# A Multiband Passive Radar Demonstrator

**Dale Gould, Robert Pollard, Carlos Sarno & Paul Tittensor**
BAE Systems Advanced Technology Centre
Great Baddow, Chelmsford,
Essex CM2 8HN
United Kingdom

email: dale.gould@baesystems.com / robert.pollard@baesystems.com / carlos.sarno@baesystems.com / paul.tittensor@baesystems.com

## *ABSTRACT*

*Passive radar systems offer a number of advantages over conventional active radar systems with the exploitation of signals from the numerous RF emissions that exist in the external environment. These advantages include procurement and operational cost savings from using these third party transmissions as sources of target illumination, leading to lower power requirements and covertness. Such systems may be used for military surveillance as well as civil applications, such as airspace surveillance and surface monitoring. Typically such systems use RF emissions produced by communications, radio or television broadcast services. Each emitter has its own characteristics in terms of coverage, power level and waveform. Following work on forward scatter radar using television transmissions BAE Systems Advanced Technology Centre has designed and built a demonstrator system for passive sensor research. The demonstrator system operates over a multi-octave bandwidth and can be configured to exploit analogue and digital transmissions from broadcast and communication systems. This maximises flexibility, and allows surveillance and tracking by exploiting the optimum radar returns based on the particular geometry, coverage, waveform and target signature. In particular, multiple observations in different bands using different geometries will allow fusion of tracks to achieve more robust and accurate tracks than are available from a single band system. This paper outlines the system and design issues that were addressed during the development of the demonstrator, including the simulation model, target signatures and trade-offs associated with the different types of transmission. Results of experimental work illustrating the operation of the demonstrator system with targets of opportunity are shown.*

## 1.0 INTRODUCTION

Following several years of development and experimental trials, passive radar systems with the capability to routinely detect and track air targets using 'transmitters of opportunity' have been widely reported [1], [2]. Such passive radar systems offer a number of advantages over conventional active radar systems since they exploit signals from many third party RF emissions, from various sources. These advantages include procurement and operational cost savings, such as lower power requirements and covertness. Passive radar systems may be used for military surveillance and civil applications such as airspace surveillance and surface monitoring.

RF emissions from communications, radio or television broadcast and other services can be exploited for passive radar. Each emitter has its own characteristics in terms of azimuth and elevation coverage, power level and waveform. Building upon previous forward scatter radar studies using television transmissions [3], BAE Systems Advanced Technology Centre has designed and built a demonstrator system to act as a

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test bed for passive sensor research. This demonstrator system is designed to operate over a multi-octave bandwidth and can be configured to use both analogue and digital transmissions from both broadcast and communication systems. This is designed to maximise flexibility, and to enable surveillance and tracking by exploiting the optimum radar returns based on the particular geometry, coverage, waveform and target signature.

# 2.0 SYSTEM DESIGN ASPECTS

## 2.1 Waveform Aspects

In conventional pulsed radar the transmitted waveform is designed to provide range and range resolution and thus influences system performance. Passive sensor systems that exploit third party transmissions have no control over the transmitted waveforms. Many of the waveforms from commercial stations have been studied for their likely passive sensor system performance [4], [5]. The systems designer has a large choice of waveforms that may be used for passive sensing. One of the major requirements is wide signal availability, which implies the use of commercial broadcast transmissions. These transmissions currently include FM radio, GSM, analogue TV, digital audio broadcast (DAB) and digital video broadcast – terrestrial (DVB-T). Analogue TV transmissions in the UK are scheduled to cease in 2012, so future availability of these waveforms will be limited.

The transition to digital transmission formats provides better spectrum efficiency and has also enabled a reduction in field strengths and consequently transmitter power. Whilst this improved efficiency assists the service provider in lower running costs, it also reduces the prime power available for target detection where the signal is used for passive sensing. Already some of the major radio stations in the UK are available via DAB. Whilst AM and FM formats have considerable support and are expected to remain for many years, there will be a considerable increase in the number of digital transmissions available in the UK over the next few years. Consequently it is important to understand the performance of the digital formats for passive sensing. Deployable passive sensor systems for out of area scenarios are expected to use FM radio transmissions, but greater flexibility would be provided by a passive sensor system that can exploit both analogue and digital signals. Cross correlation processing is applicable to DAB, DVB-T and FM formats and provides a common processing approach for producing time difference of arrival (TDOA) and Doppler information. The demonstrator system was primarily designed to investigate passive sensing using digital waveforms and cross correlation processing.

