Figure 4.8-10: Range profile of a Boeing 727

The proposed model is further simplified for implementation in the algorithms. A set of the nine most important scattering centres is used giving the range profile in Figure 4.8-11.

Figure 4.8-11
4.8.3 Adaptation of MUSIC range superresolution to pulsed radar

This section examines the adaptation of the MUSIC algorithm for a mono-frequency pulse of the type used in current ATC radar systems. The case is considered where the nominal transmitted bandwidth an ATC system is reduced from 1MHz to 500KHz and two or more targets that have the same azimuth cannot be resolved using standard techniques for the chosen pulse bandwidth. The principles of a modelled echo signal that were examined in the previous section are taken into consideration. This signal must be transformed into a special form so that the equations of the MUSIC algorithm that are discussed above can be applied.

In the scenarios studied, the difference in target velocities is smaller than the normal Doppler resolution of the radar. The MUSIC superresolution technique is used to resolve and report the separate Doppler frequencies of the targets. It does not necessarily report the actual range separation of the targets merely that they exist together within one range interval of the radar.

4.8.3.1 Analysis of the proposed model & formation of equations

A transmitted pulsed signal \( s(t) \) is assured with frequency \( f_0 \), pulse repetition frequency PRF, and pulse length \( T \) as follows:

\[
s(t) = A e^{j(2\pi f_0 t + \phi)}
\]

Equation 4.8-17

Considering \( k \) scattering points (targets) at the same azimuth at distances \( D_k \) from the radar and relative speeds \( v_k \) with respect to the radar the received signal will be:

\[
r(t) = \sum_{<k>} A_k e^{j(2\pi f_0 (t - t_k) + \phi_k)}
\]

Equation 4.8-18

Where, \( A_k \) is the Signal amplitude from each scattering point and \( t_k \) is the pulse round trip time (R.R.T.) from each target.

If \( M \) pulses are transmitted, with pulse index \( m=0..M-1 \), then the complex form of the received signal for each pulse \( m \) will be:

\[
Y_m = \sum_{<k>} a_k e^{-j2\pi f_0 t_{k,m}}
\]

Equation 4.8-19

Where \( a_k \) is the relative echo amplitude = \( \frac{A_k}{A} \)

The distance of each target from the radar for each pulse is:

\[
d_{k,m} = v_k t_{k,m} + D_k
\]

The velocities of the targets for a small period of time can be assumed constant and in this case equal to: \( v_1=250 \) knots and \( v_2=251 \) knots. The initial distances of the targets from the
radar are $D_1=50$ Km and $D_2=50.1$ Km. The system’s PRF is 1KHz and 64 pulses ($M=64$) are assumed to illuminate the target.

The pulse round trip time (RTT) is:

$$t_{k,m} = \frac{2d_{k,m}}{c}$$  \hspace{1cm} \text{Equation 4.8-20}

The received signal for each pulse $m$ takes the form:

$$Y_m = \sum_{<k>} a_{k,m} e^{-j2\pi \frac{f_0}{c}(2v_{k,m}t_{k,m}+2D_k)} = \sum_{<k>} a_{k,m} e^{-j4\pi \frac{f_0}{c}Dk} e^{-j4\pi \frac{f_0}{c}v_{k,m}t_{k,m}}$$  \hspace{1cm} \text{Equation 4.8-21}

The relative speeds of the targets $v_k$ for the small time period $(m.PRI)$ can be assumed constant so $t_{k,m} = m.PRI$.

Hence the received signal becomes:

$$Y_m = \sum_{<k>} a_{k,m} e^{-j4\pi \frac{f_0}{c}Dk} e^{-j4\pi \frac{f_0}{c}(v_k.PRI)_m}$$  \hspace{1cm} \text{Equation 4.8-22}

Defining

$$[a_k] = a_{k,m} e^{-j4\pi \frac{f_0}{c}Dk} \text{ and } \phi_k = -4\pi \frac{f_0}{c}v_k.PRI$$  \hspace{1cm} \text{Equation 4.8-23}

The received signal then takes the form:

$$Y_m = \sum_{<k>} [a_{k,m}] e^{j\phi_k.m}$$  \hspace{1cm} \text{Equation 4.8-24}

Finally white Gaussian noise is added to the received signal, hence it becomes:

$$Y_m = \sum_{<k>} [a_{k,m}] e^{j\phi_k.m} + n_m$$  \hspace{1cm} \text{Equation 4.8-25}

This is the final equation of the return signal and is actually a vector consisting of $M$ elements – equal to the number of pulses transmitted.

The autocorrelation matrix of $Y_m$, as mentioned before, is now composed of the signal autocorrelation matrix and the noise autocorrelation matrix:

$$R_{yy} = R_{xx} + R_{nn} = SPS^H + \sigma_n^2 I$$  \hspace{1cm} \text{Equation 4.8-26}
The $p$ principal eigenvectors (eigenvectors with the largest eigenvalues) of $R_{yy}$ are identical to those of $R_{xx}$ and may be used to extract every sinusoidal frequency inside the received signal.

It was shown in Equation 4.8-16 that the MUSIC spectrum is defined as:

$$P_{xx}^{\text{MUSIC}} = \frac{1}{\sum_{k=p+1}^{N} \left| S^H(f) v_k \right|^2} = \frac{1}{\sum_{k=p+1}^{N} \left| S^H(f) V(f) V^H(f) s(f) \right|^2}$$

Where $V = \{v_{p+1}, ..., v_N\}$ is the matrix of eigenvectors of the noise subspace derived from the autocorrelation matrix $R_{yy}$.

It was also highlighted that $P_{\text{MUSIC}}(f)$ is peaked at the frequencies of the sinusoidal components of the signal. In this case, every sinusoidal component is equivalent to the existence of a target.

By applying the MUSIC algorithm for any case of Equation 4.8-24 the terms $\varphi_k$ of Equation 4.8-23 can be extracted for each of the targets. As a result the speed of the targets can be calculated using

$$v_k = -\frac{\varphi_k}{c} \frac{c}{4\pi f_0 \text{PRI}}$$

Equation 4.8-27

### 4.8.3.2 Simulation results

In the examples that follow, the algorithm is first tested for the simplest case where the targets are actually single scattering centres. The profile of the more complex multi-scattering point target of the Boeing-727 aircraft is then used. In both cases different parameters are examined and finally the algorithm is evaluated for multiple scenarios to produce more general conclusions.

#### 4.8.3.2.1 Single scattering points targets

The following example simulates the return signal of 2 scattering points and calculates its spectrum in relation to the speed of the targets using both the Fast Fourier Transform (FFT) and the MUSIC algorithm application.

The parameters of the simulation were as follows:

- Transmitted frequency : $f_0 = 2.7$GHz
- Pulselength = 2µsec
- Bandwidth = 500KHz
- Pulse Repetition Frequency : $PRF = 1$KHz
Initial target distances: $D_1=50\text{Km}$ and $D_2=50.1\text{Km}$

Distance difference between targets: 100m

Number of pulses used for the algorithm: $M=32$

Velocities of targets: $V_1=250\text{Knots}$ and $V_2=251.1\text{Knots}$

Speed difference of targets: 1.1Knots, 0.56m/sec

The noise added to the return signal is white Gaussian giving SNR = 40dB

For these parameters the spectrum of the return signal is calculated and plotted in Figure 4.8-12 where the x axis corresponds to the term $\phi_k$ of Equation 4.8-23.

