

# SPECTRALLY EFFICIENT RADAR SYSTEMS IN THE L AND S BANDS

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**Keywords:** Radar, Ofcom, Spectrum, Efficiency.

## Abstract

In the L and S bands radar is extensively used in the UK for aeronautical, maritime and weather surveillance on both fixed and mobile platforms. In recent times, however, there has been a desire within the communications industry to access parts of the radar L and S bands. This tendency will certainly continue in the future under pressure from the (civil) communication market. This paper outlines the research carried out and the conclusions of a study into spectrally efficient radar technology funded by the UK communications regulator Ofcom.

## 1 Introduction

The L and S bands have traditionally been used for radar due to their favourable propagation properties allowing good range performance coupled with the ability to achieve reasonable angular resolution with practical antenna scales and the relative economy of equipment costs compared to using alternative, higher frequency bands. For similar reasons, there is a desire within the communications industry to use the radar L and S bands. This tendency will certainly continue in the future under pressure from the (civil) communication market. This trend implies an increasing demand for additional use of the spectrum by communication equipment.

In these commercially important bands, however, 31% of the spectrum is primarily allocated to radar systems and is currently largely unavailable to other users of the spectrum. Potentially large amounts of spectrum could be freed up for commercial purposes if radar systems could:

- Be moved to a different frequency band in lower demand (SHIFT)
- Be improved in terms of their spectral efficiency (SQUASH) and their allocations re-planned to take advantage of this
- Share the spectrum with commercial users (SHARE)

The purpose of this study was to investigate some of the challenges related to these approaches and a number of avenues were explored, from incremental improvements to current and developing radar technology through to entire system concept changes.

The analysis in all of this work focused on ATC requirements for radar and the practicalities of attempting to meet them using more spectrally efficient techniques.

## 2 Re-locate radar to a different frequency band in lower demand (SHIFT)

The choice of frequency for an ATC radar system is primarily driven by detection performance, angular accuracy and cost. Certain radio propagation effects must be accounted for when considering re-locating frequency bands. Atmospheric weather effects vary with operating frequency and in general are more severe at higher frequencies. In particular even modest levels of rainfall can significantly affect radar performance, thereby requiring much higher transmitted powers, with further implications for RF power generation and safety, in higher frequency operating bands. In addition, clutter effects are also more severe at higher frequencies so that detection performance reduces with increasing frequency in the presence of clutter.

Peak power levels at different operating frequencies can be calculated based on standard ATC detection requirements and a knowledge of the transmitter technologies available in each band - these are plotted in Figure 1

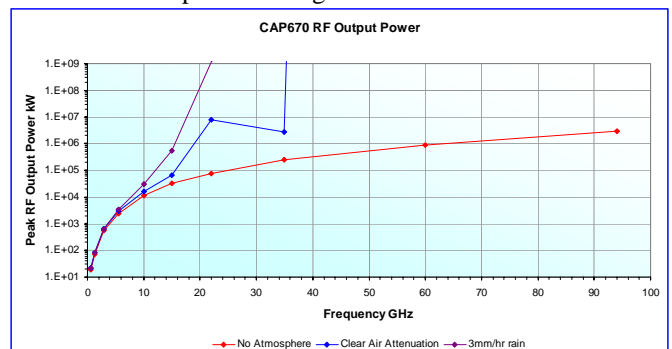


Figure 1 Estimated required peak RF output power

It is apparent from Figure 1 that power requirements increase disproportionately above about 10GHz: this is due to the atmospheric and rainfall attenuation losses.

In general the higher the operating frequency the higher the required transmitted power becomes in order to maintain detection performance. Also due to lower power conversion efficiencies at the higher frequencies the prime input power, and thus operating cost, is significantly higher at the higher frequencies with existing technologies.