## 2.2 Demonstrator Design

The demonstrator was designed to receive and process analogue and digital transmissions over a band covering 200MHz to 2GHz. It was designed to be scalable and low-cost. A four-channel system was developed, capable of capturing data at 10MHz. This provides sufficient bandwidth to process the analogue and digital transmissions of interest but also permits sustained data capture. The wider bandwidth of digital transmissions provides the potential for good range resolution.

The antenna system comprises an array of four wideband Log-Periodic Dipole antennas. Each antenna has a 200MHz to 2GHz bandwidth. The antennas are aligned at a 45° angle from vertical to permit joint reception of vertically and horizontally polarised signals, with some loss. The antennas are spaced to avoid grating lobes at the highest RF of interest.

The receiver was designed using relatively inexpensive off-the-shelf components. This led to rapid, low-risk implementation of a working demonstrator system. The main stages of the receiver include multiple IF stages with appropriate filtering. The receiver IF frequencies were chosen to enable the system to process signals in the desired RF range.

Digital signal processing follows the second IF stage through a high speed data acquisition PCI card, installed in a desktop PC. This provides four ADCs that can be clocked at up to 20MHz. The demonstrator was designed to sample four channels at a 10MHz rate with two bytes per channel, resulting in 80MB/second data capture rate. The desktop PC includes a RAID 0 array, dedicated RAID controller card and multiple PCI buses for sustained high data capture rates.

Following data capture, the main signal processing stages are performed in software.

## 2.3 Processing

The signal processing chain includes the digital down-conversion to baseband of the digitised signals recorded by a high-speed capture card, polyphase decimation to perform low-pass filtering to filter out out-of-band signals and to decimate, weighted beamforming, adaptive digital null-steering, cross-ambiguity processing and detection processing. The adaptive null-steering stage uses a reference beam formed in the direction of the transmitter of interest. The sequential decorrelation algorithm is used to derive weights which steer a null in the beams used for aircraft target detection.

The demonstrator includes channel calibration, which is provided in software prior to beamforming, and corrects the amplitude and phases of each channel to correct for mismatches in the system components. A known transmitter is used as a reference and the appropriate weighting for each channel is determined. The predicted amplitude and phase response of the system to the reference signal is calculated and used to correct the actual amplitudes and phases of each channel.

The cross-ambiguity processing provides estimates of the time-difference of arrival (TDOA) of target returns with respect to the direct signal from the transmitter (lag) and bistatic Doppler of the aircraft targets. It is estimated as follows:

$$\chi_{lag,Doppler} = \sum_{t=1}^{Nsamples} wfft_t \cdot ref^{*}_{t-lag} \cdot sig_t \cdot e^{-2\pi j \cdot Doppler \cdot t}$$

where $wfft$ are the window weights for sidelobe reduction, $ref$ is the reference signal, from a reference beam, and $sig$ is the signal from the beam of interest.

The detection processing enables fixed or adaptive (CFAR) thresholding to be applied to the cross ambiguity function, providing detections with estimated lag and Doppler values.

As the signal processing is highly computer intensive the data is transferred from the data acquisition PC to a more powerful PC processor. This is used for signal processing of recorded data and signal processing algorithm development.

## 2.4 Aircraft Signatures

A key part of the demonstrator system design is an understanding of the likely target signatures. Aircraft signatures were derived from a detailed electromagnetic simulation, using the in-house developed AGATE finite difference time domain code (FDTD) [6].

The AGATE FDTD technique was used to derive full bistatic RCS analysis using a meshed model of a Piper PA-28 Cherokee light aircraft that had been used for the earlier forward scatter trials. The PA-28 meshed model was derived from a .DXF file, see Figure 1, used in home computer flight simulators. The resulting meshed FDTD model was used to produce the data for the bistatic RCS analysis at 650MHz, see Figure 2 : 650MHz represents the analogue television scenario and could be compared with earlier simplified forward scatter modelling. The AGATE FDTD technique used approximately 55 million cubic cell elements and required several tens of CPU hours to generate the bistatic RCS data for 3 frequencies and a range of bistatic angles.

