DESIGN AND DEVELOPMENT OF A SIGNAL AND DATA PROCESSOR TEST BED FOR A PASSIVE RADAR IN THE FM BAND

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Abstract

This paper describes the design and development of the signal and data processing chain required by a passive covert radar exploiting a single non co-operative frequency modulated (FM) commercial radio station as its transmitter of opportunity. The processing chain is proved to: 1) efficiently remove interference and clutter from the received signal, 2) detect targets and extract their bistatic range, bistatic Doppler and azimuth, 3) track targets in the Cartesian domain via the innovative use of particle filtering. The whole processing sequence has been tested using emulated FM radio signals and scenarios as an input to receiving channels. Detection and tracking performance of the passive radar have been assessed comparing the performance of the signal and data processor test bed to truth data.

1 Introduction

This work aims at further developing the signal and data processing section of the experimental FM radio based bistatic radar described in [2]. The main technical advance that has been achieved is the improvement of target state estimation: target direction of arrival is now effectively integrated in the tracking algorithm and the application of particle filtering to confirmed tracks properly transforms target bistatic range, Doppler and bearing into Cartesian position and velocity. A test bed has been realized in order to verify the suitability of the whole processing chain for real time target detection and tracking and to measure the system performance when it is fed with simulated data.

This paper is organized as follows: section 2 describes the emulation of the electromagnetic environment the FM radio based passive radar has to cope with. A brief recall of the signal processing algorithms is given in section 3. Section 4 illustrates the data processing design. Section 5 describes the real time test bed. Simulation results and conclusions are respectively given in sections 6 and 7.

2 FM radio signals simulation and scenario generation

The emulated scenario generator reproduces FM stereo broadcasting according to the pilot tone standard system. The sum (Σ) signal is transmitted as baseband audio, the difference (Δ) signal is amplitude-modulated onto a 38 kHz suppressed carrier to produce a double-sideband suppressed carrier signal. A 19 kHz pilot tone, at exactly half the 38 kHz subcarrier frequency, is also generated and transmitted at 8-10% of overall modulation level. The final multiplex signal from the stereo generator modulates the FM transmitter.

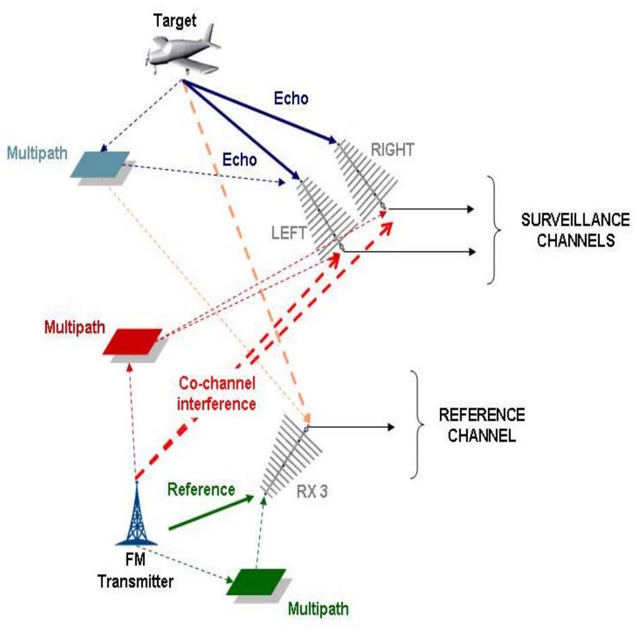

Figure 1: Passive radar electromagnetic environment.

In simulating the operative scenario, three electromagnetic sources are taken into account: 1) the FM transmitter producing the direct signal; 2) targets generating delayed and Doppler-shifted replicas of the direct signal; 3) terrestrial objects such as mountains and buildings causing multipath. The three contributions, which are depicted in Figure 1, are differently characterized in terms of power, delay and Doppler-shift, also accordingly to antennas organization. In detail, while the reference antenna - which collects the signal to be used as an optimal matched filter - points towards the transmitter, the surveillance antennas are steered so as to place the transmitter in a null of their patterns, to reduce the so-called co-channel interference (i.e., the unwanted direct signal). Noisy overall signals are finally quantized to include analogue-to-digital conversion in the simulation frame.