An analysis was also carried out on RF radiation hazards associated with such high power systems operating at higher frequencies. These are hazard to both people and equipment. RF hazards to people are based on mean power exposure, and it was found that provided there was a sufficiently large exclusion zone around a radar of approx. 100m would be sufficient for operating frequencies up to around 5GHz (C band). Avionic equipment is subjected to High intensity radiated field (HIRF) testing in order to simulate the high peak and mean RF field environments typical of radar installations. These are typically specified in terms of Peak field strength. The required peak field strength of ATC radar operating at different frequencies is plotted in Figure 2 and compared with the HIRF limits. In this case the HIRF limits are exceeded for frequencies above 10GHz (X band).

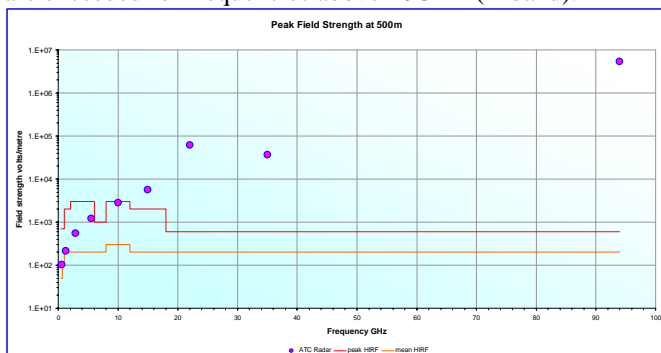


Figure 2 Estimated peak field strength at 500m

Based on detection requirements and device power and radiation hazard safety considerations it is concluded that, of the currently designated radar bands, the only frequency bands to which ATC radars could possibly be moved would be C-band (5 GHz) and X-band (10 GHz).

In principle, re-locating these radar services to a different frequency band would release all of their previous allocations in the L- or S-bands. However, sufficient un-interfered spectral allocations (of the same bandwidth – in order to maintain range resolution) would be required in the new bands. These new bands are themselves already relatively congested, and so may not offer significant opportunities for re-location of L-band or S-band radars.

### 3 Improve the spectral efficiency of radar (SQUASH)

A number of avenues for improving radar spectral efficiency were explored; these varied from changes and improvements to current and developing radar technology through to entire system concept changes.

Since it would not require a change of the current ATC radar system concept and therefore would have more straightforward regulatory acceptance, options for changing and improving high power pulsed radar designs are attractive. The benefits of this approach also include much shorter development timescales, lower costs and easier integration into the current infrastructure.

Approaches that require a change of system concept were also examined; these include narrowband Continuous Wave (CW)

radar concepts and Passive radar (which does not transmit any energy but processes target echoes from the emissions of other systems)

#### 3.1 Pulsed radar

Analysis focused on the practical problems of generating high power spectrally efficient waveforms for pulsed radar. The key component of the radar system is thus the transmitter. In nearly all developed radar systems, including the current state of the art, the transmitter is operated in class-C (saturated non-linear). This limits the types of waveforms they can transmit and the amount of spectral control that can be exercised.

Many candidate spectrally efficient waveforms rely on transmitter linearity and are thus not suitable for use in these radar. In addition, their performance can significantly degrade when used with fast moving Doppler shifted targets. It was found that long pulse Non Linearly Frequency Modulated (NLFM) chirp waveforms offer the best combination of spectral efficiency and Doppler tolerance, while being suitable for class-C transmitters.

Spectral efficiency improvement was assessed based on techniques which allow radars to operate in a way that minimises the interference to radars of a like type, thus improving overall spectral efficiency by reducing the spatial or spectral distance between neighbouring radar. With appropriate planning, this would allow a network of radars to operate over a narrower range of frequency allocations. It should be noted, that much of this analysis is based on theoretical transmitted spectra. Real world effects in practical transmitter systems would result in less spectrally efficient transmissions than predicted by this theoretical analysis. As a result of these considerations a number of conclusions and recommendation for currently deployed technologies can be made:

##### 3.1.1 Magnetron radar

The spectrum spread from a coaxial magnetron is much narrower than from a conventional magnetron. There are also fewer large spurious emissions generated at high frequencies. Changing to co-axial magnetrons should thus be considered when maintenance / upgrade intervals allow. Such upgrades have been applied to older ATC and non-ATC radar designs in the past, although some re-design effort would be required for this option.