![Figure 4.8-12: Comparison of MUSIC spectrum (upper panel) and FFT power spectrum (lower panel)](image)

It can be clearly seen that although it is not possible to distinguish between the 2 targets using standard techniques, however, by calculating the MUSIC spectrum, the targets can now be visually resolved.

This can also be demonstrated, by integrating the Rayleigh criterion as a decision threshold, whether the targets are resolved or not. Table 4.8-1 is the last output of the simulation and provides information about the input parameters, the decision based on the criterion mentioned and the system calculated velocities of the targets:
Table 4.8-1

<table>
<thead>
<tr>
<th>User Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitted Frequency (GHz)</td>
<td>2.7</td>
</tr>
<tr>
<td>Pulselength (usec)</td>
<td>2</td>
</tr>
<tr>
<td>Pulse repetition frequency (KHz)</td>
<td>1</td>
</tr>
<tr>
<td>Initial distance of targets (km)</td>
<td>50 50.1</td>
</tr>
<tr>
<td>Speed of targets (m/sec)</td>
<td>128.6111 129.177</td>
</tr>
<tr>
<td>Number of pulses used for MUSIC</td>
<td>32</td>
</tr>
<tr>
<td>Added white gaussian noise giving SNR(dB)</td>
<td>40</td>
</tr>
</tbody>
</table>

Standard Technique: UNRESOLVED
MUSIC: RESOLVED

Calculated speeds of targets (m/sec): 128.8117 129.0226

In a noisier but still with good SNR environment the algorithm still produces impressive results as plotted in Figure 4.8-13

![MUSIC Spectrum - No of pulses used: 32](image1)

![Power Spectrum of received signal](image2)

**Figure 4.8-13**

It has to be made clear that the results of the algorithm are a combination of the velocities of the targets, the number of pulses used for the calculations and the SNR of the received
signal. The following simulations test the MUSIC algorithm for multiple scenarios and provide the combination of parameters for which the algorithm can actually resolve targets.

The main plot which is 3-dimensional indicates that, for every combination of specific SNR and Number of pulses used for the calculations, the minimum difference in speed that the targets must have for the system to be able to resolve them.

Figure 4.8-14

This graph has been sliced at various Signal to Noise ratios resulting in the following plots. Curve fitting in a 'least squares' sense has been adopted for better presentation of the results:

(a) SNR = 6dB

(b) SNR = 10dB
4.8.3.2 Multi-scattering points targets

The following example simulates the return signal of 2 multi-scattering point targets and calculates its spectrum in relation with the speed of the targets using both the Fast Fourier Transform (FFT) and the MUSIC algorithm application. The range profile used is of a Boeing 727 as presented in section 4.8.2.3.

The parameters of the simulation are as follows:

Finally, for the purposes of comparison of the MUSIC algorithm with the standard technique the Figure 4.8-16 at 15dB is presented:

![Comparison of resolution performance of MUSIC vs standard FFT method at 15dB SNR](image)
● Transmitted frequency: $f_0 = 2.7\text{GHz}$
● Pulselength = 2µsec
● Bandwidth = 500KHz
● Pulse Repetition Frequency: $PRF = 1\text{KHz}$
● Initial target distances: $D_1=50\text{Km}$ and $D_2=50.1\text{Km}$
● Distance difference between targets: 100m
● Number of pulses used for the algorithm: $M=32$
● Speed difference of targets= 1.28m/sec
● The noise added to the return signal is white Gaussian giving $\text{SNR} = 40\text{dB}$

For these parameters the spectrum of the return signal is calculated and plotted as follows:

![Figure 4.8-17](image)

It can be seen from Figure 4.8-17 that the MUSIC algorithm results are superior to those of the standard technique’s calculation since the peaks regarding the first case that are related with the existence of targets are obvious. Thus, while it is not possible to resolve the two multi-scattering points targets with normal FFT, by applying the MUSIC algorithm the situation improves considerably.

This can be confirmed while setting a decision threshold embodying the Rayleigh criterion. The following table is the last output of the simulation:

| Table 4.8-2 |
Again, when testing in a noisier environment the performance of the MUSIC algorithm still remains at higher levels than the standard technique since it can still resolve the two targets as indicated in Figure 4.8-18.

As for the simple case of the single-scattering centres targets it has to be made clear that the results of the algorithm are a combination of the velocities of the targets, the number of pulses used for the calculations and the SNR of the received signal. The MUSIC algorithm must be evaluated for various scenarios to provide the combination of parameters for which the algorithm can actually resolve targets.
The 3D-plot illustrates combinations of SNR and Number of pulses used for the calculations and the minimum difference in speed that the targets must have for the system to be able to resolve them.

![3D-plot illustrating combinations of SNR and Number of pulses used for calculations](image)

**Figure 4.8-19**

As before a selection of 2-D slices are also shown for better presentation of results:

(a) SNR = 16dB

(b) SNR = 12dB
4.8.3.3 Summary

This section examined the adaptation of the MUSIC algorithm for a mono-frequency pulse of the type used in current ATC radar systems. The case is considered where the nominal transmitted bandwidth an ATC system is reduced from 1MHz to 500KHz and two or more targets that have the same azimuth cannot be resolved using standard techniques for this chosen pulse bandwidth.

The application of the MUSIC algorithm appears to provide superior results than standard FFT techniques. This was demonstrated for a variety of received signal SNR, speed and distance of targets and pulses needed for the calculations. This is because the difference in speed between two aircraft is often larger than that needed for the algorithm to be able to
resolve them. However, in the worst case scenario, that is extremely rarely met (e.g. two aircraft approaching in a closed formation during low SNR conditions), the algorithm may not be able to resolve the two aircraft.

Nonetheless, provided the conditions are met for operation of the superresolution algorithm, resolution of closely spaced targets appears to be possible using reduced bandwidth pulsed transmissions.

4.8.4 Adaptation of MUSIC to FMCW radar

This section examines the adaptation of the MUSIC algorithm for frequency modulated continuous wave (FMCW) radar. Parameters consistent to those using ATC radar systems are used for simulations and extraction of results. The case is considered where two or more targets that have the same azimuth cannot be resolved using standard techniques for the chosen bandwidth of the FM. The profile of the multi-scattering centres Boeing-727 target aircraft is used.

In the scenarios studied, the difference in target velocities is smaller than the normal Doppler resolution of the radar. The MUSIC superresolution technique is used to resolve and report the separate Doppler frequencies of the targets. It does not necessarily report the actual range separation of the targets merely that they exist together within one range interval of the radar.

4.8.4.1 Analysis of the proposed model & formation of equations

The transmitted signal is assumed to be a linearly FM modulated signal \( s(t) \) as a stepped frequency pulse train with extremely narrow pulses. The frequency of the \( n^{th} \) transmitted ‘pulse’ will be \( f_n = f_0 + n \Delta f \) and the signal will have the following form:

\[
s(t) = Ae^{j(2\pi f_0 t + \phi_0)}
\]

Equation 4.8-28

Where: \( f_0 \) is the first ‘pulse’ frequency.

\[ n=0, 1, ..., N-1 \] and \( N \) is the total number of pulses

\( \Delta f \) is the bandwidth of the system.

A typical FMCW transmitted waveform is shown below:
For $K$ scattering points at the same azimuth at distances $r_k$ from the radar, the received signal (with $k=1,2,...,K$) will be:

$$r_n(t) = \sum_{<k>} A_k e^{j(2\pi f_c (t-t_k)+\phi_k)}$$  

Equation 4.8-29

Where, $A_k$ is the Signal amplitude from each scattering point and $t_k = \frac{2r_k}{c}$ is the ‘pulse’ round trip time (R.R.T.) from each target.

