling in the adjacent band within which assignments fall. It is preferable that whatever limit nominated, and against which additional AIP will be charged, should be an absolute rather than relative level as this is of most interest to victim receivers in the adjacent band. Further work is required to more precisely identify how far into an adjacent band radars have an adverse impact.

ii Calculate the payment as A-BW x the price per MHz for the adjacent band. This would be best done on a national basis although though in practice may need to be done at a sub-national level. .

iii The out of band emissions for a given radar will be zero for radars away from the band edge, but for those using frequencies near the band edge the additional bandwidth needs to be calculated as well as the area where the impact occurs based on the limits declared by the radar operator. Note that the performance of a radar near the band edge has to in any event fall within the A-BW constraints defined in bullet (i) above. Annex F considers how one might determine the bandwidth-area space occupied by unwanted emissions

[100] As outlined in Appendix C.

[101] The analysis of Appendix C looks at out-of-band emissions and only considers propagation up to the optical horizon. Power will in fact propagate beyond this and in the case of high power in-band transmissions is likely to reach 150 km for example. For the sake of this illustration we have assumed a radius of 150 km and assumed that 25% of this area is over sea and can therefore be discounted. This gives an area of approximately 50,000 sq km which compares with the overall UK land area which is nearly 250,000 sq km in round figures.

satisfying different masks. The two options would be either for the radar operator to declare the OOB MHz km² value based on a field strength / criterion to be met or for the transmitter power, -40 dB bandwidth and relevant mask to be declared such that the OOB MHz km can be calculated independently. Again the price charged would be the AIP for the adjacent band.

Depending on the criterion used to determine whether radar out-of-band emissions are deleterious or not it can be seen that a reference radar (1 MW / 1 µsec) at 2710 MHz extends at least 100 MHz into the adjacent band even when the mask adheres to the ECC Design Objective (see Figure 4 Appendix C).

7.3 Communications bands

We have recommended that where AIP is applied to the use of frequencies in aeronautical and maritime communications bands frequency that use by both mobiles and ground stations is charged to the ground station. This is straightforward to implement because

- Aeronautical communications between a ground station and mobiles (i.e. aircraft) occur on the same frequency (i.e. there is simplex operation)
- Maritime communications between a ground station and mobiles either occur on the same frequency or over a defined pair of frequencies (i.e. there is duplex operation).

One practical complication we need to consider concerns the treatment of the small number of frequencies (one channel in the case of airplanes that may only be used in remote regions and 4 channels for ships) in the aeronautical and the maritime communications bands that are assigned solely for vessel to vessel communications. We suggest that these frequencies are excluded from the AIP calculations for a specific ground stations. First the frequencies are likely to be used well away from populated UK areas (and so would incur a low AIP) and second the amount of spectrum used is small.

The steps in setting AIP for the aeronautical communications band (118-137 MHz) would be as follows

i The AIP charged for individual assignments is a linear function of the bandwidth occupied (BO) and the fraction of the UK population in the affected areas. This requires that the bandwidth occupied and the affected areas (A) be defined.

   a The bandwidth occupied for aeronautical channels used is 25 kHz or a fraction of this for 8.33 kHz channels. We note that the number of 8.33 kHz channels that can be fitted in a 25 kHz channels is around 2.3 (see the calculations in section 6.4.1) implying around 11 kHz bandwidth occupied per channel.

   b In this case the use of frequencies in one location denies their use by other aviation users in another location, hence the area restricted or denied should be measured by reference to the height of the aircraft with whom the ground station is communicating. The higher the flight level the greater the area restricted or denied by the communications and the European frequency plan assigns specific frequencies to particular flight level sectors. We therefore suggest that areas are computed for flight level heights to match the European categorisation. There is some discretion in how this might be done but we suggest that for sectors above FL24,500ft the area at 24,500ft is used, for sectors between FL19,500ft and FL24,500ft the area at 19,500ft is used and for sectors below FL19,500ft an intermediate level of say 10,000ft is used.

ii The AIP paid then equals P x BO x share of UK population in A.

Our estimates of the area visible from an aircraft communicating from different altitudes are given in the following table.

Altitude (Feet)	Visible horizon from sub-aircraft point (km)	Visible area (sq km)
24,500	310	301,907
19,500	276	239,314
10,000	198	123,163

Area of UK ~250,000 sq km and ~1,000 km end-to-end (Mainland)

Taking account of flight paths along which the radio channels are used, there is likely to be little difference between the possible population shares covered at the different altitudes. Since the UK population density is skewed to the South East of the country, it is likely that FL24,500 covers 90% of the population, FL19,500 80% of the population and FL10,000 65% of the population at a given instant but taking account of the use of a radio channel along a flight path will increase these figures potentially to 100%. This suggests that charges for channels used for communications with aircraft flying at high levels would be simply equal to the product of the bandwidth times the price P. This implies charges of £610k x .011= £6.71k for an 8.33 kHz channel (assuming 11 kHz of bandwidth occupied) and £610k x .025 = £15.25k for a 25 kHz channel.

For maritime communications the bandwidth occupied is straightforward in this case as it is either 25 kHz for simplex channels or 2 x 25 kHz for duplex channels. The area restricted or denied will need to be calculated based on the power etc of the transmission, possibly using Ofcom's MASTS model developed for PMR. And then the share of the population that falls within this area calculated. The AIP then equals P x O-BW x POPSHARE. As discussed in Chapter 4, we envisage AIP would only be applied to those locations experiencing congestion – namely around the English Channel and the Southern Coast of England.

For example a 25 kHz channel might restrict or deny use in an area defined by a distance of about 100 km (the exact distance will depend on a number of variables including power and height of antenna). Assuming that half of the area is over the sea then the population in an area of 16,000 sq km will determine the AIP charge. This area represents approximately 6% of the UK land area. In a sparsely populated part of the country the population in this area might amount to 0.5% whereas in a heavily populated area it could be 10% or more. The range of AIP charge, subject to confirmation of the assumed population figures, would then be:

0.5% to 10% x £372k x 25kHz/1MHz = £47 to £930 for a single (simplex) 25 kHz channel.

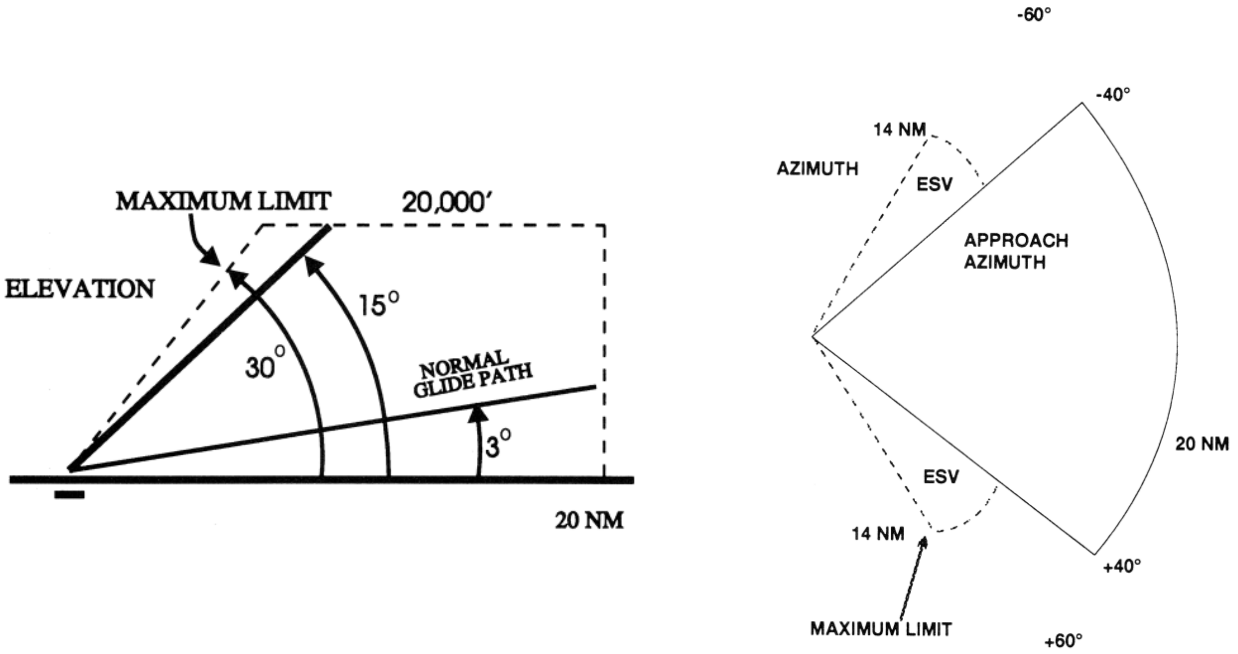
7.4 Aeronautical navigation bands

In this instance we are concerned with pricing transmissions from equipment located either on airports (ILS at 108-118 MHz and 328.4-335.4 MHz, and MLS at 5000-5150 MHz) or across the UK (DME at 960-1215 MHz). In both cases there are only ground stations transmitting in the band, the transmissions tend to point upwards towards aircraft and the next best alternative use is a terrestrial application. However, the possibility of alternative use will be determined more by the victim receiver in the air rather than the location of the transmitter. The area restricted or denied by the transmissions, taking account of the associated receiver, will therefore be determined to a first approximation by twice the ground distance from the transmitter to the sub-aircraft point at the aircraft receiver's most distant operating position. Note the shape of the area covered by transmissions will differ somewhat as DME transmissions are broadly omni-directional whereas ILS/MLS transmissions are directional.

The steps to be followed in undertaking calculations are similar to that described in previous sections, namely

- i the AIP paid by the band manger should be calculated as the product of the bandwidth of each frequency band and the relevant price/MHz (P).
- ii the charge to specific transmitters would be calculated as the AIP multiplied by the share of the UK population in the area restricted or denied by the transmission, where the latter is defined by twice the ground distance from the transmitter to the sub-aircraft point at the aircraft receiver's most distant operating position (as discussed earlier)

Figure 7.1: MLS elevation and azimuth coverage



Source: Wikipedia / Federal Aviation Administration employee

The above schematics show the operational coverage of the main part of an MLS system within which the radio emissions will have been designed to the required quality level. The left hand diagram shows the radio volume in the elevation (vertical) plane with the runway on the left – it can be seen that the MLS system is expected to be effective up to a height of 20,000 feet and when the plane is 20 nautical miles from the runway. The right hand diagram shows the radio volume in the azimuthal (horizontal) plane with the runway once again on the left – it can be seen that the MLS system is expected to be effective within at least ±40° of the runway axis and as before all the way out to 20 nautical miles from the runway. An MLS receiver on board an aircraft will be expected to lock on to the electronically controlled glide path some 20 NM from the runway and will have to be protected from other terrestrial use anywhere within the aircraft's visibility. Broadly speaking the area indicated in the right hand diagram should therefore be increased by 20 NM above, below and to the right of the area. This would then represent the area needed to calculate the AIP.

7.5 Other aeronautical bands

These frequency bands (4200-4400 MHz, 5350-5470 MHz, 13250-13400 MHz) are used only by airborne equipment. In terms of the area restricted or denied it is necessary to distinguish between applications that involve downward (altimeters and Doppler navigation aids) and forward (weather radar) transmissions. In the former case, the whole of the UK is likely to be restricted or denied. In the latter case transmissions made over neighbouring countries will also restrict or deny use in the UK (see section 3.6). In this case it will be necessary to calculate the area of the UK that is not affected by such transmissions and to apply AIP to this area only.

Next there will need to be a means of apportioning the charges between the civil and military users based ideally on some measure of use that is collected already (so as to keep administrative costs low) such as the number of flight movements.

The charge for the civil users would then need to be apportioned across individual users. The mechanism used would be a matter for decision by Ofcom and the CAA but might include, for example, en route charges or aircraft licence fees or WT Act licence fees.

7.6 Priorities for implementing AIP

The Independent Audit and the Government Response and Action Plan suggested that AIP should be applied from 2008 to selected aeronautical and maritime navigation bands. The Audit was less specific about bands used for navigation aids and communications. In these cases further reviews were to be undertaken. While such reviews could indicate the scope for making more efficient use of the spectrum, the application of AIP should not be conditional on their results. In Chapter 5 we concluded that once appropriate allowance has been made for upside and downside risks, there are no grounds, in terms of economic efficiency, for phasing in AIP gradually or implementing AIP partially. Rather the best estimate of the right level of AIP should be applied, and modified over time based on new information. We noted that there have been clear and consistent signals in relation to the application of AIP to aeronautical and maritime radio spectrum since the Cave Review in 2002, and that any additional delay or dilution of the level of AIP would involve ongoing costs in terms of inefficient use of spectrum.

However, it may be difficult in practice to introduce AIP across all the frequency bands we have identified as appropriate for AIP at once. This then raises the issue of which bands should be addressed first and which later on. In principle the bands that should go first are those where AIP would yield the greatest social and economic benefit, through promoting more efficient spectrum use. A key consideration is the materiality of the response to the application of AIP i.e. the potential for release of spectrum to accommodate future demand from existing and new users and/or the reassignment of spectrum from low to high value users. Our judgements concerning this are based on

- The extent of congestion from the current use of the band. There are two effects to take into account here.
    - First, in bands where there is relatively little congestion there may be more opportunities to release spectrum for alternative uses (and so enhance economic welfare) than in bands that are heavily congested.
    - Second in bands that are heavily congested – primarily the VHF aeronautical band and to a lesser extent the maritime VHF band in particular locations - pricing would provide incentives for users to adopt more efficient technologies.

- The extent to which release of spectrum in the UK is constrained by use outside the UK. Where these constraints are considerably less use in the UK is unlikely to release spectrum that can be used by others. The airborne only bands are the most constrained in this regard.

Taking into account these considerations we have grouped the frequency bands into high, medium and low priority as shown in Table 7.1 with reasons for the categorisation given on the right hand column of the table.

Table 7.1 Priorities for Implementation of AIP

Priority	Frequency bands	Reasons
High	590—598 MHz (if not auctioned) 960-1350 MHz 2700-3100 MHz 118-137 MHz 156-163 MHz*	High demand from own and/or alternative use.
Medium	108-118 MHz 328.6-335.4 MHz 5000-5150 MHz 9000-9500 MHz 15400-15700 MHz	Existing use not congested. Potential for alternative use but demand not as high as in the high priority category.
Low	4200-4400 MHz 5350-5470 MHz 13250-13400 MHz	All airborne uses and there is limited scope for releasing spectrum in UK

* Only some channels in this band are used for maritime communications.

7.7 Who is charged AIP?

Tables 7.2 and 7.3 summarise the conclusions we have reached on who might be charged AIP for each of the aeronautical and maritime frequency bands where AIP might be applied. There are two stages to determining charges. These stages are the apportionment between sectors (where multiple sectors operate in a band) and between individual users in the band on the basis of their use. In some circumstances it will not be possible to charge users directly, in which case alternative (possibly indirect routes) should be considered. This might include other licences issued by the regulator or charges for use of facilities (e.g. light dues in the case of the maritime sector or en route charges for aeronautical) – subject to these being legal and practically viable. Additionally, some contingency for future allocations (e.g. for new airports) may be required (although this could possibly be acquired through the market when it is needed assuming that spectrum in the band in question is tradable) and Ofcom will need to determine how these reservations should be defined and charged for and who should bear the charges; this will provide an incentive to reduce the reservation to the minimum required. In principle, spectrum kept against future requirements should be assigned to the party for whose benefit the spectrum is being reserved and that party could pay AIP on the assignment.

Where one party has unrestricted use parts of a band not currently assigned to other users, as is the case in some bands for the MOD, then that party should be liable to pay an amount corresponding to the value of the unoccupied part of the band (i.e. the total band value less existing assignments and reservations).