3 Signal processing

The signal processing block diagram is depicted in Figure 2 [2]: "Right" and "Left" correspond to the digital signals generated by the two channels of the interferometric surveillance system, whereas "Reference" is the binary data stream produced by the reference channel.

The main functions of the developed signal processor are:

- adaptive co-channel interference cancellation;
- Doppler-sensitive cross-correlation search for target echoes, using the reference signal as the optimal matched filter that provides the necessary processing gain;
- adaptive thresholding used to automatically detect targets on the two range-Doppler maps (associated to left and right channels) maintaining a constant false alarm probability via a custom bidimensional Cell-Average CFAR;
- "AND" logic to extract detections common to right and left channels, with ± 1 cell tolerance both in range and Doppler;
- bearing estimation based on the use of a simple phase interferometry. The difference between the arguments of the two range-Doppler surfaces is unambiguously related to the target direction of arrival in the azimuth sector the radar surveys, which is about ± 60°.

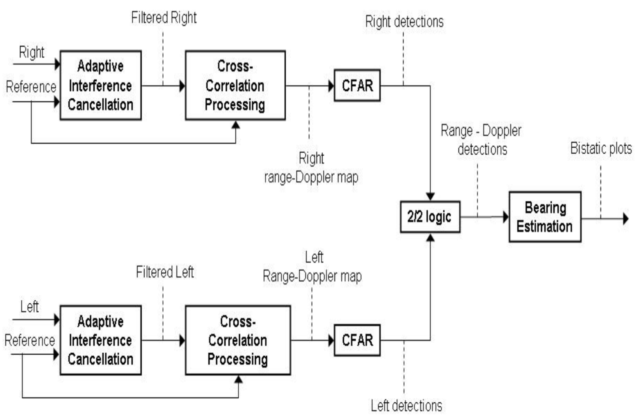

Figure 2: Signal processing block diagram.

4 Data processing

The block diagram in Figure 3 shows the algorithms that have been designed and developed to track the targets the bistatic passive radar detects.

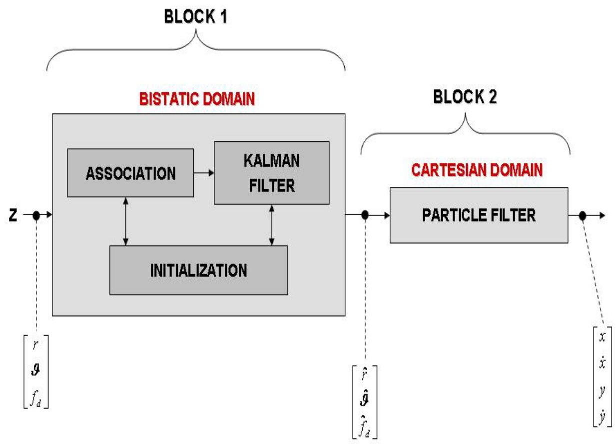

Figure 3: Data processing block diagram.

The working principle of the implemented data processor is the following. Plots relative to slowly manoeuvring targets (detection probability $P_d<1$), clutter and multipath detected in the current scan[1] are collected in the measurement vector **Z.** Each plot is a set of three measurements: bistatic range r, azimuth ϑ and bistatic Doppler frequency f_d. The measurement vector **Z** feeds the tracking algorithm, which is formed by two cascading blocks. The former implements track initialization, plot to track association and recursive filtering in the bistatic domain; in particular, target motion model linearity permits using a simple Kalman filter [2]. The need for Cartesian coordinates to be compared with Air Traffic Control (ATC) truth data has suggested the Kalman-filtered measurement vector should be followed by a particle filter [3]. Therefore the second block of the tracking architecture that has been implemented consists of a particle filter that applies to the output (i.e., confirmed tracks) of the previous block to estimate target tracks in the Cartesian domain. The simple geometric transformation is a low computational cost and less precise alternative to the particle filter, estimating only Cartesian target position.