The complex form of the received signal for each ‘pulse’ $n$ will be:

$$Y_n = \sum_{<k>} a_{k,n} e^{-j4\pi f_c \frac{r_k}{c}}$$  

Equation 4.8-30

Where $a_k$ is the relative echo amplitude $= \frac{A_k}{A}$

Finally white gaussian noise is added to the received signal, hence it becomes:
\[ Y_n = \sum_{k} a_k e^{-j 4\pi \frac{f_s r_k}{c}} + n_n \]  

Equation 4.8-31

This is the final equation of the return signal and is actually a vector consisting of \( N \) elements – equal to the number of ‘pulses’ transmitted to produce the FM waveform. Rewriting this in vector notation, it can be expressed as:

\[ y = E a + n \]  

Equation 4.8-32

Where:

\[
y = [y_1, y_2, \ldots, y_N]^T = Nx1 \text{ data vector}
\]

\[
E = [e(r_1), e(r_2), \ldots, e(r_K)] = NxL \text{ matrix}
\]

\[
e(r_k) = [e^{-j 4\pi \frac{f_s r_k}{c}}, e^{-j 4\pi \frac{f_s r_k}{c}}, \ldots, e^{-j 4\pi \frac{f_s r_k}{c}}]^T = Nx1 \text{ direction vector}
\]

\[
a = [a_1, a_2, \ldots, a_K]^T = Kx1 \text{ amplitude vector}
\]

\[
n = [n_1, n_2, \ldots, n_N]^T = Nx1 \text{ noise vector}
\]

The autocorrelation matrix of \( Y_m \) is now composed of the signal autocorrelation matrix and the noise autocorrelation matrix:

\[ R_{yy} = R_{xx} + R_{nn} = SPS^H + \sigma^2 I \]  

Equation 4.8-33

The \( p \) principal eigenvectors (eigenvectors with the largest eigenvalues) of \( R_{yy} \) are identical to those of \( R_{xx} \) and may be used to extract every sinusoidal frequency inside the received signal. Because this exact covariance matrix \( R_{yy} \) is an average over a number of snapshots and only one snapshot is available in radar applications, a special technique known as spatial smoothing prepossessing (SSP) may be used to estimate \( R_{yy} \). However, modified SSP (MSSP) has been shown to exhibit an improved performance over the SSP in decorrelating signals from various scattering centres [105].

Applying the MSSP, the covariance matrix can be estimated as follows:

\[ \hat{R}_{yy} = \frac{1}{2M} \sum_{k=1}^{M} \left( R_k + J R_k^* J \right) \]  

Equation 4.8-34

Where:

\[ R_k = y_k y_k^H \]
$y_k = [y_k, y_{k+1}, \ldots, y_{k+m-1}]^T$

$J = \begin{pmatrix} 0 & \cdots & 1 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & 0 \end{pmatrix}$

$M$ is the number of subarrays, $m$ is the subarrays dimension, $J$ is the $m \times m$ exchange matrix, $y_k$ is the data vector of the $k^{th}$ subarray of size $m$ as shown in the figure below:

![Figure 4.8-23](image)

It should be noted that the resolution of the MSSP is reduced since the effective bandwidth decreases from $N$ to $m$. In spite of this disadvantage, the MUSIC algorithm combined with the MSSP gives a much better performance than the conventional IFFT technique. In the MSSP, the decorrelation effect is obtained at the expense of a reduced effective bandwidth. If $m$ increases, the resolution of the MUSIC algorithm improves, but the decorrelation performance between signals from different scattering centres is degraded. In contrast, as $m$ decreases, the decorrelation performance improves, whereas the resolution is degraded. Therefore, in terms of target resolving, there are some tradeoffs in choosing $m$. That is, if $m$ is large, the MUSIC algorithm can provide range profiles of high resolution but some dominant scattering centres may not be detected due to the degradation of the decorrelation performance and vice versa.

The MUSIC spectrum can now be defined as:

$$p_{xx}^\text{MUSIC} = \frac{1}{\sum_{n=K+1}^{m} |v_i^H e(r)|^2}$$

Equation 4.8-35

Where $v_i$ is eigenvectors corresponding to the minimum (noise) eigenvalues of the autocorrelation matrix $R_{yy}$. 
It was also highlighted that $P_{\text{MUSIC}}$ is peaked at the frequencies of the sinusoidal components of the signal. In this case, every sinusoidal component is actually equivalent with the existence of a target. By applying the MUSIC algorithm for any case of Equation 4.8-31 the terms $r_k$ for each of the targets can be extracted.

### 4.8.4.2 Simulation results

The simulation results that follow are outputs of the algorithm using the multi-scattering centres profile of the Boeing-727 as analysed previously. Different scenarios with relevant parameters are tested taking into consideration typical ATC radar figures to produce realistic conclusions.

#### 4.8.4.2.1 Main simulation

The following example simulates the return signal of 2 targets and calculates their spectrum in relation with the range between the targets using both the original Fast Fourier Transform and the MUSIC algorithm.

The parameters of the simulation are set as follows:

- Transmitted signal waveform : FMCW
- Start frequency : $f_0 = 2.7$GHz
- Duration of FM = 1msec
- Bandwidth = 1MHz
- Initial target distances : $D_1 = 50$Km and $D_2 = 50.09$Km
- Distance difference between targets : 90m
- The noise added to the return signal is white Gaussian giving SNR = 15dB

For these parameters the spectrum of the return signal is calculated and plotted:
Figure 4.8-24

The x axis corresponds to the range of the targets from the radar.

It can be seen that although it is not possible to distinguish between the 2 targets using standard techniques, by calculating the MUSIC spectrum the targets can now be resolved.

This can also be demonstrated, by integrating the Rayleigh criterion as a decision threshold, whether the targets are resolved or not. The following table is the last output of the simulation and provides information about the input parameters and the decision based on the criterion:
Study into Spectrally Efficient Radar Systems in the L and S Bands
Ofcom Spectral Efficiency Scheme 2004 - 2005 (SES-2004-2) 225

Table 4.8-3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitted Start Frequency (GHz)</td>
<td>2.7</td>
</tr>
<tr>
<td>Length of FM (sec)</td>
<td>0.001</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>1</td>
</tr>
<tr>
<td>Initial distance of first target (km)</td>
<td>50.009</td>
</tr>
<tr>
<td>Range between targets (m)</td>
<td>90</td>
</tr>
<tr>
<td>Added white gaussian noise giving SNR(dB)</td>
<td>15</td>
</tr>
</tbody>
</table>

For a much a noisier environment such as one with SNR=10dB the algorithm still produces good results. But either the distance between the targets or the system bandwidth must be increased. Here the distance was increased to 100m.

Figure 4.8-25

4.8.4.2.2 Evaluation of the algorithm

It has to be made clear that the results of the algorithm are a combination of the range between the targets, the system bandwidth and the SNR of the received signal. The following simulations test the MUSIC algorithm for multiple scenarios and provide the combination of the parameters for which the algorithm can actually resolve targets.

The main plot which is 3-dimensional gives the minimum difference in distance between the targets for the system to be able to resolve them for every combination of SNR and bandwidth used.
This graph can be sliced at specific Signal to Noise ratios giving the following plots. Curve fitting in a ‘least squares’ sense has been adopted for better presentation of the results:

(a) SNR = 19dB  
(b) SNR = 15dB
Finally, the following graph is for the purpose of comparison of the performance of the MUSIC algorithm with the theoretical performance of a system that uses the standard technique to resolve targets. The chosen SNR for the MUSIC calculations is set at 15dB.