Table 7.2 Entities charged AIP - Aeronautical

Frequency Band		Aeronautical Usage	Entity facing band charge	Mechanisms for charging end users
From (MHz)	To (MHz)			
108	118	108-112 MHz ILS (localiser) 108-118 MHz VOR & GBAS	CAA (i.e. civil aeronautical users)	Aeronautical users pay through WT Act licences/RSA
118	137	VHF Communications	CAA (i.e. civil aeronautical users)	Aeronautical users pay through WT Act licences/RSA
328.6	335.4	ILS (Glide Path)	CAA (i.e. civil aeronautical users)	Aeronautical users pay through WT Act licences/RSA
590	598	Ground Radar (50cm)	CAA (i.e. civil aeronautical users)	Aeronautical users pay through WT Act licences/RSA
960	1215	DME, Secondary radar (1030/1090 MHz)	MOD	Aeronautical users pay through WT Act licences/RSA and CAA/DfT pay for reservations of spectrum
1215	1350	Primary radar	MOD	Aeronautical users pay through WT Act licences/RSA and CAA/DfT pay for reservations of spectrum
2700	3100	Primary radar	MOD	Aeronautical users pay through WT Act licences/RSA and CAA/DfT pay for reservations of spectrum
4200	4400	Radio Altimeters	CAA (i.e. civil aeronautical) or MOD	Charge indirectly through ground stations/vessel licences/other licences
5000	5150	MLS	MOD	Aeronautical users pay through WT Act licences/RSA and CAA/DfT pay for reservations of spectrum
5350	5470	Airborne Weather Radars	CAA (i.e. civil aeronautical) or MOD	Charge indirectly through ground stations/vessel licences/other licences
9000	9500	Ground movement and airborne radar	MOD	Aeronautical users pay through WT Act licences/RSA and CAA/DfT pay for reservations of spectrum
13250	13400	Doppler navigation aids	CAA (i.e. civil aeronautical) or MOD	Charge indirectly through ground stations/vessel licences/other licences
15400	15700	Ground movement radar	MOD	Aeronautical users pay through WT Act licences/RSA and CAA/DfT pay for reservations of spectrum

Table 7.3 Entities charged AIP - Maritime

Frequency Band (MHz)		Maritime Use	Entity facing band charge	Mechanisms for charging users
From	To			
156*	163*	Coastal station (UK) radio International maritime distress, calling and safety Coastal and inshore search and rescue; DGPS channels, AIS channels	MCA or Department of Transport (i.e. civil maritime users) if reserved for maritime; if not reserved for maritime then Ofcom may licence spare capacity	Maritime users pay through WT Act licences/RSA
2900	3100	Radar (10cm) - in and out of band emissions, RACONs	MOD	Maritime users pay through WT Act licences/RSA and MCA/DfT pay for reservations
9200	9500	Radar - in and out of band emissions, RACONs, Search and Rescue Transponders	MOD	Maritime users pay through WT Act licences/RSA and MCA/DfT pay for reservations

* Only some channels in these bands are used by the maritime community

7.8 Next steps

In order to implement our recommendations Ofcom will need to agree a number of detailed issues with representatives of the aeronautical, maritime and military users. In particular it is necessary to

- Determine how decisions about use of shared bands are made and the basis on which individual users are charged
- Identify more precisely areas of congestion for maritime communications with reference to information held by Ofcom on the ease of making assignments in different locations
- Agree a national price per MHz by band in light of our recommendations, and possibly informed by spectrum auctions that may occur over the next year or so.
- Determine the approach to out of band emissions for radars, taking account of the options given in Chapter 5 / Appendix F
- Undertake the implied quantification of impacts for each radar frequency band and for aeronautical and maritime radars separately including determining the approach to calculating the bandwidth and geographic area over which spectrum use by others is restricted or denied – models or measurement.

In addition, we have a noted a number of areas where further work is required including

- Establishing definitive data on the use of spectrum in aeronautical and maritime bands. In the course of this study we received conflicting data on the extent and nature of use in different bands.
- Estimating the extent of spectrum use in the UK restricted or denied by radars operating on passing ships

- Estimating the extent of spectrum use in the UK that would be restricted or denied by use of mobile equipment on aircraft operating outside UK airspace
- Considering whether radar receiver sensitivity should be determined through regulation as part of a wider policy review regarding the protection of receivers in relation to SURs and RSA or whether and, if so, how this should be reflected in AIP.

In conclusion, our experience gained from examining current use and management of bands allocated to aeronautical and maritime services suggests that there is considerable potential for more intensive use of these bands and that careful application of AIP would provide the necessary incentives to achieve this outcome.

Appendix A: Independent Audit recommendations for Aeronautical and Maritime

This Appendix reproduces the full set of recommendations from the Independent Audit in relation to aeronautical and maritime spectrum.

Aeronautical

6.1 AIP should be extended to military and civil aeronautical uses of the spectrum where it has the potential to help increase efficiency of spectrum use now or in the medium to long term. Beneficial effects of pricing could include:

- Maximising the benefits to aviation of its existing spectrum holdings
- Recognising and enabling other potential uses of the spectrum (where alternative use would be possible)

6.2 CAA and MoD should report their future plans for management of aeronautical spectrum holdings in the UKSSC Forward Look document, including progress on the opportunities for spectrum release or additional sharing identified in the Audit's band specific analysis (see Annex B). Plans for shared civil/military bands should be coordinated through the new radar and aeronautical subgroup of UKSSC.

6.3 Initial AIP charges should be set conservatively, in line with Ofcom policy for other AIP classes. As part of this process Ofcom will need to evaluate the opportunity cost of existing aeronautical spectrum use to an aviation user denied or granted spectrum use at the margins.

6.4 As co-ordination between the regulator and individual users will generally be needed to enable redeployment of aeronautical spectrum, where possible pricing should be imposed as an overall per-MHz band price. It would then be the responsibility of a co-ordinating body to apportion the band price and work with users to enhance intensity of use or release spectrum. Algorithms which reflect impact on other spectrum users should be employed where this is not feasible (or desirable if it could create perverse incentives).

6.5 For other airborne uses where the opportunity cost is effectively zero and there is no direct spectrum management pricing should remain at cost-recovery levels for the moment (Ofcom are considering options including a fee-free system for aircraft licensing). Currently cost-recovery licences do not always very accurately cover the true licensing costs, and where this is the case the pricing structure should be reviewed.

6.6 AIP should be introduced on the basis of both the value to aeronautical users and potential alternative users in all ground-based radar systems:

- UHF Radar (subject to decisions on clearance)
- L-Band
- S-Band
- X-Band
- Ku-Band

6.7 There may be a case for pricing DME ground stations, since they are licensed with discrete and potentially scarce assignments. The case is not clear-cut but Ofcom should assess the case for pricing

DME further as part of the exercise in determining the scope and level of aeronautical AIP to be implemented.

6.8 The MLS allocation is currently underused and there may be a case for applying pricing to this spectrum on the same basis as ground-based radar sites. This is subject to a concern that disproportionate pricing on initial users should not discourage the adoption of an effective technology, and potential pricing of MLS should be linked to a review of navigation aids and landing systems as below.

6.9 There may be an economic case for differential pricing of ground-based and/or airborne VHF communications licences to accelerate adoption of more spectrally efficient equipment in congested spectrum. Ofcom should investigate the opportunities further, in conjunction with CAA.

6.10 Ofcom, CAA and MoD should undertake a joint review of navigation aids and landing systems to consider whether any rationalisation of multiple allocations is feasible. The opportunities identified should be pursued through pressing for changes at a regional or global level, and through the use of market mechanisms where possible.

6.11 Ofcom, with assistance from the CAA, should take forward discussions with the incumbents of the 590-598MHz band with a view to vacating the band (including the option of a funded clearance project). These discussions should take place in the contact of the wider debate on broadcasting spectrum in RRC06 in order to properly assess the costs and benefits of such action.

6.12 Radar tends to produce significant levels of unwanted emissions which can adversely affect the intensity of use and hence value of other spectrum bands. The Audit considers that there is an economic case for taking account of these negative externalities through a system of penalties on radar users for the degradation they cause to spectrum use in other bands. Further research and proposals on this issue should be taken forward by Ofcom in parallel with the extension of AIP to radar.

6.13 As part of their response to this Audit, Government, Ofcom and the CAA should jointly adopt and publish a timetable for consulting on and implementing AIP for appropriate aeronautical spectrum classes. In the Audit's view implementation of AIP could realistically take place in line with Ofcom's plan to introduce trading in appropriate aeronautical licence classes between 2007 and 2009.

6.14 The arrangements for joint CAA and MoD coordination of aeronautical bands should be formalised, perhaps including the use of a joint planning tool. A new radar and aeronautical subgroup of UKSSC should be constituted with a membership of Ofcom, CAA, DfT and MCA. This group could be established in 2006, in advance of the introduction of AIP. Its eventual remit would be to:

- Apportion fees between individual users and collect them
- Take decisions on competing demands for spectrum
- Manage detailed compatibility and planning
- Use a joint planning tool to enable more efficient and dynamic assignment

Maritime

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.

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.

7.3 Ofcom and the MCA should carry out a review of international applications in the bands 156.0 MHz to 158.5 MHz and 160.6 MHz to 163.1 MHz to ascertain the feasibility of promoting simplex use of the duplex channels and/or the conversion to 12.5 kHz bandwidths.

Appendix B: Aeronautical radio systems

The brief description of systems in the following subsections is intended to aid understanding. A more complete description is contained in the InterConnect *et al* report (15 June 2004)[102] and Eurocontrol document DA243D005-1.0 Investigation of interference sources and mechanisms for Eurocontrol dated 17 December 1997. Particular usage in the UK is derived from the InterConnect report, Independent Audit report and discussions with the CAA.

For the purposes of summarising the various technologies in the subsections that follow they have been broken down into:

- Ground based radars
- Ground based navigation and landing systems
- Communications
- Other systems on board aircraft

B.1 Ground radars

The systems described in this section are primarily used by controllers on the ground to locate and identify aircraft.

B1.1 Primary Surveillance Radar (UHF, L-band, S-band, X-band, Ku-band)

Primary Surveillance Radars provide non-cooperative surveillance of aircraft, that is to say the relevant information is derived from the characteristics of the power reflected by the objects under observation rather than from signals carrying data and explicitly transmitted by the objects, as is the case with Secondary Surveillance Radar (see following sub-section).

These primary radars operate in the following frequency bands, the range capability of the radars decreasing as the frequency increases:

- **1215 – 1350 MHz (L-band)** – up to 250 nautical miles (Long range)
- **2700 – 3100 MHz (S-band)** – up to 150 nautical miles (Short to Medium range)
- **9000 – 9200 MHz and 9300 – 9500 MHz (X-band)** – up to 40 nautical miles (Local short range approach/Surface movement)
- **15.4 – 17.7 GHz (Ku-band)** – up to 20 nautical miles (Local short range approach/Surface movement) but generally used in a down-pointing mode for surface movement within an airport boundary.

In addition, as a peculiarity of the UK, two frequencies are used in Channel 36 (590 – 598 MHz) of the UHF TV broadcast band.

L-band – this band is used by the CAA subject to coordination with MoD (in practice civil radar is limited to above 1243 MHz. 1350 – 1365 MHz may also be used by the CAA subject to coordination with DTI). There are 34 assigned frequencies (bandwidths between 3.9 and 16.7 MHz) of which 4 are

[102] 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. InterConnect Communications, Connogue Ltd & Helios Technology. Ofcom Contract AY4620. 15 June 2004.

http://www.ofcom.org.uk/research/technology/archive/other/sss/ay4620/ay4620.pdf reused. Most radars require more than one frequency assignment due to multi-pulse working or frequency diversity operation. There are 11 sites across the country.

S-band – this band is used by CAA and MoD. It is heavily used by the military and sharing with maritime users takes place above 2900 MHz. There are 55 frequency assignments (bandwidths between 1.6 and 10 MHz) of which 12 are reused.

X-band – these two bands are used by CAA and MoD. There are 9 frequency assignments (bandwidths between 21 and 73 MHz) of which 9 are reused.

Ku-band – although a very wide frequency band only 3 frequency assignments are used for primary radar by DAP and MoD (15.65 GHz, 15.80 GHz and 16.40 GHz, all having a reported bandwidth of 73 MHz). There are 3 sites that all use the three frequencies for airport surface movement detection.

B1.2 Secondary Surveillance Radar (L-band)

Secondary Surveillance Radars (SSR) rely on cooperation between a target (aircraft) and the radar, and this depends on the target carrying a suitable transponder. As the radar antenna revolves it transmits pulses on a frequency of 1030 MHz. Any aircraft transponder within range will reply on 1090 MHz. The advantages of such interrogation when compared to “traditional” radar as used for Primary Surveillance are twofold; range is increased (or alternatively, transmitter power may be reduced) because the returned signal is not just a reflection, and information can be sent in the reply pulse.

The most common type of SSR is Mode A/C which indicates that the information provided by the aircraft reply is its altitude and its 12-bit squawk code. This allows the call-sign and flight level of the aircraft to be displayed on a ground controller’s screen next to the radar blip. A newer mode, Mode S (for selective), is becoming available with extended uplink and downlink messaging.

Airborne Collision Avoidance Systems (ACAS) also make use of SSR transmissions, in a mostly passive way. An ACAS system will monitor aircraft SSR replies on 1090 MHz in order to obtain altitude information of planes within range and it can also interrogate other airborne transponders on 1030 MHz. The system is able to communicate with other transponders to provide co-ordinated resolution advisories to the pilot in the event of a possible conflict.

Military IFF (Identify Friend or Foe) shares these SSR frequencies.

B1.3 Other ground based radar

Wind profiler radars operate near vertically in the frequency band 1270 – 1295 MHz and are used for weather forecasting and aircraft safety around airfields.

B.2 Ground based navigation and landing systems

The systems described in this section are primarily used by pilots to navigate their aircraft.

B.2.1 Non-Directional Beacons (255 – 526.5 kHz)

Non-Directional Beacons are low powered omni-directional transmitters located at strategic locations including airfields. They transmit a constant AM carrier modulated with a call sign. Aircraft then use direction finding equipment based on two receive antennas to determine the direction from which an NDB signal is coming – no distance information is provided. With knowledge of the call sign being transmitted and a map of beacon locations the pilot can calculate the direction in which the plane is travelling.

B.2.2 VHF Omni-directional Range (112 – 117.975 MHz)

The VHF omni-directional range (VOR) system transmits two signals; one has a constant phase for all bearings from the VOR while the other changes phase with bearing. The airborne receiver compares the phase of the two signals thereby determining the bearing to the VOR.

B.2.3 Distance Measuring Equipment (960 – 1215 MHz)

DME, based on 1 MHz channels across the whole band, is used in association with VOR, ILS and MLS to provide pilots with location information. The system is based on transponders on the ground that provide distance information when interrogated by a suitably equipped aircraft. The reply is precisely timed so that the aircraft can calculate the slant range distance to a transponder by measuring the time delay between the interrogation and the reply.

DMEs are often collocated with VORs (so that an aircraft can determine its location by combining bearing and range) and of the three DME variants, wideband, narrowband and precision, the latter is an integral part of MLS.

There are 125 DME beacons, 49 of which are paired with VOR, and 60 of which are paired with ILS (or MLS).

There is significant other use in the band by the military (TACAN and JTIDS systems) and navigation satellites.

B.2.4 ILS (74.8 – 75.2, 108 – 112, 328.6 – 335.4 MHz)

The Instrument Landing System comprises three components which taken together give an indication of the position of an aircraft with respect to the runway for landing approaches. Each component radiates a signal that varies with direction.

A number of marker beacons (between 2 and 4), operating in the band 74.8 – 75.2 MHz, are used for each runway. They are placed at points between 75 m and 7,200 m from the runway. Each one is AM modulated with a different series of tones so that an aircraft flying above them can determine progress towards the runway.

The ILS localiser, operating in the band 108 – 112 MHz) consists of two transmitters either side of the runway each modulated with a different tone. When an approaching aircraft is in line with the axis of the runway the two tones are heard equally by the pilot. If the aircraft is off-axis, one tone is heard more loudly than the other.

The ILS glide path component, operating in the band 328.6 – 335.4 MHz, transmits two signals one above and one below the correct glide path for a runway. Each signal is modulated with a different tone. When an approaching aircraft is in on the correct glide path the two tones are heard equally by the pilot. If the aircraft is above or below the correct glide path, one of the tones will be heard more loudly than the other.

B.2.5 MLS (5000 – 5250 MHz)

The microwave landing system was intended as a replacement for ILS.

The main advantage of MLS over ILS is an improved performance in cluttered airport environments and bad weather, and the ability for aircraft to conduct curved approaches. The system has not been rolled out extensively. The US has abandoned interest in the system and in the UK the system is only installed at Heathrow.

MLS has a much wider glide slope than ILS which is dimensioned 4° by 0.3°. MLS over an 80° wide by 15° deep segment with a range of about 30 km. The system uses a time referenced electronically scanned beam mode over the sector and includes a data channel that allows local information (e.g. runway length, local weather etc) to be uplinked to the aircraft. It also provides a smaller 40° wide sector broadcast from the other end of the runway to provide precise navigation for take-offs and missed approaches.

Although the allocation extends from 5000 to 5250 MHz, the MLS frequency band extends from 5030 to 5150 MHz and the core part of the plan provides for 200 channels between 5031 and 5091 MHz. The lack of extensive use of MLS has been tacitly recognised by the aviation community through the agreement for mobile satellite system feeder links to use the band 5091 to 5150 MHz albeit on a time limited basis.

Now that it has been established that satellite navigation systems will not provide reliable Category III landings, MLS implementation is gathering momentum again. ICAO now estimates that there will be a requirement for 400 MLS internationally of which 200 to 250 would be in Europe.

B.3 Communications

B.3.1 HF communications (2,850 – 22,000 kHz)

HF air-ground communications supplement VHF communications (see next sub-section) in areas where VHF coverage does not exist (e.g. over the Atlantic Ocean). Given the propagation characteristics of the HF band a worldwide allotment plan which associates specific frequency channels for use in specified parts of the world, and other channels for worldwide use, is contained in the Radio Regulations.