Block 2 of Figure 3 receives the filtered measurement vector $\hat{\mathbf{u}}(t\,|\,t)$ from Block 1 and estimates target motion in Cartesian coordinates $\boldsymbol{\chi} = [x, \dot{x}, y, \dot{y}]$, according to Equation (1):

$$\hat{\mathbf{u}}(t\,|\,t) = h(\boldsymbol{\chi}) + \mathbf{v} \qquad (1)$$

where

[1] Even if surveillance antennas do not rotate, the radar system needs about 3.5 seconds to fully elaborate the 1 second's worth of received signals, which corresponds to a sort of conventional radars scan period.

$$h(\chi)=\begin{bmatrix} r_{Rx}+r_{Tx}-d \\ \angle(x+i\,y) \\ -\dfrac{1}{\lambda}\left(\dfrac{x\,\dot{x}-y\,\dot{y}}{\sqrt{x^2+y^2}}+\dfrac{(x-x_{Tx})\dot{x}-(y-y_{Tx})\dot{y}}{\sqrt{(x-x_{Tx})^2+(y-y_{Tx})^2}}\right)\end{bmatrix} \quad (2)$$

The elements of $h(\chi)$ in Equation (2) do respectively represent: bistatic range, bearing, bistatic Doppler frequency. They variously depend on:

- distance d receiver-transmitter;
- distance r_{Rx} target-receiver, and distance r_{Tx} target-transmitter;
- transmitter position $[x_{Tx}, y_{Tx}]$ (the receiver lies at the centre of the reference system).

The target is assumed to move with uniform speed along a straight line, in accordance with Equations (3) and (4), where the process noise $\mathbf{w}$ has zero mean and covariance matrix $\mathbf{Q}_{xy}$.

$$\begin{bmatrix} x(k+1) \\ \dot{x}(k+1) \\ y(k+1) \\ \dot{y}(k+1) \end{bmatrix} = \mathbf{A}\begin{bmatrix} x(k) \\ \dot{x}(k) \\ y(k) \\ \dot{y}(k) \end{bmatrix} + \mathbf{w} \quad (3)$$

$$\mathbf{A}=\begin{bmatrix} 1 & T & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & T \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

The algorithm used for particle filtering is the Sequential Importance Resampling (SIR) [1].

In our application, particle filter initialization is the major difficulty, because passive radar large measurement error makes tracking accuracy poor and because coordinates transformation from bistatic to Cartesian is ambiguous. In fact, while the correspondence between the bistatic pair $[r, \theta]$ and the Cartesian couple $[x, y]$ is univocal, unambiguity does not hold for the relation between Doppler frequency $f_d = -\frac{1}{\lambda}\frac{\partial r}{\partial t}$ and Cartesian velocity $[\dot{x}, \dot{y}]$. It depends on the fact that Doppler shift only indicates how targets are moving with respect to the ellipse (whose foci coincide with receiver and transmitter of opportunity) they are currently lying on: if $\dot{r} > 0$, they are moving towards smaller ellipses, and vice versa. Such information generates velocity uncertainty in the Cartesian domain, i.e. there are infinite couples $[\dot{x}, \dot{y}]$ generating the same Doppler frequency.

Particle filter samples are therefore initialized according to a quasi deterministic rule for position $[x, y]$ and randomly for velocity $[\dot{x}, \dot{y}]$.

$$\begin{aligned} x &= x_{init} + n_x \\ y &= y_{init} + n_y \end{aligned} \quad (5)$$

In Equation (5), n_x and n_y are Gaussian noises with zero mean and standard deviation Δ, while x_{init} and y_{init} are evaluated using Equation (6), that transforms the bistatic estimate $[\hat{r}, \hat{\theta}]$ into the Cartesian pair $[x, y]$.