##### 3.1.2 Watchman radar

There is scope within the NATS criteria for the widely deployed TWT based Watchman radar to operate with a lower pulse bandwidth and still meet civil ATC range resolution and range accuracy requirements. Some improvements are possible with this approach; however, they are limited by the very rapid rise and fall times of TWT transmitters. Using this technique, however, could result in useful savings if the modest improvements (~1.2MHz reduced separation between radar) were rolled out over the network of around 80 installed Watchman radar and the frequency allocations re-planned.

### 3.1.3 Modern solid state radar

The spectral efficiency of modern solid state radar transmitters utilising long NLFM pulse waveforms and having longer rise and fall times is close to the best spectral efficiency of current radar technologies. The move towards solid state transmitters utilising long modulated pulses in ATC radar is thus consistent with improved spectral efficiency.

However, the silicon bipolar solid state technology utilised in these transmitters is limited in its maximum achievable rise time to less than 200ns. Since rise (and fall) time to a large extent control the transmitted spectrum, this limits the achievable spectral efficiency of this type of transmitter. If further spectrum efficiency, beyond that achievable using current solid state transmitter technology, needs to be realised a change in transmitter technology would be required.

### 3.1.4 Next generation solid state transmitter technology (LDMOS)

Looking to the future and the next generation of pulsed radar transmitters, recent technology advances have led to the availability of high power solid state LDMOS technology in L-band and its emergence in S-band. This means that near linear transmitters could become a possibility for pulsed radar.

With the possibility of near linear radar transmitters and an understanding that waveform spectral efficiency is largely controlled by pulse rise (and fall) time an analysis of different pulse rise and fall times was carried out. This indicated that significant improvements in spectral efficiency can be achieved through either trapezoidal or cosine shaped pulse edges, with longer rise times giving the best improvements. If spectral efficiency becomes a requirement of future radar systems, linear transmitters using such pulse shapes are likely to be the best approach.

On average, improvements in frequency separations between radar of between 1 – 3MHz over traditional class-C solid state systems are predicted to be achievable.

LDMOS based solid state technology is the most likely and low risk direction for the development of the next generation of radar transmitters and will allow much improved radar system spectral efficiency.

## 3.2 Continuous Wave (CW) radar

CW radar has been proposed in previous studies as offering potential to significantly reduce required radar bandwidth. More detailed analysis was carried out in this study to quantify the limits of performance and any vulnerabilities. It was shown that while in principle CW radar could have the same detection performance as conventional pulsed radar at the same frequency; in practice self interference (direct from transmitter into receiver - see Figure 3) limits the transmitter power of a CW system and long range detection with CW radar is reduced compared to similar power pulsed systems.

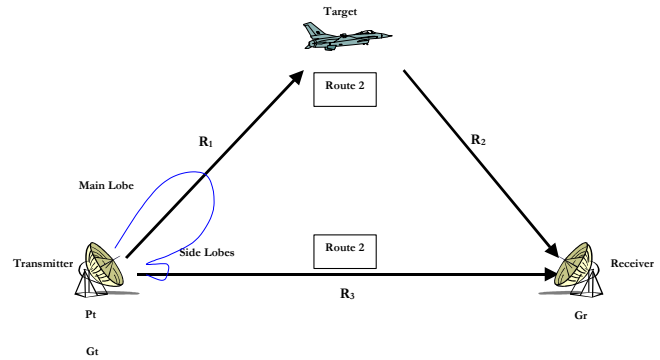


Figure 3 Bi-static CW radar self interference

Mitigation options are available; however none provide a complete solution.