**Figure 4.8-28**

### 4.8.4.3 Summary

This section examined the adaptation of the MUSIC algorithm for an FMCW type radar with parameters consistent with ATC operation.

The application of the MUSIC algorithm again appears to provide superior results than standard FFT techniques. This was demonstrated for a variety of received signal SNR, speed and distance of targets and bandwidth needed for the calculations. This is because
the difference in speed between two aircraft is often larger than that needed for the algorithm to be able to resolve them. However, in the worst case scenario, that is extremely rarely met (e.g. two aircraft approaching in a closed formation during low SNR conditions), the algorithm may not be able to resolve the two aircraft.

Nonetheless, provided the conditions are met for operation of the superresolution algorithm, resolution of closely spaced targets appears to be possible using FMCW transmissions.

4.8.5 Conclusions and recommendations

The aim of this work package was to examine the promise of techniques for recovering range information from reduced bandwidth radars. This was achieved by analysis to investigate whether a reduced bandwidth radar system could potentially maintain current ATC radar range resolution performance through the use of superresolution algorithms, which effectively trade target signal to noise ratio for resolution capability.

The adaptation of the superresolution MUSIC algorithm to both pulsed and FMCW radars was examined and computer simulations were developed for analysis. The analysis scenarios assumed that the targets under consideration were separated in range by less than the basic transmitted bandwidth limited range resolution of the radar and the difference in target velocities was smaller than the normal Doppler resolution of the radar.

The MUSIC superresolution technique was used to resolve and report the separate Doppler frequencies of the targets. It did not report the actual range separation of the targets merely that they existed together within one range interval of the radar. It is important to note that for this implementation of the technique to work the targets must have sufficiently different velocities.

For both pulsed and FMCW adaptations, over a broad range of simulated conditions, the application of the MUSIC algorithm was successfully able to resolve the existence of separate targets that were more closely spaced than was resolvable through standard bandwidth limited techniques. However, in the worst case scenario, that is extremely rarely met (e.g. two aircraft approaching in a closed formation during low SNR conditions), the algorithm may not be able to resolve the two aircraft.

It is clear from this analysis that superresolution techniques do indeed show promise when considered for application to reduced bandwidth radar systems for the purposes of maintaining range resolution. However, before such techniques can be recommended, further detailed analysis work is necessary, these are presented as recommendations in the following sub-section.

4.8.5.1 Recommendations

While superresolution algorithms do show promise for range resolution maintenance in reduced bandwidth radar systems, the following factors should be considered and further analysed:
4.8.5.1.1 Detection performance

Since superresolution algorithms trade target signal to noise ratio for resolution capability, their use could have an impact on the detection capability of the radar system. This could be evidenced by:

- Reduced probability of detection, $P_D$
- Increased probability of false alarms, $P_{fa}$

Since ATC operations are safety of life and depend on good $P_D$ and very low $P_{fa}$ it is important to understand these effects before recommending the proposed techniques. The analysis carried out so far can thus be extended to include multiple Monte-Carlo runs using representative noise distributions in order to quantify the effect on SNR, $P_D$ and $P_{fa}$ and the limits of effectiveness of the superresolution techniques.

4.8.5.1.2 Detection architecture

Depending on the detection performance analysis, it may be necessary to consider the radar processing architecture. If detection performance is likely to be significantly compromised by the adoption of superresolution techniques, alternative architectures may provide some mitigation.

For example an architecture where superresolution is only employed once target detection has been achieved by traditional optimised means could be considered.

4.8.5.1.3 Alternative superresolution algorithms

The MUSIC algorithm requires a-priori knowledge of the number of targets to be resolved and if the actual number of targets is different to the assumed number then some target estimates may be combined or false target estimates created.

In addition, the technique analysed here depended on separate targets having different velocities with respect to the radar. This may not

It is thus recommended that investigation into alternative superresolution algorithms be carried out. Since superresolution algorithms also have application to direction finding, this is an area of continuous study and many alternatives do exist, some of which have already been detailed in Annex A.

4.8.5.1.4 Variable integration times

Air Traffic Control radar requirements specify a 4 second update period (radar rotation rate). Considering typical antenna beamwidths and PRF of 1000Hz the most pulses available to illuminate a target within one scan is 16, some of which will be only for short range detection. The further analysis of superresolution performance should thus include an analysis of the effect on resolution performance of using fewer pulses.

In addition the effect of target variability over the integration time (Swerling) will have an impact on the system performance and should be included in this analysis.
4.8.5.1.5 Implementation into deployed radar systems

The implementation of superresolution algorithms into a future radar design or modified current radar would have significant implications on system design. In particular, the design and performance of the radar signal processor, which includes:

- Detection architecture
- Computational load
  - The additional processing that is required by MUSIC may already covered by the emergence of high-speed processors so that it can be accomplished in real-time – however the hardware requirements should be analysed
- Oversampling
  - A/D sampling and processing of the signal returns must be at least at the superresolution extrapolated bandwidth, not the transmitted bandwidth. The impact of this change to the design of the signal processor must be considered.

In addition, as seen from the Watchman analysis in section 4.3.4.1.1, the benefits of operating with reduced bandwidth are minimal unless other techniques can be used to control the transmitted spectrum. Such a system would benefit from the development of a linear radar transmitter to allow pulse shaping.

4.8.5.1.6 Development timescales

Due to the current immaturity of these superresolution techniques, they are unlikely to be mature enough for deployment into safety of life ATC systems within the next 5 – 10 years.

As indicated in section 4.2.3 timescales for procurement and upgrade of radar systems in the UK limit the opportunities for deployment of new spectrally efficient technologies. However, should rapid progress and a sufficiently good safety case be made, there may be an opportunity to include some superresolution capability as part of a mid or late life upgrade to the currently deployed solid state ATC systems.
4.9 Review of passive sensor systems potential

The main objective of this study is to review the potential of passive RF sensor systems that could utilise existing RF signals from the numerous emissions available that would be most suitable for civil airspace monitoring. The secondary objective is to identify candidate signals, associated high level signal processing techniques, and provide an indication of performance.

4.9.1 Background

There is an increasing interest in the potential of passive RF sensor systems, or passive radar, to provide a range of civil airspace monitoring functions that are currently provided by air traffic control (ATC) radars. The majority of long range air surveillance radars operate in the L and S bands, which historically have offered a good compromise between operating performance, detection, resolution, accuracy, and cost in real world conditions [15]. Since these ATC radars are in constant use, operating cost is not trivial. Thus if passive radar systems could offer a similar airspace monitoring performance, then that could release a portion of the spectrum, used by the ATC radars, so bringing a range of financial benefits.

Instead of having their own transmitters, passive radar systems use ‘transmitters of opportunity’. Targets are illuminated by the transmitter, and scattered energy from the target is used at the receiver for target detection. Passive radar differs to conventional radar in the types of waveforms available, output powers and the transmitter(s) - target – receiver(s) geometries involved, as illustrated in Figure 4.9-1. Passive radar performance for monitoring UK civil airspace will depend upon the types of signals (and their consistency) transmitted by other users of the RF spectrum.

![Passive radar](image)

Passive radar

![Bistatic radar](image)

Bistatic radar

Figure 4.9-1 Passive Radar Concepts

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13 The radar use of part of the spectrum is assumed to be at zero cost.
Since most passive radar systems are still the subject of research and development this study adopts a generic approach and discusses a number of potential techniques, such as bistatic and multistatic receivers, forward scatter radar and passive coherent location.