$$\begin{cases} x = \dfrac{(\hat{r}+d)^2 - x_{Tx}^2 - y_{Tx}^2}{2(\hat{r}+d-x_{Tx}\cos\hat{\theta}-y_{Tx}\sin\hat{\theta})}\cos\hat{\theta} \\ y = \dfrac{(\hat{r}+d)^2 - x_{Tx}^2 - y_{Tx}^2}{2(\hat{r}+d-x_{Tx}\cos\hat{\theta}-y_{Tx}\sin\hat{\theta})}\sin\hat{\theta} \end{cases} \quad (6)$$

The velocity vector $[\dot{x}, \dot{y}]$ is instead generated randomly, according to Equation (7).

$$\begin{aligned} \dot{x} &= V\cos(\varphi) \\ \dot{y} &= V\sin(\varphi) \end{aligned} \quad (7)$$

Absolute value V is uniformly distributed in the velocity interval of interest for PCR applications; direction φ is uniformly distributed in $[0, 2\pi]$.

5 Real time test bed development

The development of the real time test bed has been strictly conditioned by adaptive interference cancellation that, because of its non parallelizable and high computational cost nature, is the processing bottleneck. In particular, two distinct programming languages have been included and combined in the test bed to develop the signal processor code. The software architecture is managed via C++, while a number of FORTRAN 90 subroutines specifically accomplish all signal processing functions (adaptive cancellation, cross-correlation, bidimensional CFAR, bearing extraction). FORTRAN is especially suited to numeric computation and our test bed current performance rests on the fact that its use has reduced adaptive cancellation runtime from about 13 seconds in the "only C++" version to about 900 milliseconds in the "C++-FORTRAN" version.

Even if the requirements on data processing are not as demanding, particle filtering is managed via FORTRAN 90 as well.

The dedicated PPI (Plan Position Indicator) application is a three screen visualizer that allows displaying simultaneously:

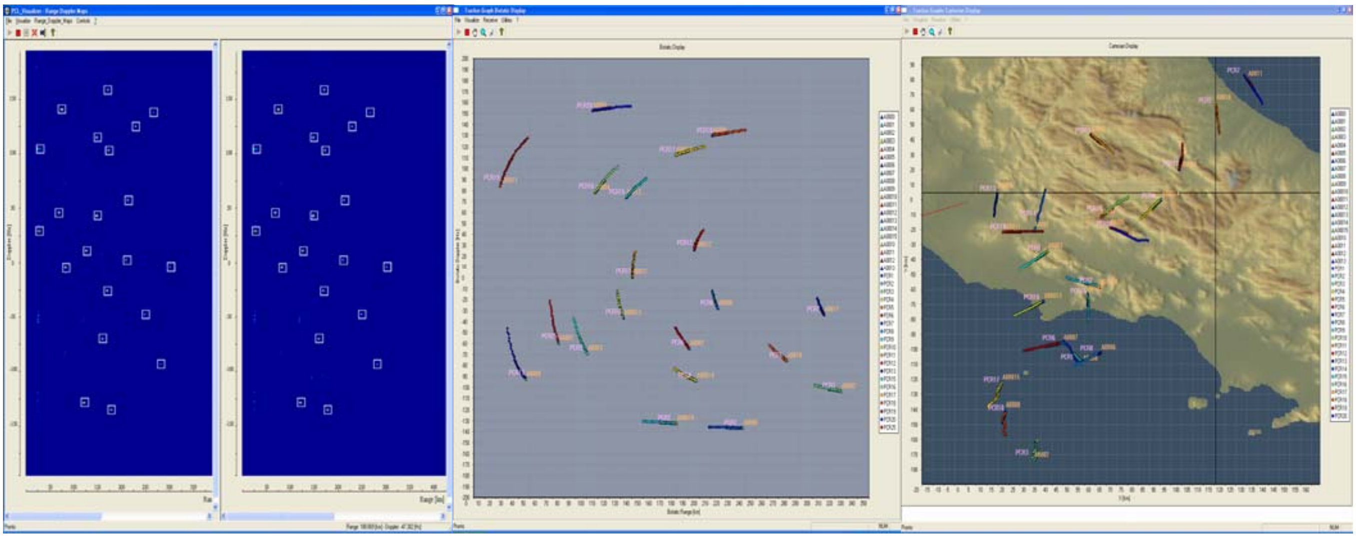

Figure 4: Three-screen visualization console.