One of the key limitations of standard CW radar is the inability to measure target range. Two methods for overcoming this lack of range information available from CW systems were explored:

- The first requires multiple receive sites to track targets and calculate their position using Doppler shift and/or angle of arrival – these multiple sites could, in principle, all be contained within a single airfield / airport or more widely scattered depending on the availability and cost of land for siting equipment. The analysis covered the case of a single target; for multiple targets the performance will be limited by the system's multi-static geometry and Doppler resolution. In the worst case scenario (e.g. multiple aircraft at low speed coming in to land) such a system may not be able to resolve the aircraft.
- The second method requires a Frequency Modulated CW (FMCW) system, which can provide range resolution at the expense of transmitted bandwidth. Superresolution algorithms were found to improve such a systems resolution in good signal to noise (SNR) conditions but would fail at low SNR.

Target Doppler frequency has been proposed as a means of discriminating and resolving closely spaced targets. However, analysis to date has only dealt with a single target. In addition, as a result of the impact of update rate requirements on target illumination time, the Doppler resolution of a CW system for ATC services may be insufficient to allow resolution of multiple slow moving targets (e.g. those on the glide path to landing)

In terms of vulnerabilities; CW radar are vulnerable to external jamming (Figure 4). A practical demonstration of a CW radar receiver and the effects of jamming was given where interference from both a pulsed radar in the vicinity and a commercial WiFi router very nearby were seen. Although it was not demonstrated, deliberate jamming is of course the worst case.

Unfortunately jammer mitigation options significantly increase system complexity and cost so that they are typically only used in expensive military systems.

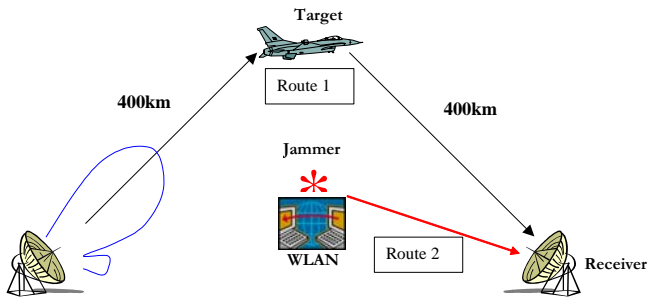


Figure 4 Accidental jamming of a bi-static CW system

There are still significant technological hurdles before CW systems can be accepted as feasible for the provision of safety of life ATC services. Further concept analysis work in the academic and radar research communities are required before a manufacturer commits to embarking on the long development process from concept design to a product. Significant time and effort would be required to develop CW radar from the current concept stage through to a fully developed system; it is therefore unlikely that any CW radar product for ATC purposes will be available to the market within the next 15 years.

### 3.3 Passive radar

Passive radar systems do not have their own transmitters but receive and process energy reflected off targets from other system's transmitters. These other systems may be broadcast (such as terrestrial TV and radio) or communications (such as mobile phone networks). Such a system would utilise multi-static geometry of multiple transmitter / receiver sites to allow target location in 2 or 3 dimensions.

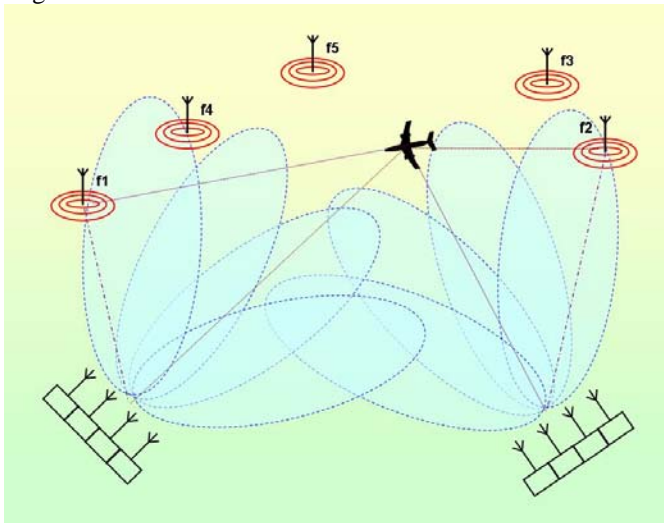


Figure 5 Multistatic passive radar system

At a technical level, ideal passive radar systems could provide reasonable detection performance of civil aircraft within several tens of kilometres of powerful broadcast transmitters. This detection performance could be comprehensive at low level but would reduce as the altitude of the aircraft increases due to the reduced vertical coverage of terrestrial broadcast transmitters. Location accuracy is dependent upon

transmitter-receiver geometry, the broadcast waveforms being used, and the type of passive radar system processing proposed.