B.3.2 VHF communications (117.975 – 137 MHz)

VHF air-ground communication is the main form of voice communication between aircraft and the ground and between aircraft themselves. Transmitters are typically 25 watts and the signals are analogue (AM) and typically use 25 kHz channels although there is some use of 8.33 kHz channels (still analogue). The range of a ground station varies between 50 and 300 km depending on the height of the aircraft.

B.4 Other systems (on-board aircraft)

B.4.1 Radio altimeters (4200 – 4400 MHz)

Radio altimeters are airborne downward looking radar systems that allow the height of the aircraft on which they are mounted to be calculated. They are used to measure heights up to 2,500 feet and are based on swept CW transmissions whereby the frequency shift between the transmitted and ground-reflected signals allow the altitude to be calculated.

B.4.2 Airborne weather radars (5350 – 5470 MHz and 9300 – 9500 MHz)

As the name implies, these radars detect certain weather formations. At the frequencies on which the system operates water particles can be detected and hence cloud formations and certain other weather formations can be detected. Airborne weather radars can, in spite of the title, be installed on the ground as well as on aircraft

B.4.3 Doppler navigation aids (13.25 – 13.40 GHz)

These systems use airborne equipment to provide ground speed and drift angle information. The Doppler shift of signals reflected from the ground can be used to calculate the speed at which the aircraft is travelling.

B.5 Satellite services

For completeness a number of supporting satellite based services used by the aeronautical industry are noted below. In general, the frequency allocations used by these services are not explicitly aeronautical. The frequencies are used to provide service to a wider community.

B.5.1 Navigation

RadioNavigation Satellite Service (RNSS) allocations at 1164 – 1300 MHz, 1559 – 1610 MHz are used by a number of systems to provide a positioning service (e.g. GPS / GLONASS / EGNOS and the forthcoming Galileo system. It can be noted that while the positioning service provided by satellite systems is widely used by aircraft, no reliance is placed on the service and other navigation systems are always used as well.

B.5.2 Communications

Communication channels can and are provided by satellite systems operating in the mobile-satellite service (for example by Inmarsat at L-band) and traditional fixed satellite systems (for example Eutelsat) that operate transponders which happen to overlap with mobile satellite allocations.

In the main these communication channels are largely directed towards supporting passenger facilities (e.g. the downlinking of passenger GSM calls to the ground via satellite) but they may also be used by the flight deck. In the case of flight deck communications no reliance is placed on this method of communications. However, it can be noted that in the bands 1545 – 1555 MHz and 1646.5 – 1656.5 MHz priority is given to the aeronautical mobile-satellite service (R)[103] providing transmission of messages with priority 1 to 6[104] (RR Article 44).

B.5.3 Safety

Low power Emergency Position Indication Radio Beacons (EPIRB), Emergency Locator Transmitters (ETL) and Emergency Low-power BeAcons (ELBA) are all variants of the same system. They radiate a signal on 406 – 406.1 MHz that is detected by satellites which can determine the location of the transmitter site. The transmission of the signal is triggered by crash sensors.

[103] For communications relating to safety and regularity of flight, primarily along national or international civil air routes.

[104] In descending order of priority: Distress calls, distress messages and distress traffic / Communications preceded by the urgency signal / Communications relating to radio direction-finding / Flight safety messages / Meteorological messages / Flight regularity messages.

Appendix C: Unwanted emissions specifically relating to radars

Introduction

This appendix summarises the regulatory situation with respect to radar unwanted emissions and looks at the impact of such emissions on other radio spectrum users operating in adjacent frequency bands. The following section starts by outlining the more general interpretation of unwanted emissions and indicates how radars are treated as a special case. It continues by summarising the various regulatory / recommended levels of emission that apply to radars and then takes these levels in an assumed practical situation to determine the impact on other spectrum users. The summary of the various regulatory / recommended levels of emission is brief so a synopsis of the source material has been appended as reference material.

Radar unwanted emissions

In diagrammatic terms we are dealing with the following general situation but note that there are specific provisions relating to radars as discussed later (this figure reproduced from ECC/REC/(02)05):

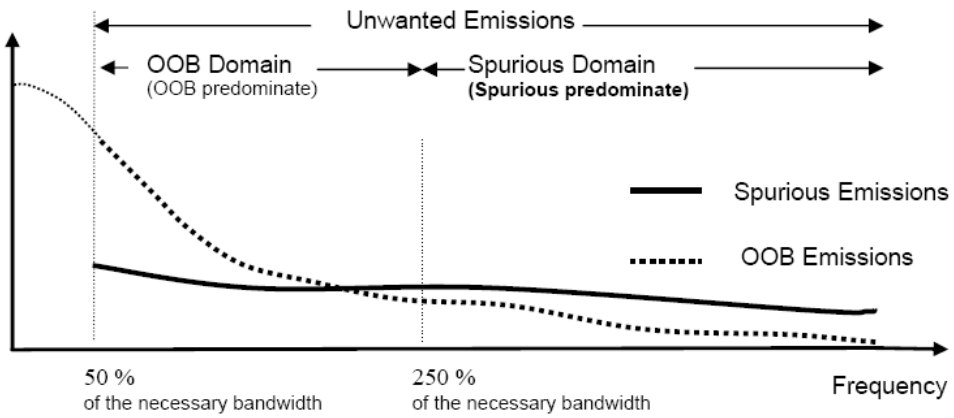


Figure 1: Illustration of the OOB and Spurious Domains (not part of Rec. ITU-R SM.329)

Note: The crossover point between OOB and Spurious emissions is not defined and Figure 1 shows only an example.

The important thing to note is that there are two emission domains that have the potential to generate interference and that one or other or both of these are specified in various regulations and recommendations as discussed below. Unwanted emissions associated with high power transmitters (e.g. broadcasting stations and radars) inevitably have a greater potential to cause interference and from a technology viewpoint it is difficult to attain the same absolute level of unwanted emissions as other lower powered transmitters. Special provisions are therefore made for high powered transmitters (especially primary radars) throughout the various regulations and recommendations. The current regulatory situation is summarised in the graph below (- further detail can be obtained from the annexed reference material).

It should be noted that for radars, the boundaries in the diagram above at 50% x necessary bandwidth and 250% x necessary bandwidth are specified differently. The former becomes 50% x the -40 dB bandwidth and the latter 500% x the -40 dB bandwidth. Furthermore, the necessary bandwidth which has to reside within the service allocation is specified as the -20 dB bandwidth. The occupied bandwidth which ideally should reside within the service allocation, but which is not required to do so, is not defined for radars.

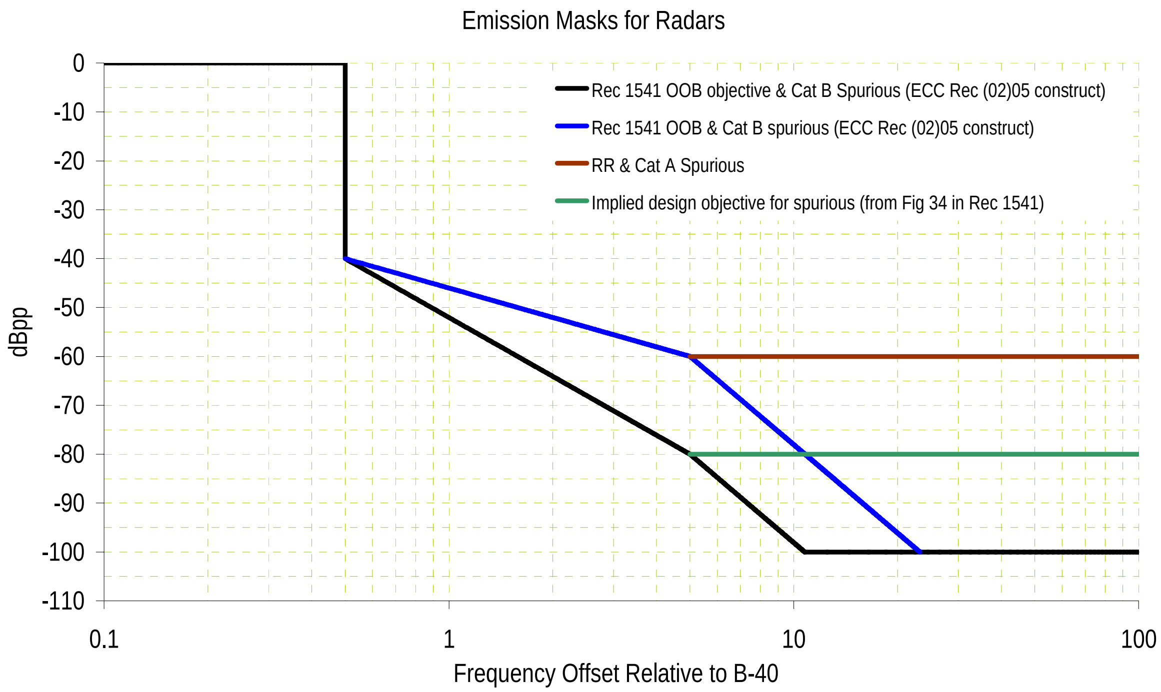


Figure 2 – Radar emission masks in the Radio Regulations, ITU-R Recommendations and CEPT Recommendations

Of the emission masks illustrated in the graph above, only the spurious level in the Radio Regulations ("RR & Cat A spurious") is mandatory, and even then only for transmitters installed after 1st January 2003 and to all transmitters after 1st January 2012. All the others have the status of a recommendation.

Unwanted emission levels when specified in terms of attenuations in the range -40 to -100dBpp (y-axis of graph) means that the emitted power level of the unwanted emission will be the peak power of the principal transmission + the derived attenuation (y-axis of graph). For a reference radar transmitter of 1 MW (60 dBW) the unwanted emissions will be in the range 20 dBW (close, in frequency terms, to the principal transmission) to -40 dBW in the spurious domain (best specified case). These values have to be specified with respect to a reference bandwidth to be meaningful. Different bandwidths have to be derived for different types of radar system depending on the individual characteristics of each radar. In any case the reference bandwidth is no more than 1 MHz and for a reference pulse length of 1 μS which we will use for a non-FM pulsed radar example later the reference bandwidth is in fact exactly 1 MHz.

For the purposes of deriving representative interference figures we will assume that the radar uses a transmitter power of 1 MW (60 dBW) as a reference, as mentioned above, while noting that ATC radars can use transmitter powers of up to 10 MW. Many of the regulations / recommendations specify spurious emission power levels for radars in terms of a transmitter power dependent expression or a given value whichever is the less stringent. For the reference transmitter power we are assuming here (i.e. 1 MW) it is always the case that the given value is less stringent than the derived power dependent value. In addition, it is necessary to assume a reference necessary bandwidth (B_{-20dB}) and/or a reference B_{-40dB} bandwidth.

Assuming a pulse width of 1 μS and rise times of 40 nS for magnetrons, the bandwidth relationships in ITU-R Recommendation SM.1541-2 for non-FM pulsed radars tells us that the 20 dB and 40 dB bandwidths are 6.4 MHz and 31 MHz respectively. It is difficult to make a direct comparison with solid state radars as the transmitter power levels are much lower (up to 20 kW) and the pulse widths and rise times differ.

Taking a representative frequency assignment of 2710 MHz at the lower end of the S-band radar allocation we can get a feel for the likely OOB/spurious figures with respect to frequency offset as follows. We will use the 6.4 MHz -20 dB bandwidth derived above rather than the actual one of 7 MHz.

In establishing the effect of radar unwanted emissions it is necessary to assume an interference criterion at a victim receiver. Given the example frequency band being used here it would be appropriate to consider 3G or WiMAX type systems. On this basis we can take some of the Mason/DotEcon modelling results that looked at the impact of UWB on 3G networks. That work determined that there would be no impact on 3G service quality/range/capacity if UWB devices were to transmit at no more than an EIRP density of -105 dBm/MHz assuming a minimum coupling loss of 10 dB. This effectively means the interference criterion (i.e. tolerable received interference power) is -115 dBm/MHz. If it is assumed that a 3G hand held receiver has a Noise Figure of 10 dB (N = -104 dBm/MHz) then the received interference power criterion translates into an I/N criterion of -11 dB. This is much in line with standard ITU-R practice of using a -10 dB I/N criterion which we will use here to determine separation distances required between radars and victim receivers.

Recommendation M.1461-1 notes that interference caused by radars will be due to front-end overload of the victim receiver (when the main transmission of the radar is insufficiently attenuated by the selectivity of the receiver) or due to the unwanted emissions of the radar falling in the passband of the victim receiver, although strictly this latter case should take account of the combined effect of the overlap between the unwanted transmitter emission spectra and the receiver selectivity curve (in both cases these represent both in-band and out-of-band effects). For simplicity we will assume that systems operating in bands adjacent to radars will be aware of the possibility of front-end overload and design in the necessary receiver selectivity to avoid the problem. In any event it is likely that the separation distances required to avoid the other effect (unwanted emissions falling in the receiver passband), to be discussed shortly, will also ameliorate the possibility of front-end overload.

It is also noted in the Recommendation that interference cases of radar transmitter emissions causing receiver degradation for radar mainbeam coupling have been documented. It is therefore recommended that the radar mainbeam gain be used in assessing the maximum potential for interference caused by radar transmitter emissions in the receiver IF passband. We note it is not clear how this relates to the definition of spurious emissions for radars the levels of which are implicitly defined after the antenna (i.e. in terms of radiated emission levels and not at the antenna transmission line).

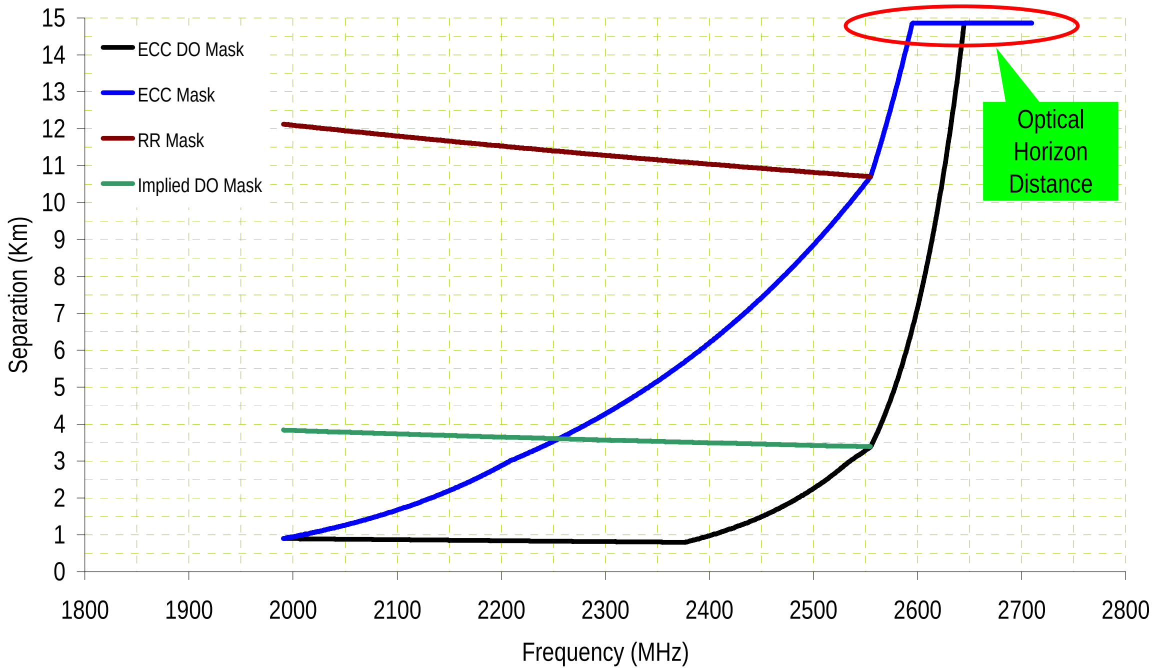


Figure 3 – Separation distances required with respect to the emission masks of Figure 2 as applied to a reference aeronautical primary radar.