### 4.9.2 Review of potential signals

The potential of a range of emissions, such as analogue terrestrial television, digital television, mobile phone systems, FM radio, DAB and direct broadcast satellite are examined for passive sensing for civil airspace monitoring. Experience indicates that greater coverage is likely to be provided by the lower frequency broadcast systems, as these have higher output powers (hundreds of kW) and broader aircraft RCS characteristics. The focus of the work is on prominent emissions in the 100 MHz to 1250 MHz region of the spectrum.

#### 4.9.2.1 Signals present

There is considerable data on broadcast signals that is widely available. The significant signals that are likely to be commonly available to most types of passive radar are summarised in Table 4.9-1 below.

<table>
<thead>
<tr>
<th>Service</th>
<th>Frequency (MHz)</th>
<th>ERP (kW)</th>
<th>Modulation</th>
<th>Transmitter polarisation</th>
<th>Transmitter mast height (m)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analogue radio</td>
<td>0.1 – 1200</td>
<td>AM</td>
<td></td>
<td></td>
<td></td>
<td>being phased out</td>
</tr>
<tr>
<td>Local FM radio</td>
<td>93.7 – 107.9</td>
<td>0.001 – 5</td>
<td>FM</td>
<td>H and V</td>
<td>10 – 270</td>
<td></td>
</tr>
<tr>
<td>BBC FM radio</td>
<td>88.1 - 99.7</td>
<td>0.01 -250</td>
<td>FM</td>
<td>H and V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local DAB</td>
<td>218.64 - 229.07</td>
<td>0.05 - 10</td>
<td>COFDM</td>
<td>V only</td>
<td>10 – 292</td>
<td></td>
</tr>
<tr>
<td>BBC DAB</td>
<td>225.648</td>
<td>0.5 – 10</td>
<td>COFDM</td>
<td>V only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analogue TV</td>
<td>474 – 850</td>
<td>0.001 – 250</td>
<td>PALD</td>
<td>H and V</td>
<td>20 – 313</td>
<td>being phased out</td>
</tr>
<tr>
<td>DVB-T</td>
<td>474 – 850</td>
<td>0.003 – 250</td>
<td>COFDM</td>
<td>H and V?</td>
<td>99 - 734</td>
<td></td>
</tr>
</tbody>
</table>

Clearly in normal analogue broadcasts there will be apparent breaks in modulation of some transmissions, for example natural pauses in conversations and discussions, brief silent spells in music, etc, and so the signals may not be entirely continuous. Whilst this could present a problem for a passive radar system using a single modulated signal for target detection, passive radar systems that use multiple signal sources and multiple bands are unlikely to experience a complete lack of suitable signals and so should maintain surveillance coverage.
4.9.2.2 Transmit antenna

There is a considerable amount of information on broadcast transmitters provided on the broadcasters’ websites, BBC, ITA, etc. A number of independent websites also include photographs of broadcast transmitters and antenna configurations, together with technical information on the transmitters and services transmitted. This often includes details of antenna arrangements for many of the above services.

Many websites include photographs that show typical Digital Audio Broadcast (DAB) antennas. The examples given show antennas with 2 to 8 vertically polarised dipoles radiating at 225MHz. From the pictures the element spacing (assuming half wavelength dipoles) is about 0.8 wavelengths. Assuming uniform illumination, this gives half power vertical beamwidths of approximately 32°, 16° and 8° for 2, 4 and 8 element arrays respectively. High power transmitter sites will use more directive arrays to achieve coverage and so reduce output power requirements. Thus it would be expected that the 2 element arrays would be used for low EIRP sites and 8 element arrays for high EIRP sites. Higher power transmitters usually employ tall transmitter masts to give extra height to increase the coverage area. Surface coverage is assisted by the natural refraction of the atmosphere for radio waves and the radio horizon extends beyond the optical horizon.

The BBC website includes details of the EIRP of the BBC Digital Radio Transmitter sites [173]. One local transmitter (at TL779050) was viewed. Visual observation of the transmit antenna showed it had four vertical dipoles in its DAB antenna.

The vertical Far-Field power patterns of 2, 4 and 8 dipole arrays were calculated, using the approximation that the array pattern is the Fourier Transform of a uniformly illuminated aperture (i.e. the sin(x)/x or ‘sinc’ function). The free space power patterns are shown in Figure 4.9-2. The sidelobes shown are higher than would be in practice as these do not include the contribution of the antenna element in pattern.

![Vertical Power Pattern](image)

*Figure 4.9-2 : Transmit antenna vertical power patterns*
This vertical power pattern indicates where the transmitted energy will be radiated. Broadcast transmitters are designed to provide coverage to predominantly ground based users, while passive detection of civil aircraft will rely on the energy that is radiated into the hemisphere above the transmitter. This will depend upon the aircraft altitude, range from transmitter and transmitter vertical radiation pattern. The relative elevation angle with range for different elevation aircraft is shown in Figure 4.9-3, for a standard atmosphere and a smooth curved earth.

![Elevation angle at launch](image)

**Figure 4.9-3 : Aircraft elevation variation with ground range**

### 4.9.2.3 Receiver dynamic range aspects

Passive radar requires a reference signal, usually the illuminating signal, in order to correctly process signals received from the target. For typical sized targets the direct signal, $S_D$, will inevitably be much greater than the indirect (target) signal, $S_I$:

$$S_D \propto (R_t)^2 \text{ compared with } S_I \propto 4\pi\sigma(R_1)^2(R_2)^2$$

assuming an omnidirectional transmitter. Where $R_B$ is the baseline range, $R_1$ and $R_2$ are the target ranges, and $\sigma$ is the target RCS, as illustrated in Figure 4.9-4.
This aspect was examined by analysing a number of scenarios with 10m$^2$ and 100m$^2$ RCS sized targets, representing civil aircraft, and transmitters at 5, 10, 20 and 50km ranges ($R_B$). Figure 4.9-5 and Figure 4.9-6 show graphical results for 10m$^2$ and 100m$^2$ sized targets respectively.

Figure 4.9-4: Bistatic Geometry

Figure 4.9-5: Direct versus Indirect signal strength - 10m$^2$ target RCS
The results indicate a difference in signal strength of at least 105dB for the 10m² target. This dynamic range, together with a margin for larger and smaller targets, presents a demanding technical requirement for a passive radar receiver.

4.9.3 Passive radar

A number of passive radar concepts are briefly discussed.

4.9.3.1 Bistatic radar

Current ATC radar systems are monostatic, i.e. they use a common antenna for transmission and reception of radar signals. In bistatic radar [174] the transmitter and receiver systems are not co-located and may be separated by large distances. This geometry has a number of advantages and limitations compared to monostatic radar. Historically bistatic radar has been the subject of considerable research [175], but few microwave systems have become operational.

Bistatic radar is assessed here in the context of using existing broadcast signals for the detection of aircraft targets. A significant body of research into quantifying the performance of bistatic and multistatic radar has been undertaken, and this continues to be a theme of
current radar research, see [176] and [177]. The bistatic RCS signature of a civil aircraft has been reported as being greater than the monostatic signature.

In general the performance of a passive radar with a given broadcast waveform can be quantified in appropriate detail. However this tends to be scenario, geometry, waveform and time dependent. Whilst detection performance can be quantified in a given scenario, aircraft range and Doppler measurement of sufficient accuracy for ATC is also required.