There are signal availability, reliability and redundancy issues affecting safety that need to be examined for ATC applications of passive radar systems. These aspects need to be considered in the context of other international developments in air traffic management.

It is unlikely that practical passive radar systems, using terrestrial broadcast transmissions, on their own could replace ATC radars in the near future. However, there may be opportunities to provide support to other systems. Similarly to the proposed CW radar options, further analysis work and long timescales are required to develop passive radar from concept to product and it is not a near or mid term prospect.

## 4 Share the spectrum with other users (SHARE)

This analysis has considered the benefits of sharing the spectrum of the L- and S- band radars with other potential users.

In this context, bandsharing is assumed to refer to the situation where a secondary user occupies bandwidth that is licensed to a primary user within the same general geographic area as the primary user on a mutual non-interference basis.

One possible solution to the problem is to consider how the waveforms of the radar and the secondary systems could be designed in an integrated way to maximise the performance of both. However, it was felt that such an approach would lead to a stove-piped design that could not be fully exploited in the wider markets. A more ad hoc approach to bandsharing would result in greater flexibility in the use of the spectrum.

There are two approaches to this type of bandsharing; 'Underlay', where secondary users transmissions are wideband, noise-like and operate at low power compared to the radar and 'Overlay' based on spectrum monitoring and dynamic allocation of narrowband sections of spectrum. Because of radar receiver sensitivity and co-channel operation, the underlay method has been found to be suitable only where the individual ERP of sharing transmitters is low, i.e. 1mW. The situation can be improved by defining an exclusion zone around the radar inside which co-channel transmissions are prohibited.

The overlay method promises better bandsharing performance for the case of narrowband CW radar with good mutual protection both to the radar receiver and to the bandsharing secondary users. Cognitive radio designs could exploit this method by sensing the RF environment and optimally adapting their operation. Pulsed radar are not so amenable to this analysis due to their wider transmitted spectrum and low duty (off for ~90% of the time), which would make operation of a sensing cognitive radio much more difficult.

Thus it is unlikely that this type of sharing will be possible until the possible development of CW radar, at the earliest in 15 years time.

## 5 Economic and programmatic considerations

The main customers for radiolocation services in the UK are National Air Traffic Services (NATS), regional airports and the UK Ministry of Defence (MoD). Between them they operate in excess of 100 S-band pulsed radar of various configurations.

NATS are currently engaged in a wide reaching radar replacement programme as they replace their older systems with the current state-of-the-art Raytheon ASR 10-SS solid state radar, these new radar will have a nominal lifetime of around 15 – 20 years unless life extension upgrades are procured. The radar deployed at regional airports are of various ages and configuration, each airport, however, manages its own radar service support with new procurements or life extension upgrades.

Meanwhile, the UK MoD has a large number of radar approaching the end of their useful life over the next 3 – 7 years. In order to maintain military ATC capability beyond this timescale new radar or life extension upgrades will need to be procured.

Figure 6 summarises these timescales along with indications of the likely opportunities for insertion of new spectrally efficient radar technologies.

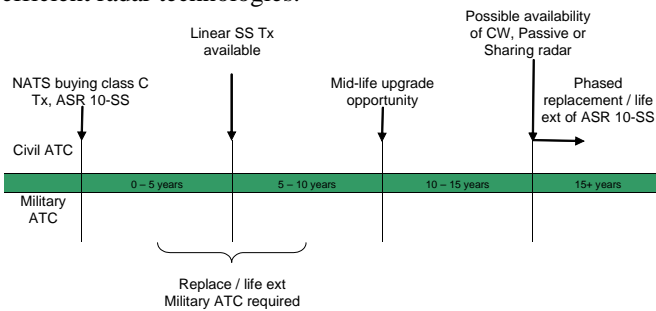


Figure 6 Timescales of likely radar procurement and technology availability in the UK

The potential spectrally efficient technologies such as Passive, CW or Shared systems will not be near to maturity for ATC radar application within the next 3 - 7 years and thus would not be considered as part of military ATC capability provision at that time. Further, considering civil ATC radar:

- the current programme of NATS radar procurement of Raytheon ASR 10-SS class C transmitter based systems, which provide close to the best spectral efficiency of current radar technologies,
- the nominal 15 – 20 year lifetime of these radar and
- the considerable expense of radar replacement before the end-of-life.