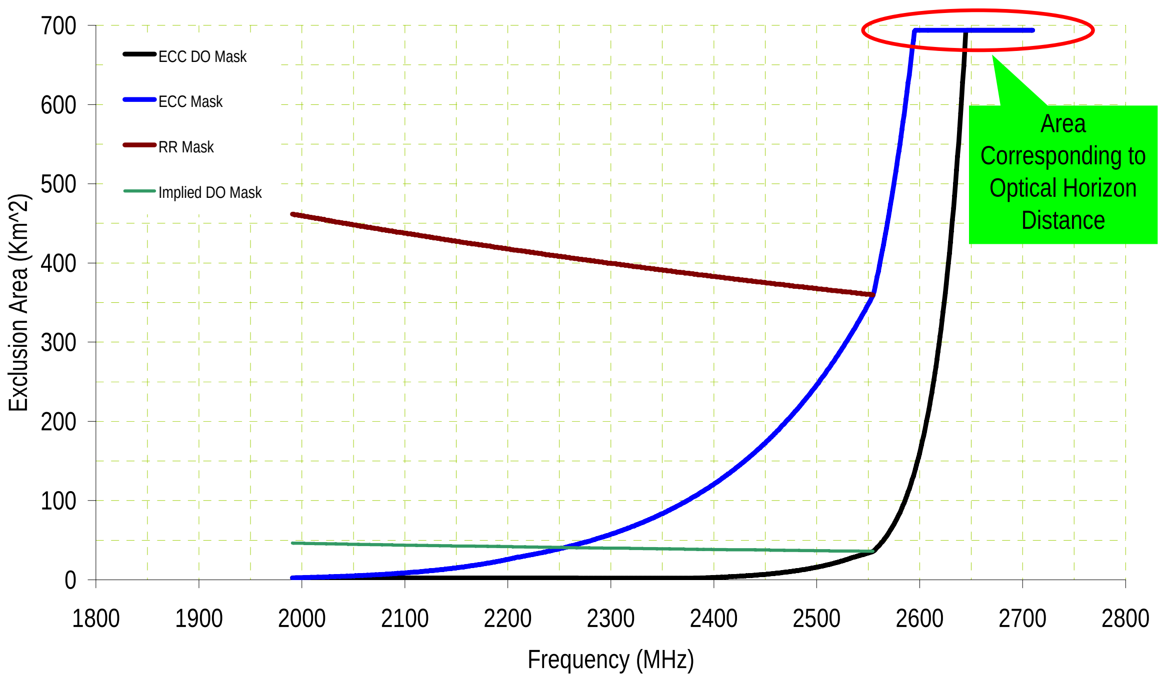


Figure 4 – Affected areas with respect to the emission masks of Figure 2 as applied to a reference aeronautical radar

The negative slope of the near-horizontal lines is due to the decrease in path loss with decreasing frequency and the corresponding impact on an otherwise constant emission level with respect to frequency.

The key assumptions behind the two aeronautical graphs shown previously are as follows:

- Radar assigned frequency = 2710 MHz
- Transmitter power = 1 MW
- Pulse width = 1 μS
- Rise time = 40 nS
- -20 dB bandwidth = 6.4 MHz
- -40 dB bandwidth = 31 MHz
- Victim receiver, NF = 10 dB, omni-directional
- Interference criterion I/N = -10 dB
- Radar height = 10 m
- Victim receiver height = 1 m
- Propagation = Free space to 200m, exponent 3 to 3 km, exponent 4 beyond.

It can be noted that the effect of radar on the 2.5 to 2.69 GHz band has been addressed in Ofcom's consultation document[105] relating to the proposed auction of this frequency band. The effect is analysed in further detail in an accompanying technical document[106]. The geographic areas affected by radar out-of-band emissions are broadly in line with our analysis but they also take account of terrain effects since specific radar sites are addressed.

The Ofcom analysis however goes a step further by considering the time domain. This looks at the relationship between the pulsed nature of radar emissions and the digital bits being used by potential victim systems (e.g. 3G and WiMAX), as well as considering that peak main beam radar emissions are rotated. It is postulated that the number of bits affected by a radar pulse is small and that error correction techniques in a victim system could mean that there may not be any significant impact on use of the band 2500-2690 MHz. Further information on this issue is expected to emerge as part of Ofcom's consultation process on the award of the band 2500-2690 MHz and it may be the case that conclusions regarding the application of AIP to radar out-of-band emissions might have to be modified to reflect the resulting analysis of the extent of the impact of radars on use of the band 2500-2690 MHz.

The following two graphs show, to the same scale, the equivalent results (in power terms and without any consideration of the time domain) for a maritime radar. In this case the frequency of the radar is 9.45 GHz and the power is 25 kW (40 times less than the aeronautical example). It is assumed to be a magnetron with a 1 μs pulse width / 40 nS rise time as for the aeronautical example. It can be seen that the lower power and less benign propagation at higher frequencies reduces the impact on

[105] Award of available spectrum: 2500 – 2690 MHz, 2101 – 2015 MHz and 2290 – 2300 MHz. Consultation Document - 11th December 2006.

http://www.ofcom.org.uk/consult/condocs/2ghzawards/2ghzawards.pdf

[106] Adjacent and In-Band Compatibility Assessment for 2500 – 2690 MHz. Technical Study / Research Document - 11th December 2006

http://www.ofcom.org.uk/consult/condocs/2ghzawards/technicalassessment/assessment.pdf adjacent bands significantly. The use of a shorter pulse width would however partially counter-balance this by widening the spread of energy into the adjacent band.

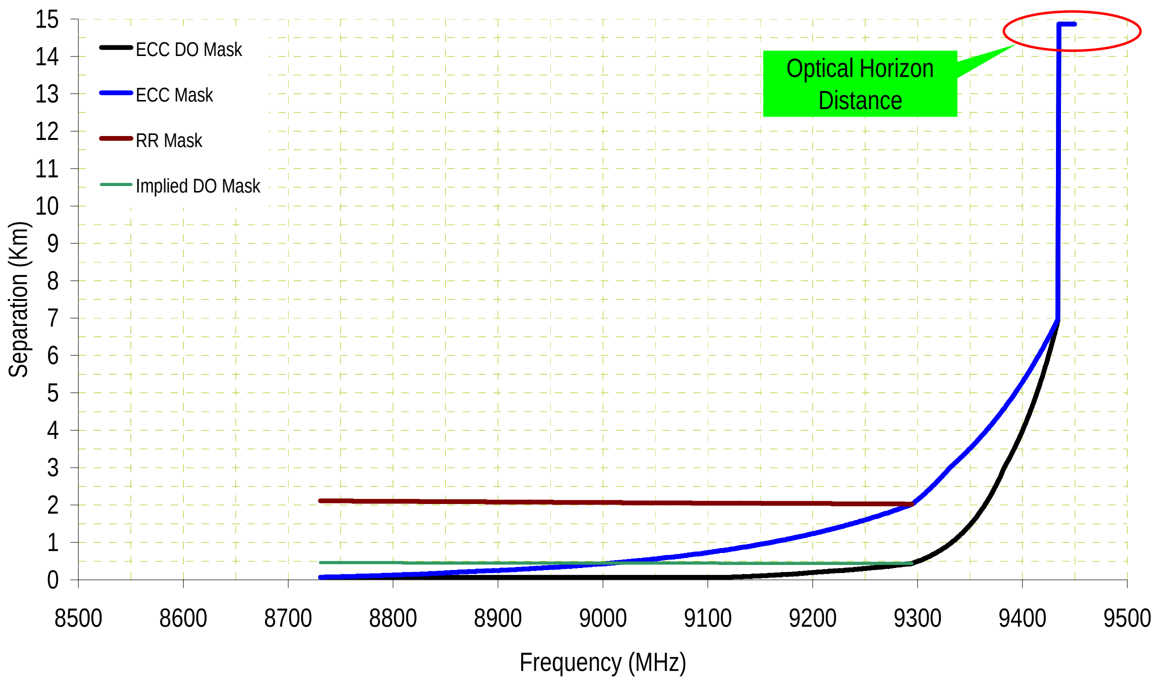


Figure 5 – Separation distances required with respect to the emission masks of Figure 2 as applied to a typical maritime radar.

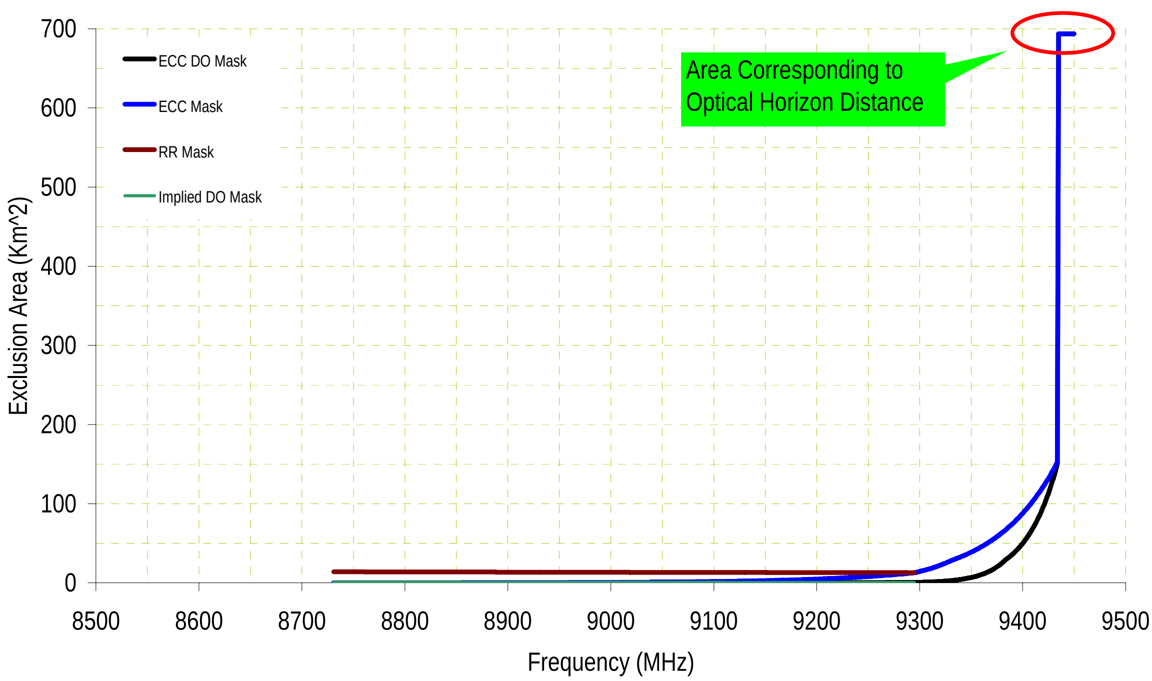


Figure 6 – Affected areas with respect to the emission masks of Figure 2 as applied to a typical maritime radar

References

Radio Regulations

Appendix 3 – Tables of maximum permitted power levels for spurious or spurious domain transmissions.

Section I – applicable until 1st January 2012 to transmitters installed on or before 1st January 2003. Radar systems are exempt under this section. It is required that the lowest practicable power of spurious emission should be achieved.

Section II – applicable to transmitters installed after 1st January 2003 and to all transmitters after 1st January 2012. The level of spurious emission, specified as the attenuation (dB) below the power supplied to the antenna transmission line, is generally 43 + 10 log (Mean Power)[107]. However, this is regarded as too stringent for high power transmitters so the specification for Radiodetermination Services is:

43 + 10 log (Peak Envelope Power in Watts supplied to the antenna transmission line), or 60 dB, whichever is less stringent. The attenuation shall be determined for radiated emission levels, and not at the antenna transmission line, as is the more general case. The measurement methods for determining the radiated spurious domain emission levels from radar systems should be guided by the most recent version of Recommendation **ITU-R M.1177**. The reference bandwidth for specifying the spurious emission level is specific to the type of radar system but in any event is no more than 1 MHz. Once again Recommendation **ITU-R M.1177** is called up in relation to the reference bandwidth to be used for radars operating with multiple waveforms.

For primary radar, the boundary between the out-of-band and spurious domains is the frequency at which the out-of-band domain limits specified in the applicable ITU-R Recommendations are equal to the spurious domain limit defined above. Further guidance on the boundary with specific reference to radars is contained in Recommendation **ITU-R SM.1541** Annex 8.

The Radio Regulations do not specify any values relating to the OOB Domain.

ITU-R Recommendations

SM.328-10 (1999) and Draft Revision (2005) – Spectra and bandwidth of emissions.

Definitions, calculation methods and mitigation techniques.

The draft revision proposes an extension to the definition of x dB bandwidth as reproduced below:

The width of a frequency band such that beyond its lower and upper limits any discrete spectrum component or continuous spectral power density is at least *x* dB lower than a predetermined 0 dB reference level.

The definition of *x* dB bandwidth may vary according to the determination of 0 dB (see Recommendation ITU-R SM.1541):

- *x* dBsd bandwidth: *x* dB bandwidth in a situation where the reference level is chosen to the maximum value of power spectral density (psd) within the necessary bandwidth;
- *x* dBc bandwidth: *x* dB bandwidth in a situation where the reference level is chosen to the unmodulated carrier power of the emission. When the carrier is not accessible for measurement, the reference level is the mean power;

[107] Note that this translates into a constant absolute level of -43 dBW (or -13 dBm) for all transmitter power levels.

- *x* dBpp bandwidth: *x* dB bandwidth in a situation where the reference level is chosen to the maximum value of the peak power, measured with the reference bandwidth within the occupied bandwidth.

NOTE 1 – The *x* dB bandwidth method gives results acceptable for the estimation of the 99% occupied bandwidth as defined in RR Article 1, No. 153, under the appropriate choice of *x* dB and 0 dB reference levels.

It will be seen elsewhere that the necessary bandwidth for radars is usually defined in terms of the -20 dBpp bandwidth and that the OOB domain starts at the -40 dBpp bandwidth. However, in spite of Note 1 above suggesting that the occupied bandwidth can be specified by way of an x dB bandwidth, there appears to be no ITU-R or CEPT material where this is done.

SM.329-10 (2003) – Unwanted emissions in the spurious domain.

Definitions and limits on spurious emissions, methods of measurement, protection of passive sensors, land mobile and fixed service specifics.

Category A limits form the basis of the limits in the Radio Regulations.

Category B limits are more stringent limits based on those defined and adopted in Europe and other countries. For fixed radars (excluding wind profiler, multi-frequency and active array radars) installed after 1st January 2006 the spurious limit is -30dBm or 100 dB attenuation whichever is less stringent.

SM.853-1 (1997) – Necessary bandwidth.

Derivations (including unmodulated pulse emissions)

SM.1138 (1995) – Determination of necessary bandwidths including examples for their calculation and associated examples for the designation of emissions.

Derivations (including unmodulated pulse emissions)

SM.1539-1 (2002) – Variation of the boundary between the out-of-band and spurious domains required for the application of Recommendations ITU-R SM.1541 and ITU-R SM.329.

Adjustment of the 250% necessary bandwidth boundary for narrowband and wideband signals.

Special provision for primary radars: "For the case of primary radar systems the OoB mask rolls off at 20 dB per decade from the 40 dB bandwidth to the spurious limit specified in Table 2 (Category A limit) of Recommendation ITU-R SM.329. The detailed definition of the OoB/spurious domain boundary is contained in Annex 8 of Recommendation ITU-R SM.1541.

The above specification of the boundary is the subject of ongoing ITU studies with a design objective of 40 dB per decade roll-off from the 40 dB bandwidth."

SM.1540 (2001) – Unwanted emissions in the out-of-band domain falling into adjacent allocated bands.

Recognises the problem of OOB emissions falling in adjacent allocations. Recommends that the necessary bandwidth and preferably the occupied bandwidth should fall within the band allocated to the service in question.

Does not recognise that this does not solve the problem for high power transmitters.

SM.1541-2 (2006) – Unwanted emissions in the out-of-band domain.

Important supplement to the Radio Regulations, as the latter only addresses spurious emissions, and as such complements SM.329-10 which also only addresses spurious emissions.

Many definitions, derivations and measurement methods but most importantly Annex 8 is specific to primary radar systems. This Annex contains derivations of necessary and 40 dB bandwidths. The OoB mask is specified as a 20 dB per decade roll-off from the 40 dB bandwidth to the spurious level specified in the Radio Regulations (see the Recommendation's Figure 30 reproduced below). Examples of roll-off with respect to the necessary bandwidth are also given for non-FM pulsed radar, linear FM pulsed radar and frequency hopping radar. Finally, a design objective is specified for future radar systems based on a 40 dB per decade roll-off from the 40 dB bandwidth to the spurious level specified in the Radio Regulations. Implicit in the graph (see the Recommendation's Figure 34 also reproduced below) that illustrates this improved roll-off, but not stated, is an improvement in the spurious level from the current RR level of – 60 dB to -80 dB at 5 times the 40 dB bandwidth.