4.9.3.2 Multistatic radar

![Multistatic passive radar](image1)

![Forward scatter radar](image2)

Figure 4.9-7: Multistatic & Forward scatter radar

4.9.3.3 Forward scatter radar

Forward scatter radar (FSR) is a special case of bistatic radar, with the receiving antenna pointed directly at the transmitter, along a baseline. FSR exploits Babinet’s principle to provide the forward scatter signature [178] of the target, which results in an enhanced signal in the forward scatter direction along the baseline with the strength of this signal that depends upon the physical size of the target. Analytical techniques have been developed [179] to estimate this forward scatter signature, which for a small aircraft can be >30dBm² at UHF frequencies, and so would be even greater for civil aircraft. The peak of this forward scatter signal is along the baseline, i.e. at 180°. As a diffraction pattern this forward scatter signal also has an angular extent, in both azimuth and elevation. This angular extent depends upon the target size and operating frequency. In general the higher operating frequencies produce greater forward scatter signal strengths for the same transmitter power, while the angular extent of the high forward scatter signal reduces. Lower frequencies give broader angular extents, but lower peak forward-scatter signals. The accuracy of target angular measurements tends to be inferior at lower frequencies for
practical antenna sizes. Clearly there is an optimisation of sensitivity and coverage as a trade off between these parameters. Predictions have indicated that FSR systems will operate over a limited arc of coverage, typically several tens of degrees, provided by the forward scatter signature. A reasonable compromise between angular coverage and accuracy for FSR is around the 400MHz to 800MHz region. However outside of this limited FSR arc, other passive radar techniques, bistatic radar and Passive Coherent Location (PCL) operation can be used.

FSR operates with limited bandwidth or CW signals and thus only measures Doppler, caused by aircraft velocity (rate of change of range) and aircraft angle. Tracking methods have also been developed [180].

The FSR system geometry includes a region, close to the transmitter - receiver baseline, where the reflected target signal has a low to zero Doppler, which competes with the direct signal. This can limit or exclude target detection in this region and other technical factors can affect detection:

- Doppler signal, which is a function of the operating frequency, target velocity and FSR system geometry,
- Doppler resolution (typically of the order of a few Hz), which is dependent on the integration time, FSR system geometry and equipment performance.
- transmitter performance, especially close to carrier noise performance and stability

4.9.3.4 Time difference of arrival / Passive coherent location

Passive Coherent Location (PCL) is another passive radar method which uses transmitters of opportunity as sources of illumination. Here the direct signal is used as the reference signal, and reflected signals from the target, which have a longer path length and thus arrive at the receiver slightly later. Advanced signal processing algorithms are used to extract time difference of arrival (TDOA) of the target signal with respect to the reference signal. Some approaches may also measure frequency, such as Doppler, caused by target motion. Depending upon the antenna and receiver configurations, angle of arrival (target bearing) may also be derived.

In the horizontal plane a single TDOA measurement will locate the target to an ellipse, also known as an isorange contour, with the major axis formed by the transmitter receiver baseline, as shown in Figure 4.9-8. The ellipse is the locus of all points with the TDOA path length difference. The isorange contours are shown for 10\(\mu\)s time (path length) difference intervals, which results in uneven range resolution over the region. This produces better range resolution along the axis of the receiver sites compared with off axis.

Further measurements using different transmitter geometries will produce separate TDOA ellipses. The intersection of these ellipses enables the position of the target to be determined within certain limits.
The lower diagram of Figure 4.9-8 illustrates a transmitter at Hemel Hempstead and a passive receiver at Heathrow, and then a second transmitter at Crystal Palace, again with iso-range contours for 10µs time (path length) difference intervals.

In practice the errors in determining target position are related to the intersection geometry. Near tangential intersections introduce large errors (the region North West of Hemel Hempstead), while minimum errors occur with near normal intersections (the region North East of Heathrow). As can be seen from [181] this dilution of precision (DOP) aspect affects many measurement systems, and these effects can be well characterised. Clearly a passive radar system will have greater accuracy when it uses multiple transmitters and transmitter locations that result in several near normal intersecting ellipses. However this will be highly location and scenario dependent. In practice civil aircraft targets operate in three dimensions, although the direct signal is almost two dimensional, and so the
constant-time-delay surface, discussed above, is actually an ellipsoid and aircraft position in three dimensions can be estimated from the intersection of multiple ellipsoids.

Tracking techniques can be used with successive position estimates to provide updated target position, velocity, etc., for each target from the TDOA measurements. In general good 2D tracking of a target is achieved when the target is detected with two or more spatially diverse TOO illuminators; and 3D tracking is possible where the target is detected on three geometrically diverse TOO illuminators. 3D tracking will be required for civil airspace applications.

4.9.4 Passive radar sensor performance

Passive radar system performance was evaluated using a basic model based on the bistatic radar range equation. This provided results in graphical form.

Example performance was estimated assuming a notional (ideal) passive radar receiver system located at Heathrow airport, using local DAB signals as illuminators and 1m² target RCS (0dBm²), used in CAP 670 for comparison. Civil aircraft are likely to exhibit larger RCS values than this.

Six example altitudes are shown in Figure 4.9-9, 500m, 1000m, 2000m, 3000m, 5000m and 10000m, which illustrate the effect of the vertical power pattern of the transmitters. For this illustration a common vertical power pattern has been assumed, with 8° main beam and -13dB first sidelobe, etc, as plotted in Figure 4.9-2.

![Graph showing SNR (dB) vs Latitude and Longitude for 500m and 1000m altitudes.](image)
Study into Spectrally Efficient Radar Systems in the L and S Bands
Ofcom Spectral Efficiency Scheme 2004 - 2005 (SES-2004-2) 241

4.9.4.1 Detection coverage estimates

The detection performance estimates have assumed an ideal passive radar system with quantified gains and losses, and for a system free from practical imperfections such as limited dynamic range (see Section 4.9.2.3), direct signals reducing receiver sensitivity and other non-linearities. Actual passive radar systems may not achieve this level of performance.

The detection performance estimates illustrate how the detection performance varies with aircraft altitude, which is not surprising as broadcast transmissions were assumed. The elevation pattern of the broadcast transmitters will have been optimised for terrestrial coverage. Civil aircraft in controlled airspace are normally flying above 2500 feet or 800 metres altitude and higher, such as 30,000 feet. When high altitude civil aircraft are nearly overhead of a ground transmitter, the aircraft are above the main beam of the transmitter, and so are only illuminated by the sidelobe signals, at -13dB, -18dB or even lower, as illustrated in Figure 4.9-2. In other cases an aircraft could be close to a null in the transmit
elevation pattern, and so would receive almost no signal at all from that transmitter. Thus detection would be extremely limited when using that transmitter as an illuminator.

Thus from a civil airspace surveillance viewpoint it will be important that civil aircraft are illuminated by higher power transmitters from longer ranges, where they are most likely to receive main beam or first sidelobe illumination. This may present issues from a passive radar system viewpoint, where the direct signal from the distant higher power transmitter, to form the reference for the signal processing, is limited by the radio horizon. Also it will be desirable for multiple signals to be present at all times. However once a track has been established for an aircraft, detection information from a single transmitter geometry may be sufficient to maintain track for limited periods.

The passive radar systems detection performance was estimated using a 0.33 sec integration interval. Passive radar could provide a more frequent update of aircraft position than that provided by rotating ATC radars. Assuming a SNR of 20dB or greater, Figure 4.9-9 shows that consistent passive radar detection coverage could be obtained over most of the region, which is about 111km North-South and 69km East-West, for altitudes up to ~3000m, and reducing progressively above that.