It is clear that the first opportunity for deployment of alternative spectrally efficient radar technologies such as CW, Passive or Shared systems is unlikely to be before 15 – 20 years hence.

However, new high power linear S-band pulsed radar transmitters could be developed and deployed (as part of a life extension upgrade to an existing radar or in a new pulsed radar design) within approximately 5 years. This timescale is consistent with both the procurement of new military ATC

capability and mid-life upgrade opportunities in civil ATC radar.

It is clear that the significant spectral efficiency improvements available through the adoption of linear solid state transmitter systems, their relatively low technological risk, the predicted development timescales and the expected costs mean that should spectral efficiency become requirements of ATC radar, then this technology is by far the best candidate for procurement into both Civil and Military ATC capability.

## Conclusions

The study has investigated some of the challenges of improving radar spectral efficiency with a view to allowing alternative commercial uses of the L and S radar spectral bands.

A number of avenues have been explored, from incremental changes to current and developing radar technology through to entire system concept changes:

### SHIFT

- It is technically feasible to SHIFT ATC radar to a different band, development would take ~6 years. However, considering the high powers, other performance issues and
- development costs for such a radar in the candidate C or X bands, this is not a favourable option.

### SHARE

- Underlay approaches could allow sharing with very low ERP devices ( $\sim 1\mu\text{W}$ ) with the provision of well defined exclusion zones.
- Overlay approaches require cognitive radio capabilities in both radar and other users and is more amenable to sharing with CW radar than with wider band pulsed systems. It is thus unlikely to be an option unless CW is adopted (at the earliest ~15-20 years time)

### SQUASH

- CW : There are significant technological hurdles (such as lack of natural range information and susceptibility to interference) before CW radar systems become feasible for ATC applications. Significant time and effort (~15 years) is required to move from the current concepts through development to possible products
- Passive radar systems : Could also provide detection of civil air targets, however, elevation cover is limited by the available transmitter antennas. There are also signal availability, reliability and redundancy issues that need to be examined for safety of life applications. It is unlikely that such passive systems on their own could replace primary ATC radar in the near future. However, there may be opportunities for supporting roles.
- Pulse radar :
  - Reduced BW Watchman is feasible, would yield modest improvements but may not be consistent with military requirements

- Modern silicon bi-polar solid state radar have the best spectral efficiency of current radar technologies. They are, however, limited by rapid rise/fall times.
- LDMOS technology is the most likely and low risk option for next generation radar transmitters and will allow much improved spectral efficiency.

#### Economic issues

- CW, Passive and Sharing techniques for ATC applications are still in the concept stage and not yet mature enough to begin industrial R&D towards products. It is thus unlikely that these technologies will appear as products within the next 15 years
- A number of options for improving the spectral efficiency of pulsed radar are available. Of these LDMOS near linear transmitters would be most effective and entail the least risk. Such a solution could be available to market within 6 years as either a upgrade or in a new radar product. This timescale is consistent with new military ATC capability requirements and mid-life upgrade opportunities in civil ATC radar.

#### Recommendations

- Further academic research into CW radar techniques for ATC
- Analysis of signal availability, reliability and redundancy for safety of life passive radar applications
- Industrial development of next generation pulsed radar technology, such as LDMOS.

## Acknowledgements

This work was funded by the UK treasury through the UK communications regulator, Ofcom's, Spectral Efficiency Scheme 2004 - 2005 (SES-2004-2) under Ofcom contract No. 410000259.

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