FIGURE 30

OoB mask for primary radars

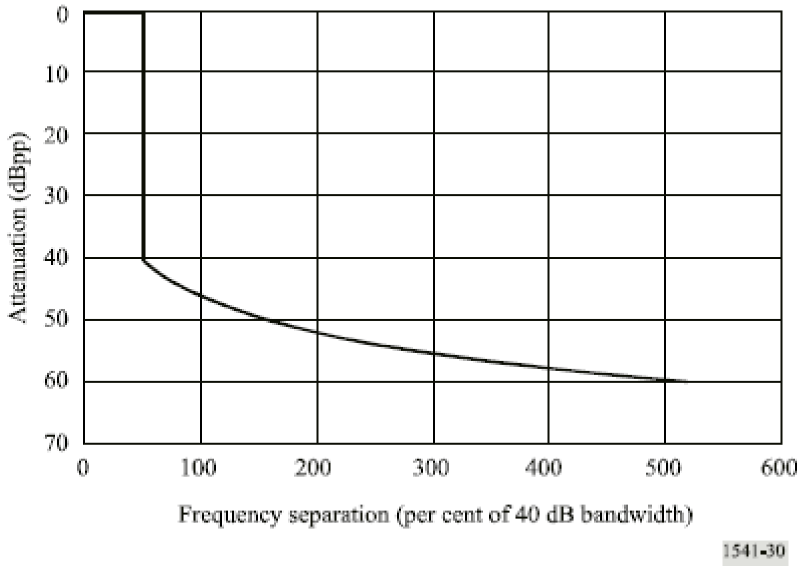
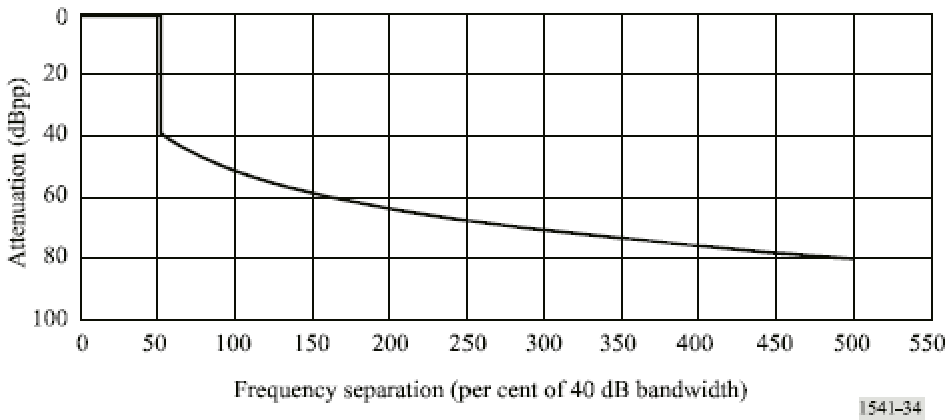


FIGURE 34

Design objective for future radar systems



The design objective mask is valid until the 2006 Radiocommunication Assembly (note that this is now to be held towards the end of 2007) at which point the design objective mask will supersede the others or other arrangements will be put in place.

M.1177-3 (2003) – Techniques for measurement of unwanted emissions of radar systems.

Includes the relationship between the reference bandwidth (as specified in regulations / recommendations) and the appropriate measurement bandwidth. Identifies the correction factor that needs to be applied to measured values in order to compare with regulatory / recommended values.

M.1179 (1995) – Procedures for determining the interference coupling mechanisms and mitigation options for systems operating in bands adjacent to and in harmonic relationship with radar stations in the radiodetermination service.

Measurement of front end overload of victim receivers due to radar and of spurious emissions. Several spectrum analyser plots provided. Mitigation techniques discussed.

M.1313-1 (2000) – Technical characteristics of maritime radionavigation radars.

Operating parameter values provided for radars in the three categories; IMO and fishing, river, and pleasure, based on operations in the 3, 5 and 9 GHz bands.

M.1314-1 (2005) – Reduction of unwanted emissions of radar systems operating above 400 MHz.

Recommends inter alia that when necessary and when possible radar output filters should be used to reduce radar unwanted emissions.

Characterises radar output devices and quantifies the harmonic and non-harmonic levels contributing to the spurious emission level. The harmonic levels are significantly higher that the non-harmonic levels but with mitigation techniques (e.g. harmonic {low pass} filter) they can be reduced below -100 dBc. It is noted that for radars employing distributed output devices (phased arrays) filtering may not be practical.

M.1460-1 (2006) – Technical and operational characteristics and protection criteria of radiodetermination radars in the 2 900-3 100 MHz band

Operating parameter values provided for three ship borne radiolocation radars, three land-based radiolocation radars and a maritime (ship borne) radionavigation radar (IMO category – including fishing).

The protection criterion for such radars is discussed in relation to the aggregate -6 dB I/N of Recommendation 1461. Results of interference susceptibility tests for three types of radar are presented and these suggest that a level of -8 to -12 dB might be more appropriate.

M.1461-1 (2003) – Procedures for determining the potential for interference between radars operating in the radiodetermination service and systems in other services.

Defines algorithms for assessing interference both due to radars and into radars. Interference caused by radars will be due to front-end overload of the victim receiver (when the main transmission of the radar is insufficiently attenuated by the selectivity of the receiver) or the unwanted emissions of the radar falling in the passband of the victim receiver. All calculations are based on the radar's peak power.

Assessment of front end overload requires knowledge of, or assumptions to be made about, the output saturation level (1 dB gain compression) and gain of the receiver front-end, and the frequency dependent rejection of the radar fundamental from any RF selectivity that may be ahead of or inherent in the RF amplifier itself.

The less severe type of interference described above as unwanted emissions of the radar falling within the passband of the victim receiver strictly speaking covers more than just that. This analysis should take account of the combined effect of the overlap between the unwanted transmitter emission spectra *and the receiver selectivity curve (in both cases these represent both in-band and out-of-band). In the case of this recommendation this is represented by the Frequency Dependent Rejection (FDR) function[108]. In other places and for different types of interference scenario this is often known as the Net Filter Discrimination (NFD).*

It is noted in the Recommendation that interference cases of radar transmitter emissions causing receiver degradation for radar mainbeam coupling have been documented. It is therefore recommended that the radar mainbeam gain be used in assessing the maximum potential for interference caused by radar transmitter emissions in the receiver IF passband. There is some ambiguity as to how this relates to the definition of spurious emissions for radars the levels of which are implicitly defined after the antenna (i.e. in terms of radiated emission levels and not at the antenna transmission line).

The Recommendation contains the statement that identifies the problem being addressed by this work: "Since many radars have high transmitter power and antenna gains, large frequency separations, guardbands, may be required to ensure compatibility". In a world of spectrum management through market mechanisms and spectrum usage rights, it is not clear where these guard bands should come from and who should be paying for them.

M.1463 (2000) – Characteristics of and protection criteria for radars operating in the radiodetermination service in the frequency band 1215 – 1400 MHz.

Operating parameter values provided for 4 typical radar systems operating at L-band and for a wind profiler radar.

M.1464-1 (2003) – Characteristics of radiolocation radars, and characteristics and protection criteria for sharing studies for aeronautical radionavigation and meteorological radars in the radiodetermination service operating in the frequency band 2700 – 2900 MHz.

Operating parameter values provided for 6 typical aeronautical radionavigation radars, 2 typical meteorological radars and 4 typical military radiolocation radars operating at S-band.

Analysis, based on measurements, of the susceptibility of these radars (excluding the military ones) to interference.

[108] Which in turn consists of the on-tune rejection (OTR) and the off-frequency rejection (OFR), the latter being frequency offset dependent.

ECC (ERC) Recommendations

CEPT/ERC/REC 74-01 (Edition of October, 2005) – Unwanted Emissions in the Spurious Domain.

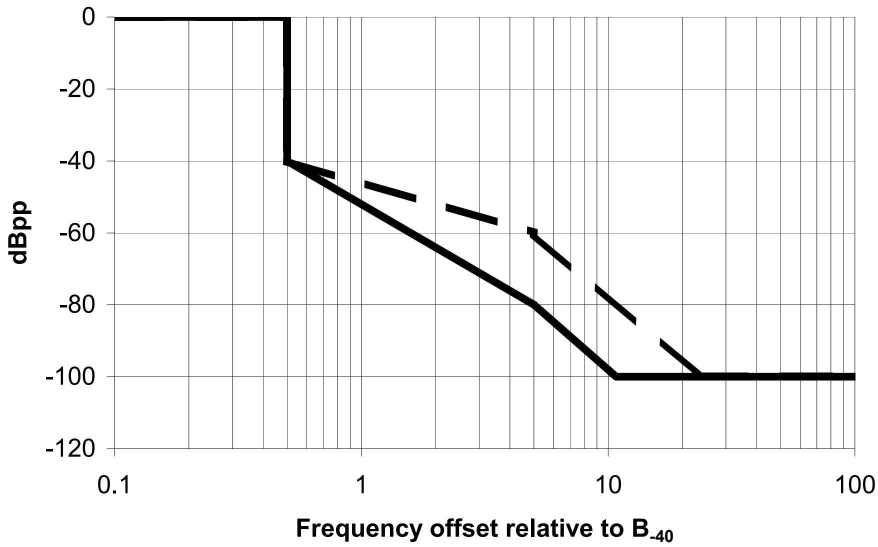
Annex 5 identifies specific requirements for radar systems in the radiodetermination service, more specifically it identifies maritime radar (shipborne and shore-based, both coast and port), aeronautical primary radar, military radar and meteorological radar (precipitation or weather radar, wind finder, wind profiler).

SPURIOUS DOMAIN EMISSIONS LIMITS FOR RADAR SYSTEMS IN THE RADIODETERMINATION SERVICE (for all transmitters installed after 1st January 2006)	
Type of Radars for radiodetermination	**Limits** Absolute levels (dBm) or Attenuation (dB) below the power supplied to the antenna port
Fixed stations (wind profiler, multi-frequency, and active array radars are excluded)	PEP in the reference bandwidth: -30 dBm or 100 dB , whichever is less stringent
All other types of radar for radiodetermination	(43 + 10·log(PEP)), or 60 dB, whichever is less stringent these limits may be expressed in absolute PEP level in the reference bandwidth as: -13 dBm, where PEP $\leq$ 50 W (10·log(PEP) - 30) dBm, where PEP $>$ 50 W
Radar systems operating in standby mode	- 57 dBm, for 9 kHz $\leq f \leq$ 1 GHz - 47 dBm, for 1 GHz $< f \leq F_{UPPER}$ - no limit within ±250% of the necessary bandwidth

For a reference radar of 1 MW, which can be assumed to be fixed, the spurious limit in absolute terms is -60 dBW (-30 dBm) or 60 dBW (90 dBm) – 100 dB = -40 dBW (-10 dBm) whichever is the less stringent. It can be seen that the 100 dB attenuation requirement is less stringent.

ECC/REC/(02)05 (revised edition of October, 2004) – Unwanted Emissions.

Annex 2 specifies requirements for primary radars. Whereas Recommendation 74-01 only deals with the spurious domain this Recommendation deals with the OOB domain as well. Two masks are shown. One is based on the 20 dB per decade roll-off and the other on the 40 dB per decade design objective (both as per ITU-R Recommendation SM.1541-2). A further construct (a 60 dB per decade roll-off) is then needed to meet the Category B spurious limit of -100 dB.



Emission masks for radars

(The dashed line shows the limit for unwanted emissions in the out-of-band domain. The solid line represents the proposed design objective)

Definitions (ITU Radio Regulations)

1.9 *radiodetermination*: The determination of the position, velocity and/or other characteristics of an object, or the obtaining of information relating to there parameters, by means of the propagation properties of radio waves.

1.10 *radionavigation*: Radiodetermination used for the purposes of navigation, including obstruction warning.

1.11 *radiolocation*: Radiodetermination used for purposes other than those of radionavigation

1.144 *out-of-band emission*: Emission on a frequency or frequencies immediately outside the necessary bandwidth which results from the modulation process, but excluding spurious emissions.

1.145 *spurious emission*: Emission on a frequency or frequencies which are outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products and frequency conversion products, but exclude out-of-band emissions.

1.146 *unwanted emissions*: Consist of spurious emissions and out-of-band emissions.

1.146A *out-of-band domain* (of an emission): The frequency range, immediately outside the necessary bandwidth but excluding the spurious domain, in which out-of-band emissions generally predominate. Out-of-band emissions, defined based on their source, occur in the out-of-band domain and, to a lesser extent, in the spurious domain. Spurious emissions likewise may occur in the out-of-band domain as well as in the spurious domain

1.146B *spurious domain* (of an emission): The frequency range beyond the out-of-band domain in which spurious emissions generally predominate.

1.147 *assigned frequency band*: The frequency band within which the emission of a station is authorized; the width of the band equals the necessary bandwidth plus twice the absolute value of the frequency tolerance. Where space stations are concerned, the assigned frequency band includes twice the maximum Doppler shift that may occur in relation to any point on the Earth' surface.

1.152 *necessary bandwidth*: For a given class of emission, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions.

1.153 *occupied bandwidth*: The width of a frequency band such that, below the lower and the upper frequency limits, the mean powers emitted are each equal to a specified percentage β/2 of the total mean power of a given emission.

Unless otherwise specified in an ITU-R Recommendation for the appropriate class of emission, the value of β/2 should be taken as 0.5%.

It follows from the above definitions that the necessary bandwidth has to fall within the relevant allocated band. It is recommended that the occupied bandwidth falls within the allocated band but it is not obligatory – if it does not, there is a risk that an operator in an adjacent allocation will complain of interference. From a spectrum efficiency point of view the optimal situation is when the necessary bandwidth and the occupied bandwidth are the same (see ITU-R Recommendation SM.328-10: Spectra and bandwidth of emissions), although this is qualified by the statement that this may not be optimum from the standpoint of spectrum usage in a sharing situation.

Appendix D: Details of the GMDSS System

Digital Selective Calling (DSC)

DSC is introduced on VHF, MF and HF maritime radios as part of the GMDSS to eliminate the need for persons on a ship or on shore to continuously listen voice radio channels. The primary aim of the DSC is to initiate ship/ship, ship/shore and shore/ship emergency communications using automatically formatted distress alerts with radiotelephones.

The IMO requires that on SOLAS vessels the DSC-equipped VHF and MF/HF radios be externally connected to a GPS receiver to ensure that accurate location information is sent to a rescue coordination centre if a distress alert is transmitted. In an emergency, one push of a button sends the Maritime Mobile Service Identity (MMSI) number of the vessel (if registered) as well as the position and nature of distress (if entered).

Another feature of the DSC radio is the ability to place private (routine/individual) ship-to-ship calls to other vessels equipped with DSC radio. To initiate a private call, the MMSI number of the radio being called is entered and the relevant VHF voice channel is selected. Radios at both ends are then switch to the chosen voice channel for subsequent communication.

DSC channels used for distress alerts are Channel 70 (156.525 MHz VHF), 2187.5 kHz (MF) and simplex HF frequencies (including 4207.5 kHz, 6312 kHz, 8414.5 kHz, 12,577 kHz and 16,804.5 kHz). Once DSC calls are sent, corresponding radiotelephone frequencies are used for voice communications. For example, in HF, these frequency include 4125 kHz, 6215 kHz, 8291 kHz, 12,290 kHz and 16,420 kHz.

The minimum standard for small craft DSC equipped radios for fixed use in Europe is ETSI EN 301 025. In addition, ITU-R Rec. M.493 provides information on DSC protocol while Rec. M.541 defines DSC operation.

Emergency Position Indicating Radio Beacons (EPIRBs)

EPIRBs are the simplest system for automated distress alert. They are required on various types of ships including ships subject to the provisions of SOLAS and commercial fishing vessels. If a vessel sinks, EPIRBs are designed to detach automatically, float-free and transmit a distress signal which will be routed to the nearest rescue coordination centre.

The most common EPIRBs operate at 406 / 121.5 MHz. In addition, 121.5 / (243) MHz EPIRBs will be terminated by 1st February 2009.

The 406 MHz EPIRB is designed to operate with a satellite in a distress situation only. No other communications is allowed on this channel. The 406 MHz EPIRBs may also have an integral GPS receiver. The EPIRB distress signal is encoded with the vessel’s identity. It is therefore necessary that vessels are registered in the database accessible to search and rescue authorities. Most 406 MHz EPIRBs also transmit a signal on 121.5 MHz which enables search and rescue vessels to obtain a radio bearing of the EPIRB (for homing).

EPIRB devices are detectable by COSPAS / SARSAT polar orbiting satellites as well as geostationary satellites including GOES and INSAT series.

NAVTEX

NAVTEX is an international automated direct-printing service, broadcast on 518 kHz, for instantly distributing maritime navigational warnings, weather forecasts and warnings, search and rescue notices and similar information to ships. A small printing radio receiver is used in a ship for NAVTEX messages. ITU Recs M.540 and M.476 provide information on the NAVTEX system. A further frequency is available in the HF band for use in tropical regions.

A national system is broadcast on 490 kHz and one of the UK stations includes transmissions in French.

Inmarsat

Three types of Inmarsat ship Earth station terminals are recognised by the GMDSS. These are Inmarsat B, C and F77 terminals. The Inmarsat B and F77 provide telephone, telex and data services, including a distress priority telephone and telex service to and from rescue coordination centres. The Inmarsat C provides store-and-forward data, e-mail messaging, the capability for sending pre-formatted distress messages to rescue coordination centres and the Inmarsat C SafetyNET service.

The Inmarsat C SafetyNET is a satellite-based worldwide maritime safety information broadcast service for vessels on high seas. The SafetyNET system works similarly to NAVTEX in areas outside NAVTEX coverage. It operates on a designated satellite channel at 1.5 GHz with an effective information transmission rate of 600 bits per second.

Inmarsat C equipment is relatively small and lightweight, and costs much less than an Inmarsat B or F77 which require relatively large gyro-stabilized antennas. The SOLAS convention rules require that Inmarsat C equipment have an integral satellite navigation receiver or be externally connected to a satellite navigation receiver to ensure accurate location information to be sent to a rescue coordination centre if a distress alert is transmitted.