4.9.4.2 Accuracy and resolution

Accuracy in a multi-static passive radar system, as with conventional monostatic radars, is governed by inherent resolution and SNR [12]. The resolution of a radar system is principally determined by the waveform characteristics of the transmitters used. The modulation bandwidth of modern, digital transmissions, such as DAB or DVB-T is large (1.5MHz to 8MHz) whilst those of traditional, analogue, e.g. FM, waveforms (several 10s of kHz) is small. Consequently, these former waveforms give an inherent improvement in range resolution compared to the latter. In a bistatic or multi-static configuration, where the receiver is not co-located with the transmitter(s) the relative positions of the transmitter(s), receiver and aircraft target govern the actual resolution of the system, as illustrated in Figure 4.9-8.

Where a target is on the extended baseline formed by the transmitter and receiver positions, and is behind one or the other, the situation resembles the monostatic case. Here, the resolution is determined, as stated above, by the waveform modulation. When the target is on, or near the baseline, and between the transmitter and receiver, the resolution is extremely poor (more than twice as bad as the monostatic case) or non-existent 14. For target positions further off the baseline the resolution improves and tends towards the monostatic case, but not as quickly as for a target on the extended baseline as described above. Recent work [184] has examined some of the resolution (both range and Doppler) aspects of passive radar system waveforms via the bistatic ambiguity function and quantifies the conclusions given here.

The SNR of a passive radar system may be predicted by the bistatic radar equation [2]. Contours of equal SNR give so-called ovals of Cassini, which are a family of quartic curves.

---

14 The target Doppler is zero or close to zero and will usually be masked by the direct transmitter signal.
In most cases these resemble ovals, with the transmitter and receiver at their focii. For high SNR the contours resemble either a lemniscate (figure of eight curve) or two disconnected loops, one around the transmitter and the other around the receiver. In essence, then, range and Doppler accuracy would be greatest when a target is closest to either the transmitter or receiver or between them and close to the baseline.

Civil aircraft also need to be located in altitude as well as range and bearing. In a conventional radar a monopulse method is often used. Here the radar receiver system forms two elevation beams and the relative target strength in each beam is used to derive aircraft elevation. Passive radar systems could adopt a similar approach. As with any measurement, high accuracy requires a good signal to noise ratio and reasonably narrow beamwidths, not unlike those used by the L and S-band ATC radars. However, as most passive radar systems would use lower frequencies than these, their absolute angle measurement capability for the same size of antenna would not be as good.

In TDOA systems, outlined above, a single TDOA measurement will locate the aircraft to an ellipse in the horizontal plane, and multiple TDOA measurements provide an intersection of these ellipses. These ellipses are in fact hyperboloids, and thus the intersection of multiple TDOA hyperboloids provide aircraft position in three dimensions. However due to the geometry involved, at least three hyperboloids are required to provide unambiguous position and this requires three transmit receive baselines. This is likely to involve several, suitably located, receive sites, which could also be shared with neighbouring passive radar systems. Further the intersection of the hyperboloids in the vertical (altitude/height) plane is almost tangential, resulting in poor elevation accuracy.

### 4.9.4.3 Other signals

Most larger civil aircraft are fitted with SSR transponders that relay information about the aircraft, the flight and its position, as determined by on-board instruments.

Automatic Dependent Surveillance- Broadcast or ADS-B, is a new reporting system that is being developed by the international aviation industry [182]. In operation aircraft (or other vehicles or obstacles) will broadcast a message on a regular basis, which includes their position (such as latitude, longitude and altitude), velocity, and possibly other information. Other aircraft or systems can receive this information for use in a wide variety of applications. Current surveillance systems, such as ATC radar measure aircraft position, while ADS-B based systems will receive accurate position reports broadcast by the aircraft. These position reports are based on accurate navigation systems, such as GPS satellite navigation systems.

In the longer term we can also expect mobile phones to be allowed to operate on passenger aircraft, either directly or more likely through an aircraft installed mobile phone micro base station. Thus there may be mobile phone control channels, or other continuous transmissions which could be used to locate the aircraft.

This seems an attractive approach, with regular transmissions from the aircraft which could be used by passive ground based systems to locate and track the aircraft position. Clearly this could work well, provided that the signals are radiated and the navigational information is correct. However, there have been a number of high profile events where SSR or transponder equipped aircraft have suffered equipment malfunction [183], incorrect setting...
or deliberate switch off, which highlight the limitations of relying on active transmissions alone to monitor aircraft position. Additionally there may be other aircraft that do not require to be fitted with transponders, etc., so locating these will continue to require primary or passive radar systems.

The European Commission is funding the CAPANINA project [185]. This aims to develop high altitude platforms (HAPs), such as solar-powered aircraft and airships, which can maintain near stationary position at heights of about 20km on a continuous basis. These HAPs would be used to provide lower cost telecommunications and other services. The HAPs could also provide services such as mobile phones, broadband internet, digital television and radio, and military and civilian surveillance. Transmissions from these HAPs, which are expected to cover a region of about 60km diameter on the ground, may be suitable for passive radar applications, depending upon the waveforms and output powers employed.

4.9.4.4 Passive radar systems

Individual passive radar system coverage is a useful parameter, as it is directly linked to the number of passive sensor systems required within a network of such systems to provide a specified level of detection capability. However as indicated in Section 4.9.3.4, the passive radar system generally needs to receive signals from at least two and preferably three spatially diverse TOO illuminators for TDOA processing to provide accurate aircraft location. Thus the passive radar receiver must have line of sight to the TOO, except where accurate predictions of the reference signal can be made. As the distribution of broadcast transmitters is somewhat localised across the UK, practical passive radar system coverage tends to vary with geographical location. Nevertheless the individual system coverage is a useful initial measure.

This can be assessed by considering the broadcast transmitter and passive sensor receive antennae heights to give an indication of the maximum distance obtainable between the transmitter and the receiver, assuming a smooth curved 4/3 earth, see Table 4.9-2. It is assumed that the passive radar receive antenna would be installed at heights of not less than 30m. 200m is a typical height of a commercial broadcast radio or television broadcast antenna.

This maximum distance then provides an indication of the plan area of the surveillance region that the passive radar sensor could achieve, assuming the target was not masked by the terrain, curvature of the earth, etc. For simplicity a one third area was assumed, as three transmitters are required for good target location. From this the number of passive radar sensors required for ATC surveillance can be estimated for a given region, say the area of the United Kingdom at 214,600km² 15, assuming a perfect lay-down of passive radar systems, with three transmitters at 120° intervals, and assuming no overlap between systems.