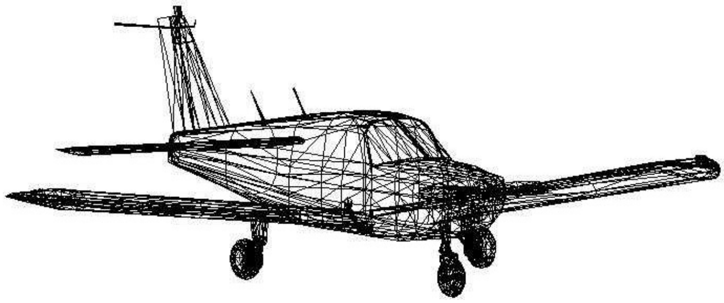

Figure 1: Piper PA-28 .DXF file

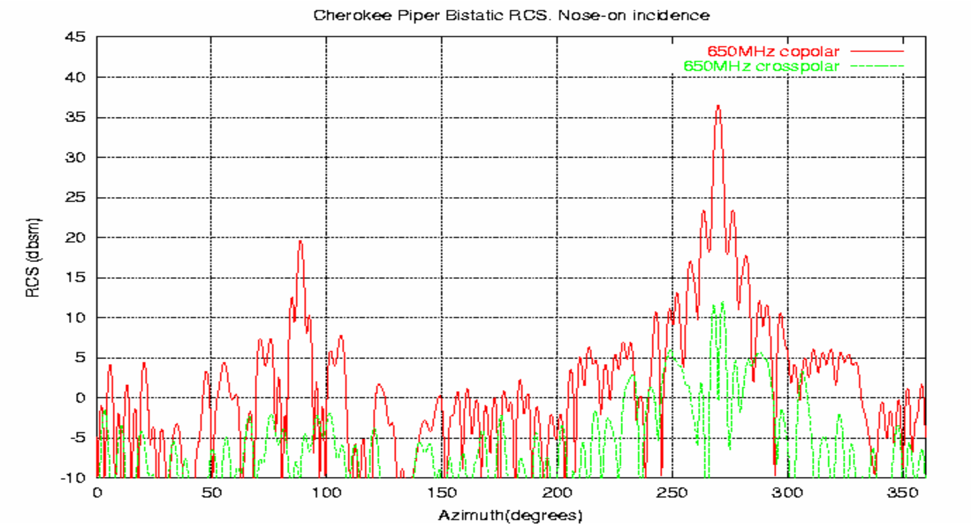

Figure 2: Estimated Bistatic RCS for Piper PA-28 at nose on incidence

For larger aircraft, e.g. Boeing 737, an excessive amount of computer time would be required for rigorous FDTD prediction of the RCS at the frequencies of interest. Instead physical optics methods offer an acceptable approximation to their RCS for the system calculations.

The results show the maximum RCS of a Piper Cherokee is estimated as the order of 30dBm$^2$ at 220MHz and 38dBm$^2$ at 650MHz, but in general is approximately 0 to 5dBm$^2$, and is lower at higher RF. However a Boeing 737 aircraft is estimated to have a maximum RCS of 39dBm$^2$ at 220MHz and 43dBm$^2$ at 650MHz, but averages out at between 10 to 20dBm$^2$.

## 3.0 PCL SYSTEM MODEL

A PCL system simulation model was developed to support the hardware and software development of the passive demonstrator system. This built on earlier work in developing a Forward Scatter radar system [3]. The PCL application was developed in MATLAB, and includes the synthesis of signals from aircraft responses to transmitters typical of analogue and digital radio and television transmissions, and the digital signal processing of the system. The primary interest is the coded orthogonal frequency division multiplexing (COFDM) family of waveforms, transmitted by DAB and DVB-T transmitters. The COFDM waveform produces a 'thumb tack' cross ambiguity function [7], enabling good bistatic range and Doppler resolution.

The signal processing simulation uses the same software as described in section 2, with the exception of the calibration stage, and the inclusion of the synthesis of the illuminating waveform (COFDM), the bistatic target response and receiver noise.

Using realistic power levels representative of transmitter and bistatic aircraft target signals, simulation studies confirmed that aircraft targets would be detectable with the processing architecture discussed above. The studies also quantified the performance required for null-steering to support aircraft target detections in the presence of the direct signal.

## 4.0 INITIAL RESULTS

Some initial results of experimental work illustrating the operation of the demonstrator system with aircraft targets of opportunity are shown in Figure 3 and Figure 4.

One target is clearly visible in Figure 3 with plots from the top to bottom of the figure. It can be seen that the bistatic Doppler was initially positive but reducing with time, indicating the bistatic range rate was reducing until the Doppler fell to zero: after which the Doppler became negative, indicating the bistatic range rate was increasing. The loci of constant range for a bistatic system are generally elliptic. Thus one can interpret that the aircraft flew on an almost tangential path to a range ellipse. The range ellipse at which the target is tangential is identified by the lag at which the Doppler was zero. Intersecting ellipses from different transmitter locations can provide unambiguous position.