Search and Rescue Radar Transponders (SARTs)

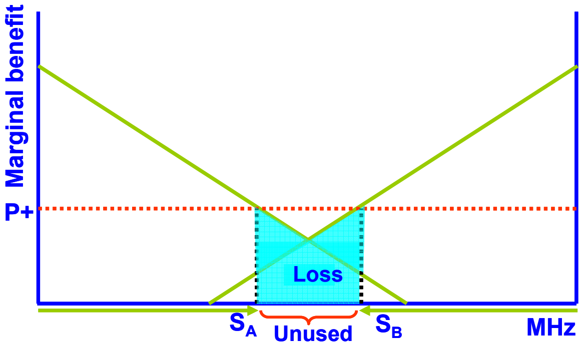
The GMDSS installation on ships includes one or more SARTs. A SART may be triggered by any X-Band (3-cm) radar within a range of approximately ten miles. Each radar pulse received by a SART causes it to transmit a response which is swept repetitively across the complete radar frequency band. When interrogated, it first sweeps rapidly (0.4 μsec) through the band before beginning a relatively slow sweep (7.5 μsec) through the band back to the starting frequency. This process is repeated for a total of twelve complete cycles. At some point in each sweep, the SART frequency will match that of the interrogating radar and be within the pass band of the radar receiver. If the SART is within range, the frequency match during each of the 12 slow sweeps will produce a response on the radar display, thus a line of 12 dots equally spaced by about 0.64 nautical miles will be shown.

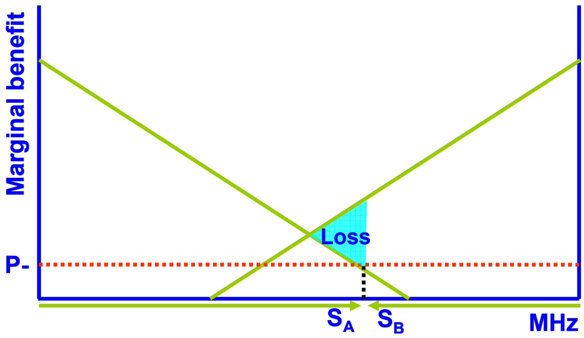
The radar bandwidth is normally matched to the radar pulse length and is usually switched with the range scale and the associated pulse length. Narrow bandwidths of 3 – 5 MHz are used with long pulses on long range scales and wide bandwidths of 10 – 25 MHz with short pulses on short ranges.

Appendix E: Loss functions

This Appendix relates specifically to how to set a radio spectrum price given an uncertain estimate of opportunity cost and an assumption about the nature of the loss function from setting prices too low versus too high. The approach can be generalised to (almost) any policy problem where there is a risk of unintended consequences and the decision is to some extent "sticky" (rapid iteration to an optimum would eliminate the problem of unintended consequences, as it does in an ideal market, thus "stickiness" is required). For example, a similar approach has been proposed in relation to setting the assumed cost of capital under a price control.[109]

E.1 Symmetric case





The losses for prices above and below the optimum are illustrated above.

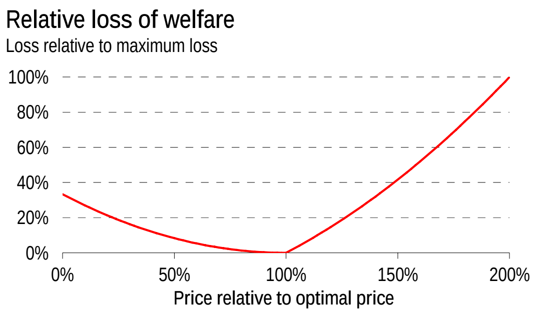
For prices above the optimum (up to the point where spectrum demand is reduced to zero) the area of lost welfare is given by:

$Area = \Delta Q / \Delta P.(P - P^*).(P + P^*)$, where $\Delta Q / \Delta P$ is the inverse slope of the demand curves.

For prices below the optimum the area of lost welfare is given by:

$$Area = \Delta Q / \Delta P.(P - P^*)^2$$

These relationship between price relative to the (unknown) optimal price based on actual opportunity cost and the welfare loss (based on the above formulas) is shown below for linear demand curves with equal slope. The losses rise more steeply for prices above the optimum.



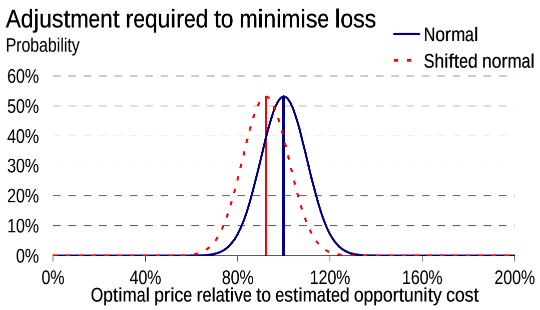
Source: Indepen calculations

[109] Stephen Wright, Robin Mason and David Miles. 2003. "A Study into Certain Aspects of the Cost of Capital for Regulated Utilities in the U.K." http://www.ofcom.org.uk/static/archive/Oftel/publications/pricing/2003/cofk0203.htm

Combining the asymmetric function plotted above with a distribution for opportunity cost, it is possible to iteratively solve for the optimal price taking account of the risks of setting the price too high versus too low. The solution depends, as one might expect, on the extent of uncertainty for the opportunity cost estimate.

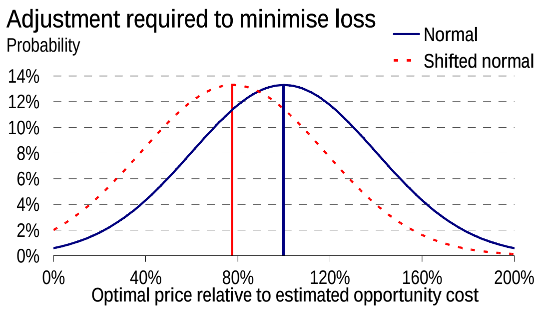
The following figures show the optimal shift in AIP relative to the opportunity cost estimate in order to minimise the loss of welfare from upside and downside errors in setting AIP i.e. the price that maximises expected surplus. Assuming a normal distribution for opportunity cost with a ratio of the standard deviation to the mean of 10 per cent and 40 per cent respectively, for relative slopes of demand of 1:1, the shift required in order to set an optimal price relative to estimated opportunity cost is shown.

Equal slopes, σ/μ ratio = 0.1, shift = -11.8%



Source: Indepen calculations

Equal slopes, σ/μ ratio = 0.4, shift = -38.3%

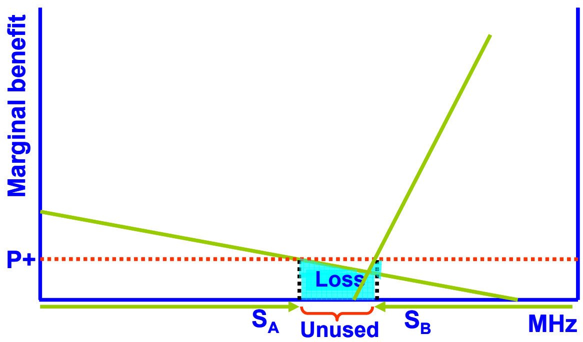


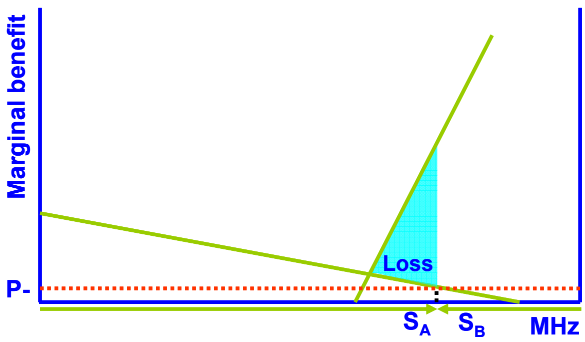
Source: Indepen calculations

In the left hand figure the optimal shift is negative 11.8 per cent.

In the right hand figure the optimal shift is larger, at negative 38.3 per cent.

E.2 Asymmetric case





For prices above the optimum and below the level at which the lower demand curve meets the vertical axis, the area of lost welfare is given by:

$$Area = (P - P^*).(\Delta Q_1 / \Delta P_1 + \Delta Q_2 / \Delta P_2)(P^* + P)/2$$

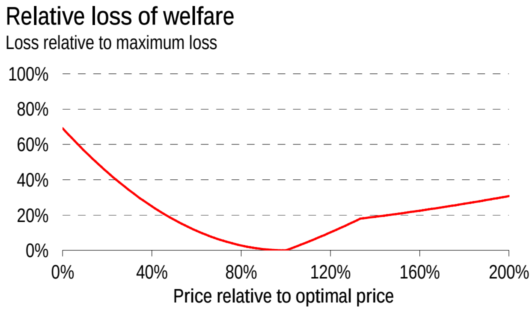
For prices above the level at which the lower demand curve meets the vertical axis, only one area representing further losses continues to increase and the additional area of lost welfare is given by:

$$Area = (P - P^*).(\Delta Q_2 / \Delta P_2)(P^* + (P - P^*))/2$$

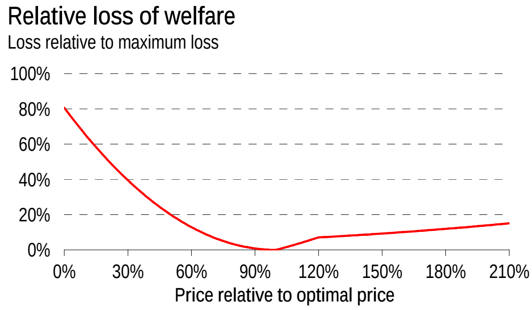
For prices below the optimum the area of lost welfare is given by:

$$Area = (\Delta Q_1 / \Delta P_1)^2.(P - P^*)^2(\Delta P_1 / \Delta Q_1 + \Delta P_2 / \Delta Q_2)/2$$

These relationship between price relative to the (unknown) optimal price based on actual opportunity cost and the welfare loss (based on the above formulas) is shown below. The losses rise more steeply for prices above the optimum, and may continue well beyond the 200 per cent point shown in the figure, depending on the relative slopes. Two loss functions are shown, the left hand figure for a demand slope ratio of 1:3 and the right hand figure for a slope ratio of 1:5 (assuming an excess initial allocation to the demand with lower slope relative to the optimum).



Source: Indepen calculations

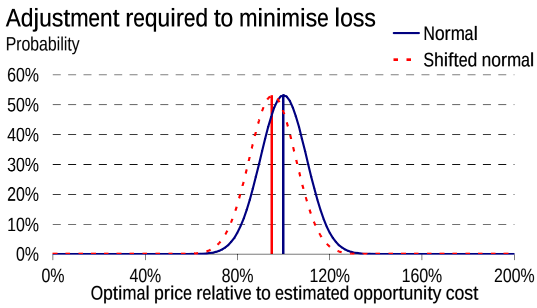


Source: Indepen calculations

Combining the asymmetric function plotted above with a distribution for opportunity cost, it is possible to iteratively solve for the optimal price taking account of the risks of setting the price too high versus too low. The solution depends, as one might expect, on the extent of uncertainty for the opportunity cost estimate.

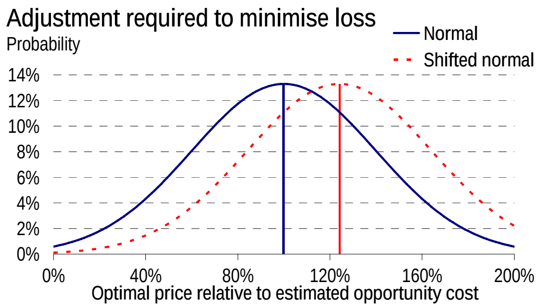
The following figures show the optimal shift in AIP relative to the opportunity cost estimate in order to minimise the loss of welfare from upside and downside errors in setting AIP i.e. the price that maximises expected surplus. Assuming a normal distribution for opportunity cost with a ratio of the standard deviation to the mean of 10 per cent and 40 per cent respectively, for relative slopes of demand of 5:1, the shift required in order to set an optimal price relative to estimated opportunity cost is shown.

Slope ratio 5:1, σ/μ ratio = 0.1, shift = -4.6%



Source: Indepen calculations

Slope ratio 5:1, σ/μ ratio = 0.4, shift = +21.7%



Source: Indepen calculations

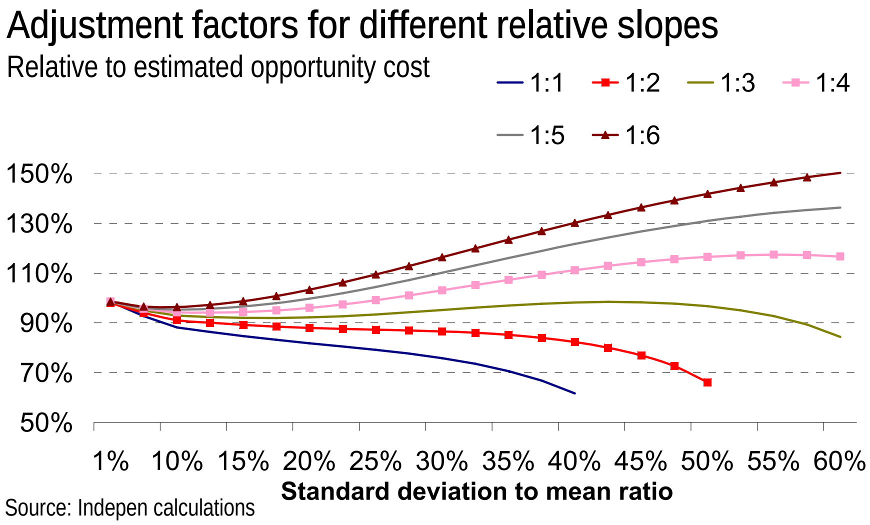
In the left hand figure the optimal shift is negative 4.6 per cent. This is smaller than the optimal shift in the symmetric case considered in Section E.1 of -11.8 per cent.

In the right hand figure the optimal shift is now positive 21.7 per cent. This is of appositive sign to optimal shift in the symmetric case considered in Section E.1. where the shift was -38.3 per cent. For sufficiently large asymmetry and uncertainty AIP should in principle therefore be marked-up compared to a best estimate of opportunity cost.

E.3 Generalised results

Solving for a range of uncertainty over the estimate of opportunity cost, and a range of relative slopes of demand curves, yields the following general result in terms of the optimal shift in price relative to the estimate of opportunity cost.

The horizontal axis shows the level of uncertainty in the opportunity cost estimate in terms of the ratio of the standard deviation to mean ratio (assuming the distribution of opportunity cost is normal and truncated at zero). The vertical axis shows the increase or decrease of AIP relative to the opportunity cost estimate. Each of the curves shows the relationship between uncertainty and the price adjustment factor for a given ratio of slope of two linear demand curves. All the curves shown are for a situation in which the slope of the demand curve with a sub-optimal level of spectrum is greater than or equal to that for the demand which currently has excess spectrum.



Source: Indepen calculations

A number of points are apparent:

- As the level of uncertainty in the opportunity cost estimate falls to zero the required adjustment falls to zero i.e. if opportunity cost were known precisely then there is no risk of unintended consequences and therefore no adjustment is required.
- For the bottom curve, for demand curves with equal slopes (1:1), the adjustment is always downwards and reaches a 40 per cent downward adjustment on opportunity cost with a standard deviation to mean ratio of 40 per cent.
- For demand curve slope ratios greater than around 1:3 the optimal adjustment is upward with sufficient levels of uncertainty over the opportunity cost estimate. This reflects the fact that a more valuable use is restricted or denied spectrum, and the cost of this circumstance persisting if prices are set too low can exceed the cost involved in setting prices too high and leaving some spectrum unused.
- For ratios of less than 1:1 (not shown) the optimal downward adjustment increases relative to the 1:1 case. This would correspond to a situation in which the demand curve for the allocation which currently had excess spectrum (relative to an optimal allocation) had a lower slope than that for the potential alternative use.

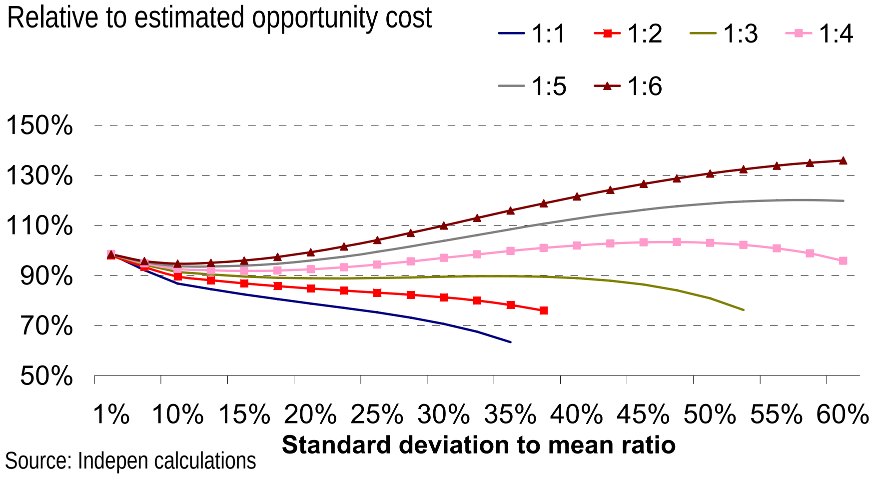
With trading at least some of the inefficiency might be eliminated via trade, but the social loss would remain if AIP were set too high. A more conservative approach to pricing is therefore appropriate with trading since the asymmetry of losses from setting prices a little too high versus a little too low is more pronounced than in the absence of trading.