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15 see http://worldatlas.com/webimage/countrys/europe/uk.htm
Table 4.9-2: Passive Radar coverage

<table>
<thead>
<tr>
<th>Transmitter height, m</th>
<th>Passive receiver height, m</th>
<th>Maximum LOS distance, km</th>
<th>Passive radar plan area, km²</th>
<th>Number required for UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>30</td>
<td>51.8</td>
<td>2812</td>
<td>87</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>58.4</td>
<td>3572</td>
<td>69</td>
</tr>
<tr>
<td>50</td>
<td>70</td>
<td>63.8</td>
<td>4256</td>
<td>58</td>
</tr>
<tr>
<td>100</td>
<td>30</td>
<td>63.9</td>
<td>4278</td>
<td>57</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>70.5</td>
<td>5205</td>
<td>47</td>
</tr>
<tr>
<td>100</td>
<td>70</td>
<td>75.9</td>
<td>6025</td>
<td>41</td>
</tr>
<tr>
<td>200</td>
<td>30</td>
<td>81.0</td>
<td>6875</td>
<td>36</td>
</tr>
<tr>
<td>200</td>
<td>50</td>
<td>87.6</td>
<td>8037</td>
<td>30</td>
</tr>
<tr>
<td>200</td>
<td>70</td>
<td>93.0</td>
<td>9049</td>
<td>27</td>
</tr>
</tbody>
</table>

Not surprisingly this assessment shows that fewer passive radar systems would be required with the greater height antennas. This analysis is for plan coverage and aircraft altitude coverage will be affected by the vertical power pattern and transmitter powers. Additionally in real world scenarios some of the higher antenna systems are likely to contribute coverage into two or three adjacent passive radar regions, and this may include the coastal-offshore regions.

In addition to the technical and coverage performance aspects there are other considerations as to which signals should be used for passive radar. Clearly the fewer the number of passive sensor installations required, the lower would be the initial and in-service operational costs. However a number of broadcast transmitting antenna sites are used for several broadcast services, so while these provide additional frequencies and waveforms they do not assist in the system geometry. Thus clearly passive radar coverage will be highly scenario specific.

4.9.4.5 Signal reliability and availability

The passive radar concept uses a few of the many existing transmissions from a variety of broadcast operators. However there may be a reliability or availability issue associated with these signals that could translate into a safety critical issue for passive radar.

For example how acceptable is it for ATC services to be reliant on third party transmissions over which they have no control? In a technology neutral spectrum trading environment the transmissions used by passive radar could cease without warning, the waveforms could change, etc. Thus passive ATC radar system design would need to consider alternative transmissions and signal redundancy to anticipate such changes, in case they arise. Whilst there are likely to be several alternative transmissions available, they may not be able to provide as favourable a geometry for the passive radar as the missing signal, which could affect detection and accuracy performance. One option might be for the ATC system to have agreements with broadcasters on signal availability or to provide their own. Normal ATC communications traffic is probably too intermittent to be viable on its own.

It is not clear how this signal availability issue might affect passive ATC radar systems in practice, however it is clear that it would complicate the system architecture and thus hardware and locations, and the planning processes.
4.9.5 Summary

This assessment indicates that, 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, considering the transmitter beamshapes generated by TOO, would be expected to reduce commensurately as the altitude of the aircraft increases.

It seems unlikely that practical passive radar systems, as outlined above and using terrestrial broadcast transmissions, could replace the ATC en-route radars in the near future, due to the higher altitudes at which en-route aircraft travel. When high altitude platforms (HAPs) are used as broadcast or communications repeaters, this situation will change.

However at lower level (up to around 3,000 m altitude), there is potential for passive radar systems to detect civil aircraft in scenarios with favourable transmitter geometry as indicated by Figure 4.9-9.

Location accuracy is highly dependent upon transmitter-receiver geometry, the broadcast waveforms being used, and the type of passive radar system processing proposed. Update rates on target position from passive radar systems could be more frequent than conventional rotating ATC radars. Obtaining accurate aircraft altitudes however, could prove to be more difficult.

This assessment has also provided an indication of the numbers of passive radar systems required for a given UK-type coverage, and these do not appear to be excessive.

There are, however, signal reliability 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.
5 Conclusions and recommendations

This study has investigated some of the challenges related to improving the spectral efficiency of ATC radar systems. A number of avenues have been explored, from incremental improvements to current and developing radar technology through to entire system concept changes.

Since it would not require a change of system concept, options for changing and improving high power pulsed radar designs are attractive. The benefits of this approach include much shorter development timescales, lower costs and easier integration into the current infrastructure. In addition, it would not need as complex and rigorous certification and adoption of new regulations that alternative approaches would require.

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).

The conceptual approaches have been categorised in three ways. Conclusions about the various technical options for each approach are outlined below:

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

- It is technically feasible to SHIFT ATC radar to a different band, product development timescales would be of the order of 6 years. However, considering the much higher power required, performance issues, development timescales, development and procurement costs and congestion in the candidate C- and X-bands this option has a low probability of actually occurring.

Improve radar in terms of their spectral efficiency (SQUASH) and re-plan their allocations to take advantage of this

A number of options for achieving this were explored. The conclusions reached for pulsed radar designs included:

- Reducing the transmitted bandwidth of TWT based Watchman ATC radar is feasible. This would yield some modest reductions in required radar spectral separations but may not be consistent with military radar requirements.

- Since modern solid state radar have close to the best spectral efficiency of current radar technologies. The move towards solid state transmitters in ATC radar is consistent with improved spectral efficiency.
The silicon bipolar solid state technology utilised in these transmitters is limited in its achievable spectral efficiency. If further spectrum efficiency needs to be realised a change in transmitter technology is required.

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.

In terms of alternative radar technologies:

While in principle CW radar systems may have the potential to reduce radar spectral requirements, there are a number of limitations including their susceptibility to interference and their inability to directly measure range. Solutions for these limitations are as yet immature. This means that there are a number of significant technological hurdles before CW systems can be accepted as feasible for the provision of ATC services.

It is clear that 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.

At a technical level, ideal passive radar systems could provide reasonable detection performance of civil aircraft, however, elevation cover is limited by transmitter antenna patterns. There are also signal availability, reliability and redundancy issues affecting safety that need to be examined for ATC applications of passive radar systems.

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.

Allow radar to share the spectrum with commercial users (SHARE)

There are two conceptual approaches to sharing radar bands with other users

Underlay – where secondary users transmissions are wideband, noise-like and operate at low power compared to the radar. This 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.

Overlay – requires ‘Cognitive radio’ capabilities in both radar and other users. This approach is more amenable to sharing with CW type radar rather than pulsed and is thus unlikely to be feasible until the possible development of CW radar, at the earliest in 15 years time.

Economic / Timescale factors

In addition to technological issues, this study has considered economic and timescale issues for radar technology development. The main conclusions are:
CW, Passive and Sharing techniques for ATC radar applications are still in the concept stage and not yet mature enough to begin industrial research and development towards possible future products. It is thus unlikely that these technologies will be available in developed products within the next 15 years.

A number of options are available for significantly improving the spectral efficiency of pulsed radar. Of these LDMOS based solid state transmitter technology, capable of near linear operation, is likely to be the most effective at reducing required radar spectral separations and thus allowing more efficient planning and allocation of radar spectrum. This is the most likely and low risk direction for the development of the next generation of radar transmitters and could potentially be available to the market within 6 years. This timescale is consistent with both the procurement of new military ATC capability and mid-life upgrade opportunities in civil ATC radar.

5.1 Recommendations

While CW radar concepts are, as yet, not mature enough to demonstrate their feasibility for meeting ATC requirements, further academic research into target location and discrimination techniques for CW radar is recommended and should be assessed against both ATC requirements and other radar application areas.

Currently available broadcast transmitters limit the elevation coverage of potential passive radar systems, however, analysis of the potential of any future transmitters of opportunity should be continued. At the same time, the issues of signal availability, reliability and redundancy affecting safety need to be examined for passive radar systems.

Should there be sufficient incentives to improve the spectral efficiency of radar systems, industrial research and development of linear transmitter technology such as LDMOS devices is highly recommended. This should include transmitter replacement options for current ATC radar systems, consideration of new ATC radar designs and alternative radar application areas.
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