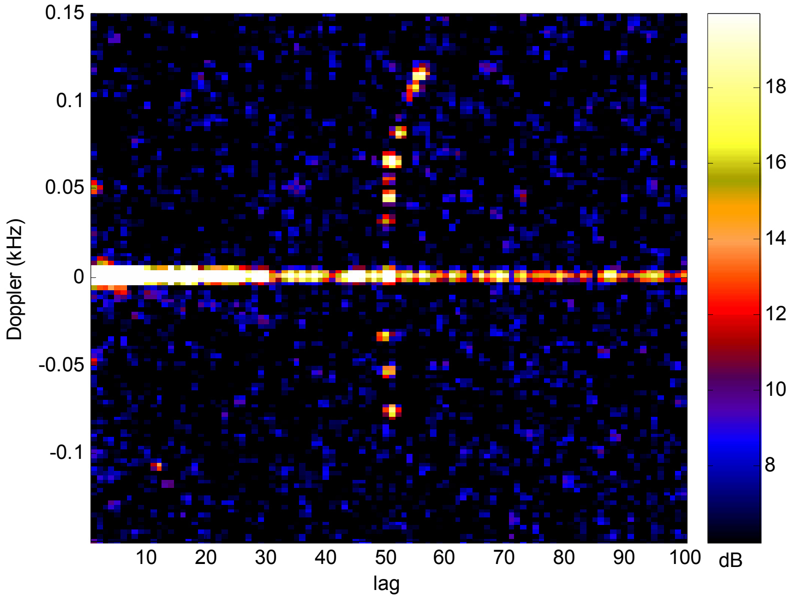

Figure 3: Single aircraft, no ADS-B data

Aircraft ADS-B data was recorded at the same time as further passive sensing data to provide aircraft positions. Figure 4 shows selected ADS-B data that has been translated to lag and Doppler and overlaid on the passive demonstrator sensor output. The ADS-B data in the lag and Doppler domain shows good correlation with the passive sensor detections. The ADS-B data reports that the aircraft were civil air traffic. The first aircraft, 'ADS-B plot 1' was departing from London Stansted Airport (EGSS), whilst the second aircraft 'ADS-B plot 2' was in the 'stack' prior to landing at Stansted.

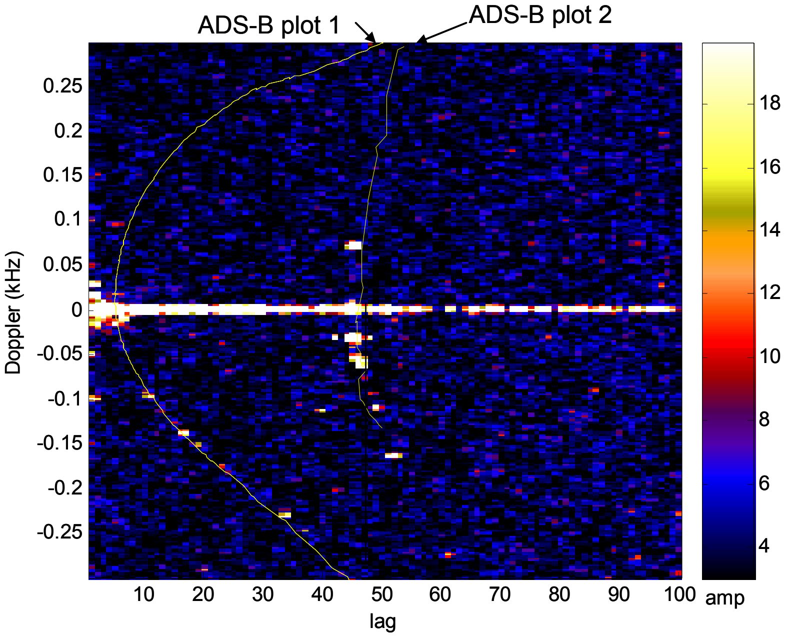

**Figure 4: Two aircraft, with ADS-B data**

Null steering is applied to the beams used for surveillance, however the cross ambiguity processing gain is sufficiently high that detection of the direct signal can still be seen in those beams, with the detections at zero lag. Figure 3 and Figure 4 also show the presence of ground clutter, which is distributed in lag along the zero Doppler line, as expected.

## 5.0 SUMMARY

The ATC passive sensing demonstrator has detected civil airliners at reasonable ranges, using distant DVB-T transmissions as the illuminating source, and off-line processing. These detections show good agreement with the ADS-B reports from civil aircraft.

There are still considerable challenges to be made to achieve real time processing. However the wide availability of large scale FPGAs, DSP processors, PC clusters and servers, offer several options to achieve real time operation within the near future. The demonstrator will now be used to investigate technology aspects associated with potential operational passive systems, such as automatic calibration and alignment for multi-channel, multi-band systems. Other work will refine the adaptive RF front end receiver design, to improve sensitivity and investigate the use of other signals, in other frequency bands, for detection and tracking. The PCL model will also be used to refine system performance, coverage and accuracy predictions.

## 6.0 ACKNOWLEDGEMENTS

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