The impact of possible future spectrum trading on the optimal level of AIP depends on assumptions about the efficiency of trading. In the limit, if trading and the incentives it provides to different institutions is a perfect substitute for spectrum pricing, then the optimal adjustment factors would converge towards -100% i.e. the downside risk of implementing pricing would be large relative to the anticipated negligible benefits above and beyond those achieved via trading. However, in practice trading will not achieve the full potential efficiency if markets are thin (which appears likely based on international experience) and due to the fact that the potential to realise value from spectrum trading may be a less powerful incentive to economise on use than having to pay for spectrum for non-commercial agencies. By introducing a direct cost for spectrum holdings AIP is anticipated to introduce strong incentives for change in the use of publicly held spectrum.

The following figure illustrates the results of the recalculation assuming 50 per cent trading efficiency. Partial trading reduces the downside cost of setting AIP too low, and therefore results in a downward movement in the magnitude of all of the adjustment curves. Hence, the introduction of trading for spectrum subject to AIP implies that greater conservatism in setting AIP is optimal.

Adjustment factors with 50% efficient trading

Relative to estimated opportunity cost



Source: Indepen calculations

Appendix F: Applying AIP to out of band emissions from radars

This Appendix discusses options for pricing out of band emissions from radars. The following discussion is in terms of spectrum masks associated with individual transmitters. In practical terms, and when the time comes to implement real numbers, masks can be readily transformed into area field strength levels which is the currently preferred format for Spectrum Usage Rights (SURs).

Definitions

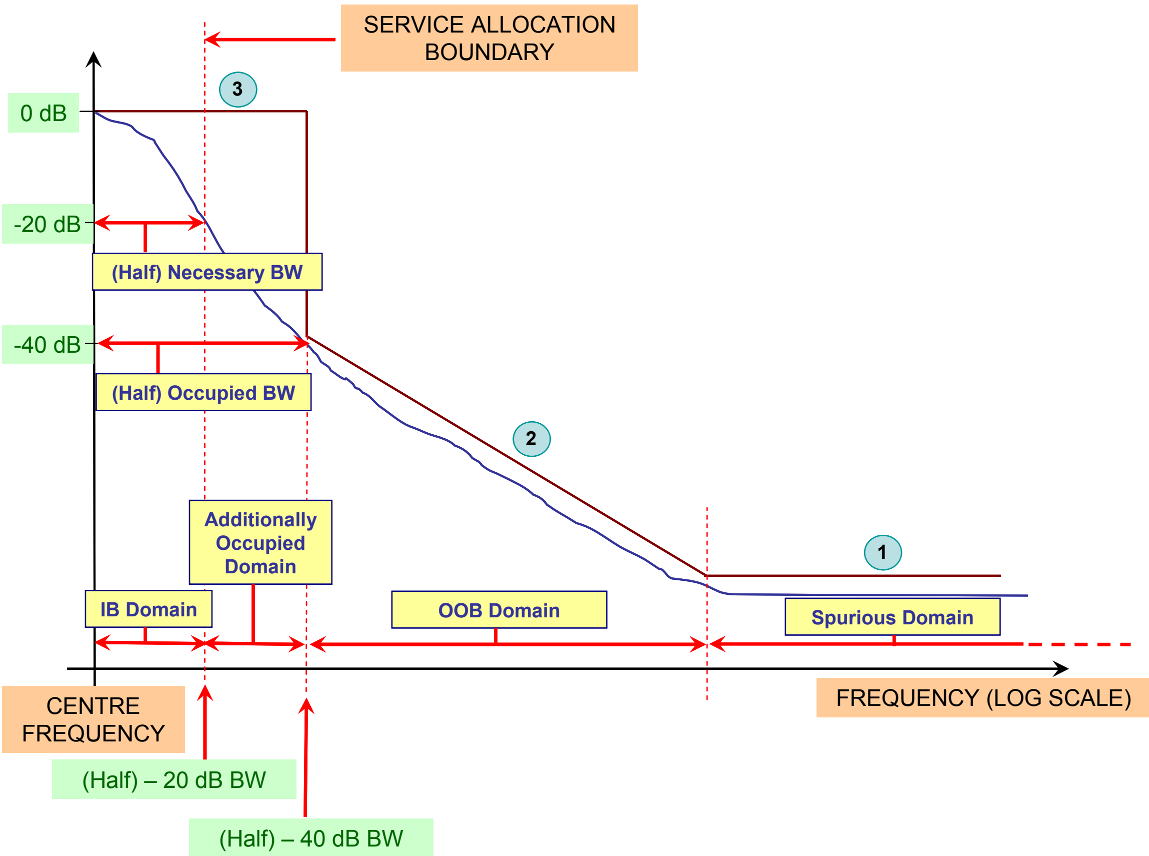


Figure 1 – Radar emission domains

In implementing AIP with respect to the unwanted emissions generated by radars it is firstly necessary to recall how these unwanted emissions are currently specified and secondly to examine some of the terms used in defining them.

In the first instance masks are generally specified in three parts (as represented by the brown line designated by the sections 1, 2 and 3 in the diagram above):

A flat power level to control spurious emissions which are well removed in frequency from the main transmission. There is a relatively lax and obligatory power level specified for these in the Radio Regulations. However, ITU-R and European recommendations propose lower levels.

A power level decreasing away from the main transmission, or more precisely from the -40 dB point, to control closer in unwanted emissions. There are no obligatory power levels set for these emissions.

ITU-R and European recommendations propose various levels and steepness of slope, in some cases two different steepness of slopes one after the other.

A flat power level at 0 dB representing the power level of the main transmission against which all other emissions are referenced. By default this extends to the -40 dB point where the segment of the mask immediately above starts to be defined. It will be seen below that there are some difficulties with this 0 dB region of the mask when it is related to the various definitions of bandwidth outlined below.

The various emission power levels are delineated with respect to the frequency scale using the following definitions:

- the **necessary bandwidth** (which is obliged by the Radio Regulations to reside within the service allocation) is generally specified for radars by the -20 dB bandwidth
- the **occupied bandwidth** (which is recommended to fall within the service allocation but for which it is not obligatory to do so)[110] is not defined for radars but by implication might reasonably be assumed to be specified by the -40 dB bandwidth as all the unwanted emission spectrum masks effectively start at this point.
- the **out-of-band domain** stretches in frequency from 50%[111] of the -40 dB bandwidth to the point at which the falling level meets the constant spurious level. This latter point depends on the slope(s) of the OOB mask and the level at which the spurious is set.
- the **spurious domain** exists beyond the latter point defined immediately above. Depending on slopes and the spurious level (which are defined variously by the ITU-R and European recommendations) this will be in the range 500 to 2320% of the -40 dB bandwidth.

In addition we can define two further domains derived from the bandwidth definitions above:

- the **in-band domain** might reasonably be defined by the necessary bandwidth.
- the **additionally occupied domain** could be defined by the area between the necessary bandwidth and the occupied bandwidth. The various ITU-R / ECC masks indicate that the allowable level in this domain is the same as the in-band level. In practice, the level falls away from -20 dB towards -40 dB.

In all there are four domains that need to be addressed when applying AIP to incentivise efficient use of the spectrum both within a service allocation (e.g. lower power and/or narrower band technologies) and with respect to adjacent allocations (e.g. assigning radars operating in populous areas towards the middle of the allocation and/or assigning narrowband radars at the edge of the allocation).

In the first instance we will address the additionally occupied domain as this is the least well defined in terms of existing emission masks.

Additionally occupied domain

If radar assignments are made such that it is only the necessary bandwidth that resides within the service allocation, the emissions in the additionally occupied domain could cause significant disruption to other users in the immediately adjacent band.

There are two options to address these emissions in the adjacent band:

[110] There is at least one radar assignment at the edge of an allocation for which the necessary bandwidth falls within the allocation but the occupied bandwidth does not.

[111] This reflects the other half falling on the other side of the centre frequency reference point.

Option 1: Extend the OOB mask between the -20 dB and -40 dB points. The slope and form of the mask between these two points would need to be determined by Ofcom if this option were to be adopted. The additionally occupied domain then becomes part of the out-of-band domain as addressed below.

Option 2: Ensure that assignments are made within the service allocation based on the -40dB bandwidth rather than the -20 dB bandwidth (necessary bandwidth). The additionally occupied domain then becomes part of the in-band domain as addressed below.

Noting that the emission levels and the frequency offsets at which these levels occur are all relative to the main characteristics of the radar transmission (i.e. transmitter power and pulse shape), neither of which are of any real interest to a victim receiver in an adjacent frequency band, a third option, which is more in line with technology neutral spectrum usage rights, presents itself, namely:

Option 3: Identify an absolute level of emission at the service allocation edge (and an associated mask covering OOB and spurious in the adjacent band specified in absolute terms – addressed further below). This means the protection of adjacent services then becomes the responsibility of radar planners rather than victim receivers not knowing whether there will be a low power or high power, narrowband or wideband radar immediately adjacent.

Option 1 effectively represents the current situation in practice but does at least formalise the power level in the additionally occupied domain rather than assuming that the level is the same as the main transmission. Unwanted emission levels are imprecise as they remain relative to the main emission level. In practice this option is a formality and is unlikely to have an impact on improving spectrum usage.

Option 2 effectively places the additionally occupied domain within the service allocation of the spectrum user generating unwanted emissions in this domain. With reference to Figure 1 this moves the service allocation boundary so that it coincides with the vertical part of the brown mask. This provides additional protection to the spectrum user in the adjacent band. The onus is on the radar user to provide this additional protection at the expense of using more bandwidth within their service allocation. However, unwanted emission levels once again are imprecise as they remain relative to the main emission level.

Option 3 removes the uncertainty for an adjacent band user that arises from the fact that radar masks are currently specified in relative terms. As is always the case in specifying spectrum usage rights in absolute levels there is the pure option of specifying a single level that has to be met by any unwanted emission (cliff edge option), or a sloping level (for OOB) followed by a flat level (more akin to current masks but in absolute terms). The latter implies at least some impact on adjacent band users while the former, depending on the level at which it is set, rather less impact. The former would also generally encourage narrowband rather than wideband assignments at the allocation edge leading to a potential improvement in spectrum efficiency.

These options are shown in the diagram below which shows, in schematic rather than quantitative form, the trade-off between the amount of spectrum that would need to be assigned versus the impact on adjacent spectrum users.

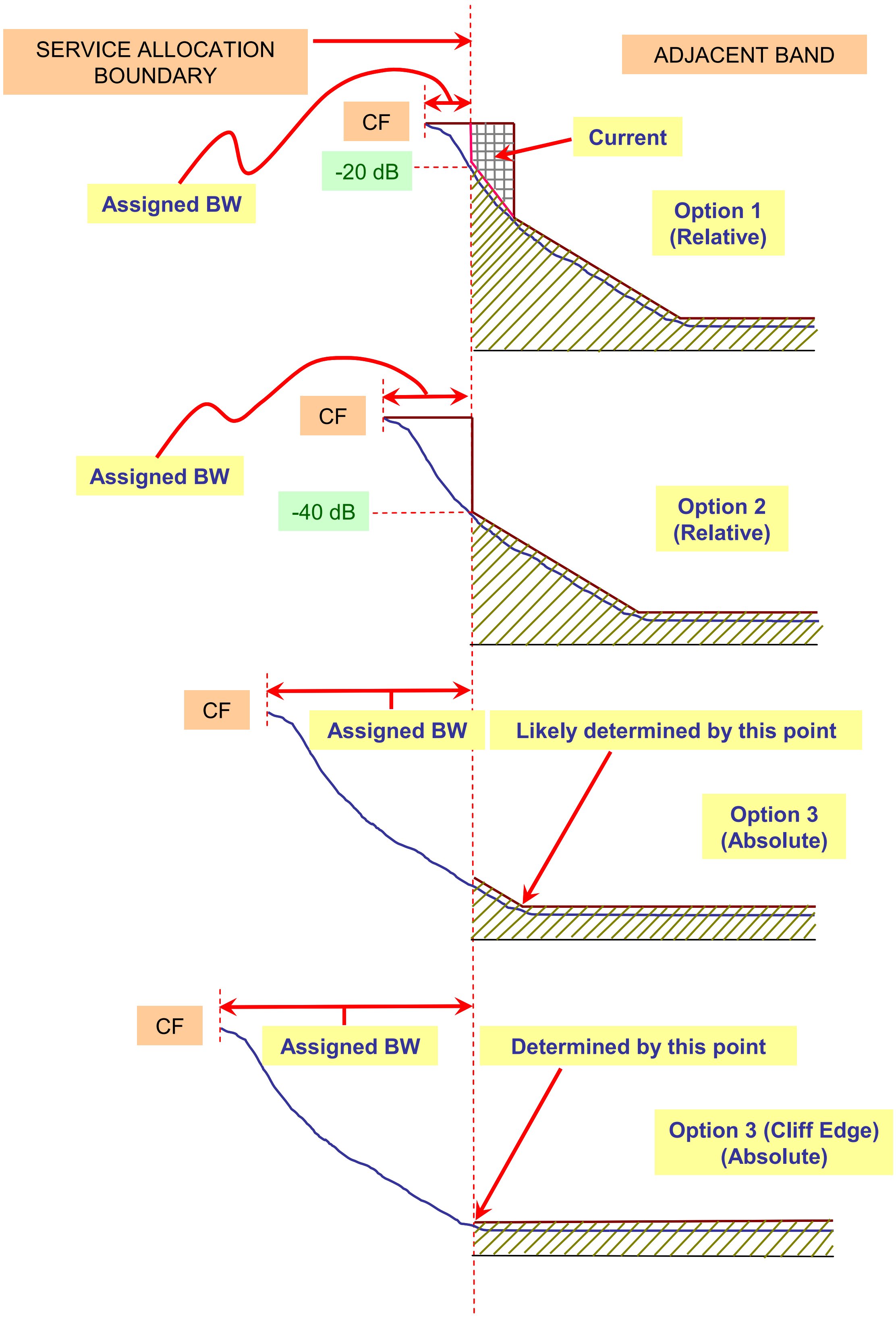


Figure 2 – Impact of spectrum mask options

(CF = centre frequency)

In the light of the general move towards technology neutral spectrum usage rights, the preferred solution is for a single absolute out of allocation level to be specified (i.e. the cliff edge option). This level then effectively defines the necessary bandwidth of a transmission (which has to reside within the service allocation). Given all other things being equal this means that a high power radar will have a larger necessary bandwidth than a low power one and the impact of both will be the same on adjacent spectrum users. This is contrary to the existing situation where a high power and a low power radar would have the same necessary bandwidth but would have a different impact on adjacent channel users.

In-band domain

It can be noted that in the aeronautical case there is little frequency reuse and in the maritime case there is extensive reuse (essentially maritime radars operate on a common frequency). This difference in approach results from very different operational requirements (e.g. resolution and distance) and circumstances when comparing the two sectors. The degree of frequency reuse does however need to be reflected in the levels at which AIP is to be set.

In terms of licensing and the application of AIP there are two situations:

- A national licence – In this instance it is simply a case of applying AIP in relation to the bandwidth of the spectrum attributable to the licence with additional AIP relating to the impact of the OOB level specified in absolute terms (see next section). The only requirement for applying a limit to the in-band power is to meet international obligations. In this regard there is in any case an incentive to use the minimum power necessary in order to cause as few coordination problems with other countries thereby maximising utilisation of the spectrum that has been licensed. The holder of the national licence will also ensure that the band is used efficiently with respect to interference between the users of the band.
- Individual licences – In this case it is a question of how much spectrum "space" a transmission uses. As before, there is the out-of-band impact that is addressed in the next section but here we will address the in-band power. The spectrum "space" should have the dimensions of bandwidth and geographic area and can be modified according to population covered and the potential for frequency reuse within the geographic area covered. The bandwidth will be determined by the assigned bandwidth, as discussed in the previous section, and the geographic area will be determined by the in-band power, potentially modified by terrain and other mitigating factors.

Out-of-band domain and spurious domain

The earlier discussion addressing the additional occupied domain has already identified that there are a number of options for specifying unwanted emission limits ranging from effectively the status quo, where levels are relative, to a single adjacent allocation level of unwanted emissions (the cliff edge option) expressed in absolute terms. These options apply as much to the out-of-band and spurious domains addressed here as they do to the additionally occupied domain addressed earlier. In the case of the cliff edge option the single value that would be specified applies to all three domains as a whole.

Whichever option is chosen it will be necessary to associate a different level of AIP with a number of specified unwanted emission limits in order to incentivise improved unwanted emission performance and thereby lessen the impact on adjacent spectrum users.

If existing masks are to be retained then it will be necessary to associate an AIP level in terms of the mask that is met and the power of the transmitter since the masks are relative and both these pieces of information are therefore required in order to determine spectrum occupancy. In this instance occupancy means the geographic area and bandwidth over which the unwanted emissions have an adverse impact. For example this is represented by the area under the curves of Figure 4 in Appendix C as reproduced below:

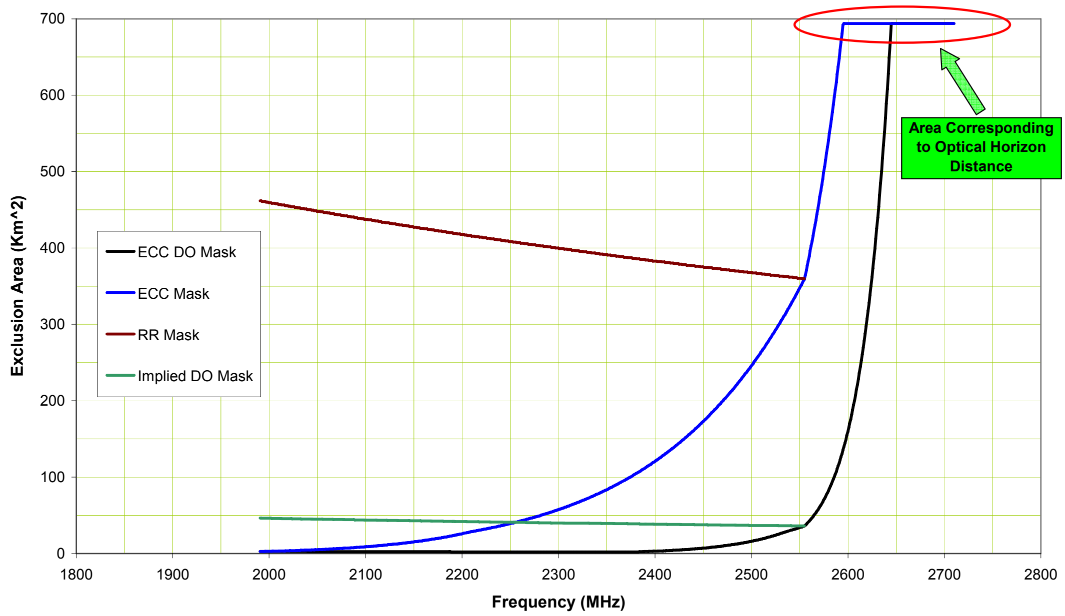


Figure 3 – OOB spectrum occupancy

(Same as Figure 4 / Appendix C)

Figure 3 is based on a reference radar having a 1 MW transmitter and using a 1 µS pulse with a 40 nS rise time. Increasing the transmitter power will move the curves upwards (i.e. increase the exclusion area at a given frequency) and reducing the transmitter power would have the converse effect. Reducing the pulse length and/or rise time would increase the -40dB bandwidth of the emission and consequently move the curves to the left (i.e. increase the exclusion area at a given frequency in most cases) and increasing the pulse length and/or rise time would have the converse effect.

For the purposes of illustration and using the unwanted emission performance of the reference radar according to the four different masks we can determine the area under the curves (masks) to be approximately as follows[112]:

1. ECC + RR: Slow roll-off to spurious level in the Radio Regulations

   320,000 MHz km^2
2. ECC: Slow followed by very fast roll-off to European spurious level

   160,000 MHz km^2
3. ECC DO + Imp DO: Fast roll-off to spurious objective in ITU-R Recommendation

   90,000 MHz km^2
4. ECC DO: Fast followed by very fast roll-off to European spurious level

   70,000 MHz km^2

[112] This assumes that the bandwidth area assessment is made between 2000 MHz and 2700 MHz, the latter being the edge of the allocation. The radar assignment is assumed to be at 2710 MHz. The optical horizon has been assumed to be the limiting case for convenience. In practice the impact of radars is likely to go beyond this depending on many factors including the terrain.

The above options are based on masks that already exist within ITU-R and CEPT. There is of course every possibility of defining tighter masks which would have the benefit of attracting a lower AIP.

As noted for the in-band case, these areas (or more precisely area x bandwidth values) may be modified according to the population encompassed, noting that there is the complication of the area varying with frequency offset.

It can be further noted that the method used to determine the area should be the same as that used to determine the area "used" by the in-band emission (the main transmission) for consistency. The most important aspect of this common requirement is that the field strength / PFD criterion to be met is the same. This criterion is directly related to alternative use of the band. The difference between the in-band and out-of-band cases will be the power levels used to determine the area at a given frequency.

It has to be remembered that the masks themselves are specified in terms of the -40 dB bandwidth of an emission and this in turn is determined by factors such as the pulse length and the pulse rise and fall times. Furthermore, the masks are specified in relative terms (i.e. with respect to the power of the emission). This means that there is an infinite number of possible masks (expressed in absolute terms) and begs the question as to what exactly a radar should be judged against and/or what should a radar operator have to declare to show what performance requirement the radar is or is not meeting for the purposes of the application of AIP. It seems there are two options here:

- Operators to declare MHz km² based on a field strength / PFD criterion to be met
- Operators to declare transmitter power, -40 dB bandwidth and the relevant mask met (the above – i.e. MHz km² – can then be calculated independently)

The need to provide this information would not be necessary if the unwanted emission requirement were specified in absolute terms, whether as a single value or as a more complicated mask. The radar operator would then simply declare which (absolute) mask is met and AIP applied accordingly.

The discussion so far has been in terms of individual radars. For a national licence it is difficult to apply the same method as a natural assumption might be that a radar could be generating unwanted emissions in an adjacent band from any location in the UK. It would then follow that significant parts of the adjacent band would be unusable across the whole UK. This would clearly not be the case as there would not be a continuum of co-channel radars across the whole UK. Depending on the operational requirements the radar systems have to satisfy there may be a few (e.g. aeronautical) or many (e.g. maritime) radars operating on the same frequency. It is therefore difficult to estimate how much spectrum in an adjacent band would be restricted or denied use by another service, as calculated by aggregating results from using the individual method for multiple locations

This argument supports one of the earlier options discussed for the additionally occupied domain, namely the use of a single unwanted emission level that has to be satisfied by the additionally occupied domain, the out-of-band domain and the spurious domain. This level would be set so as to afford protection to a typical service in an adjacent band and it would then be up to the radar planners to place the radar centre frequency a sufficient distance from the allocation edge in order to afford the specified protection. In this instance there may be no AIP charged for the unwanted emissions falling in the adjacent band as the protection is good enough for services in the adjacent band to operate satisfactorily. However the incentive to improve radar unwanted emissions derives from the fact that the radar assigned bandwidth is determined by meeting the unwanted emission level[113] and may therefore be significant resulting in an increased AIP charge.

[113] The assigned bandwidth would be twice the amount of spectrum between the centre frequency and the band edge at which point the unwanted emission level has to be met.

Recommendations

It is recommended that AIP is related to the assigned bandwidth of a radar emission and its transmitter power potentially weighted by population density in the area. In association with this it is proposed that there should be a single absolute value defining allowable unwanted emissions falling in the adjacent allocation. No AIP charge would be directly attributed to the unwanted emissions falling in the adjacent band. However, there would be an indirect charge through the AIP associated with the assigned bandwidth as this is determined by the placement of the radar centre frequency in order to satisfy the unwanted emission requirement.

However, recognising that the recommended format for applying AIP to radars (i.e. single absolute OOB level) may be difficult with respect to existing installations, and at the same time recognising that some control should be exerted over radar unwanted emissions, a transitional solution will have to be considered. This would have to be based on retaining the format of existing spectrum masks (expressed in relative rather than absolute terms). Different levels of AIP would then be applied according to transmitter power, -40 dB bandwidth and the mask declared to be met by the radar. The level of AIP relating to out of band emissions can be calculated from the MHz km² affected (i.e. not meeting a given field strength criterion). In addition, the -20 dB bandwidth will be required in order to determine the AIP relating to the main transmission (i.e. from the necessary bandwidth).

This approach, while in line with current definitions, is to some extent inconsistent as it only takes account of the main transmission (within the -20 dB bandwidth, i.e. the necessary bandwidth) and unwanted emissions beyond the -40 dB bandwidth. The region between the -20 dB and -40 dB bandwidths is not taken into account. This region should be taken into account by either including it as part of the main transmission (i.e. basing the assigned bandwidth on the -40 dB (occupied) bandwidth rather than the -20 dB (necessary) bandwidth), or by extending the unwanted emission mask upwards towards the main transmission as currently defined (i.e. from the -40 dB point to the -20 dB point).

In summary therefore, and with reference to the options given earlier in Figure 2, we are recommending that Option 3 with an absolute cliff edge mask be applied (bottom of Figure 2). AIP would then be related solely to the in-band assigned bandwidth. This effectively moves radars away from the band edge and users in the adjacent band suffer no interference as the OOB unwanted emission level for the radars is set at an acceptable absolute level for other users.

A transitional approach could use existing masks (see schematic at the top of Figure 2) but in this instance AIP would be related to both the in-band assigned bandwidth and the impact of unwanted emissions outside the band. This could be refined to accommodate the ill-defined region between the -20 dB and -40 dB points.

Appendix G: Increasing the spectrum efficiency of aeronautical radars

There are two aspects here; firstly, the efficiency with which radar assignments can be fitted into a piece of spectrum and secondly, once the assignments have been made, what effect do the OOB emissions (especially from radar assignments at the edge of the band) have on other spectrum users in the adjacent band and to what degree can these OOB emissions be controlled. At the same time it is necessary to protect radar receivers from interference that would degrade the overall system performance (e.g. reduce the probability of detection).

The QinetiQ report[114] addresses some of these issues and provides a cost-benefit analysis with respect to a number of options. The options are:

- The use of filter technology (fixed frequency inductive-iris band-pass filters) to reduce the bandwidth occupied to the necessary bandwidth
- The use of different waveform techniques to the systems within a band to ensure minimum interference between radar systems
- The use of filter technology and waveform techniques combined
- The use of ultra narrow band (continuous wave) transmissions which only use 10% of the spectrum required by pulsed radars

Application of these options to magnetron radars would release the amounts of spectrum shown in the table below:

	Band 1 (L band)	**Band 2 (S band)**	**Band 3 (Ku band)**
Frequency range (GHz)	1.240 – 1.350	2.700 – 3.100	15.40 – 15.70
Current bandwidth (MHz)	110	400	300
Number of radars	11	36 (civil) + 84 (military)	3
Released by filters (MHz)	70	105	0
Released by waveforms (MHz)	40	200	200[(2)]
Released by filters and waveforms (MHz)	70	200	200[(2)]

Table 1 – Spectrum released by the application of various technologies

The costs of retrofitting existing radars for each of the options are shown in the table below. One-off costs are amortised over 10 units (3 units for Ku-band) and the costs are dominated by outage time – 10 days at £100k per day for L- and S-band, and 2 days for Ku-band. [115]

[114] Project AY4490 – A study into techniques for improving radar spectrum utilisation. QINETIQ/S&E/SPS/CR040434/1.1, 19th April 2004.

[115] The Interconnect report indicates that the application of filters would cost £20 – 100k per installation, an order of magnitude less than the QinetiQ estimates. It is known that the QinetiQ estimates are dominated by the cost of outage time so it is quite possible that the Interconnect costs are more hardware based. 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. Interconnect et al. Ofcom contract AY4620. 15 June 2004.

Table 2 – Total costs for implementing the technologies

	Band 1	Band 2[1]	Band 3
Filters (£M)	11.1	36.4	-
Waveforms (£M)	11.6	37.9	0.8[2]
Filters and waveforms (£M)	11.7	38.2	0.8[2]
Ultra narrow band (£M)	286 – 2816	936 – 9216	-
For the three options involving filters / waveforms a replacement cost would be (£M)	*166 – 606*	*542 - 1982*	-

Table 3 – Cost per MHz to release the spectrum

	Band 1	Band 2[1]	Band 3
Filters (£M/MHz)	0.16	0.35	-
Waveforms (£M/MHz)	0.29	0.19	0.004[2]
Filters and waveforms (£M/MHz)	0.17	0.19	0.004[2]
Ultra narrow band (£M/MHz)	2.86 – 28.2	4.68 – 46.08	-

Notes applicable to Tables 1, 2 & 3:

(1) Based on the cost of modifying the 36 civil radar systems only.

(2) Same because filters are not applicable for Band 3.

The various approaches above deal with the idea of making the radar assignments themselves more efficient. The second issue concerns the associated effect of OOB emissions falling in adjacent spectrum which is available to other users.

Table 4 – OOB suppression

	OOB benefit	Cost per radar (£M)	Comments
Filters	Not quantified – *BW reduction of 4 for L-band NLFM ATC radar and 20 for S-band pulsed ATC radar.*	1.015	-
Waveforms	13/14 dB (matched transmitter bandwidth) – *-40 dB BW reduced by a factor 2 (short pulses) and 10 (long pulses).* 18/19 dB (10μS FM pulse and matched bandwidth) – *-40 dB BW reduced by a factor 10 to 20.* Also allows for reductions of 30 dB in peak power with a corresponding reduction in OOB and spurious.	1.055	£0.267M (Ku-band)(2)
Filters and waveforms		1.0675	£0.267M (Ku-band)(2)

The BAE Systems report[116] provides corroborating evidence for cost per unit of achieving similar reductions in out of band emissions as can be seen from the summary given in Table 5.

Table 5 – Costs and benefits of reducing radar emissions as identified by BAE Systems

Technique	Cost	Effect	Benefit
Change to pulse length with chirp (TWT transmitters)	£2.8M development + £0.72M per unit	20 μS NLFM 1 MHz pulse reduces theoretical -40 dB roll-off point from 17 MHz to 4.7 MHz. ITU-R -40 dB roll-off point for a current 0.4μS pulse is indicated as being more than 30 MHz.	Closer channel spacing and/or separation distance. OOB suppressed by 24 dB at a given frequency offset.
Solid state transmitters and pulse shaping	£2.3M development + £1.3M per unit	SS (100μS NLFM 1 MHz pulse) reduces –40 dB roll-off point further to 2 MHz and pulse shaping even further to 0.5 MHz.	Even closer channel spacing and/or separation distance. OOB suppressed by 46 dB at a given frequency offset and even more with pulse shaping.
New conventional radar in higher frequency band	£14M development + £2.5M per unit	Move out of band	Higher bands (C-band and X-band) noted to be congested already.

[116] Study into spectrally efficient radar systems in the L and S bands. BAE Systems et al. SP-A21524-18304-RPT Issue 001. May 2006.

Glossary

ATS.	Air Traffic Services. Includes flight information service, alerting service, air traffic advisory service, air traffic control service (area control service, approach control service or aerodrome control service and provision of navigation aids & distress services
ACAS.	Airborne Collision Avoidance Systems. Enables pilots to detect the presence of other aircraft and where necessary provides instructions to reduce the risk of collision
CNIS	Channel Navigation Information Service. Provides a 24 hour radio and radar safety service for all shipping in the Dover Strait
DME.	Distance Measuring Equipment. Used by aircraft to determine their distance from the land-based transponder by sending and receiving radio pulses. The ground stations are typically collocated with VORs
ELBA	Emergency Low-power Beacons. See EPIRB
EPIRB	Emergency Position Indicating Radio Beacon - a component of the Global Maritime Distress Safety System (GMDSS). See appendix C for details
ELT	Emergency Locator Transmitters. See EPIRB
GBAS	Ground Based Augmentation System. Corrects Global Positioning Satellite signals to allow Category precision landings.
GMDSS.	Global Maritime Distress Safety System. An internationally agreed-upon set of safety procedures, types of equipment, and communication protocols used to increase safety and make it easier to rescue distressed ships, boats and aircraft. See Appendix C for details of the system.
ILS	Instrument Landing System.
LAAS	Local Area Augmentation System. Corrects Global Positioning Satellite signals to allow Category precision landings – the same as GBAS.
MLS	Microwave Landing System
NAVTEX	An international automated medium frequency direct-printing service for delivery of navigational and meteorological warnings and forecasts, as well as urgent marine safety information to ships. See Appendix C
NDB.	Non-Directional Beacon. Provides a constant signal carrying a call sign which, with direction finding equipment and a map of beacon locations, allows an aircraft to have its course plotted.
Primary Surveillance Radar.	Detects the position of aircraft by means of reflected radio signals.
Secondary Surveillance Radar.	Detects the identity, position and altitude of aircraft and can exchange other digital information between aircraft and ground.
TACAN	Tactical Air Navigation. The military version of combined VOR & DME.
VOR	VHF Omnidirectional Range. A navigation system which indicates the identity of the station and the direction (but not the range) the aircraft lies from the VOR station. Often collocated with a DME to allow a one station fix.