1. range-Doppler maps and CFAR detections;
2. bistatic range-Doppler tracks;
3. Cartesian tracks.

Tracks displays do also present and overlap truth data to passive radar bistatic and Cartesian outputs.

6 Simulation results

Performance evaluation of the PCR processing chain has been achieved by measuring detection probability and tracking accuracy provided by the FM based passive radar with respect to simulated truth data. In the scenario under analysis, twenty aircraft with RCS = 10 m^2 are assumed to move along a straight line with uniform speed in the x-y plane. They are observed for forty consecutive radar scans. PCR outputs (i.e., range-Doppler maps, bistatic tracks, Cartesian tracks) are presented on the three-screen visualization console depicted in Figure 4.

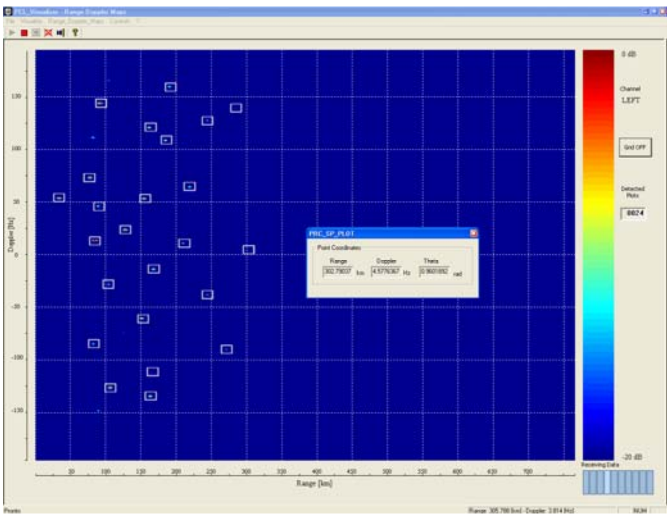

Figure 5: Range-Doppler map.

Each range-Doppler map is furnished with (see Figure 5):

- enlightened CFAR detections;
- a counter showing how many plots have been detected in the current scan;
- an interactive graphical interface that, for each plot, presents the values of bistatic range, Doppler and azimuth.

Range-Doppler tracks provided by the passive covert radar are visualized on the middle display that also presents truth data. Figure 6 points out that all twenty targets are tracked; on its turn, Figure 7, which is obtained zooming Figure 6, clearly indicates that PCR tracks and truth data overlap.

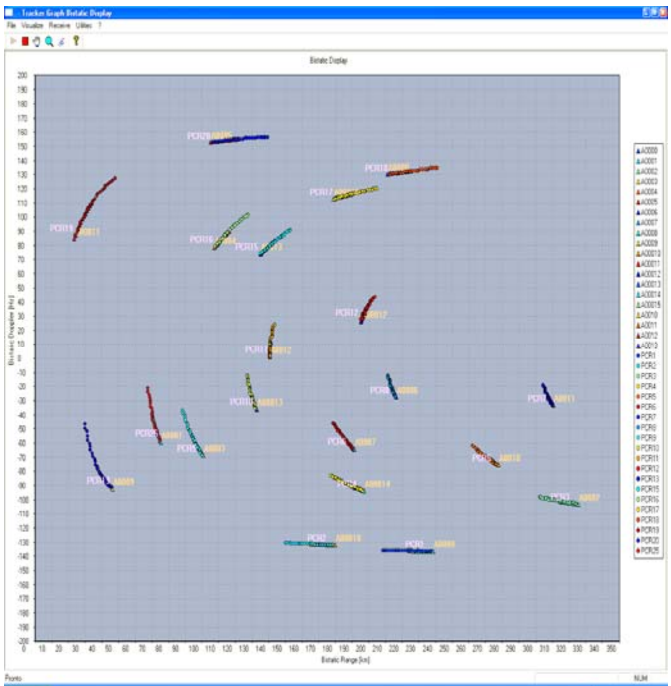

Figure 6: Range-Doppler tracks.

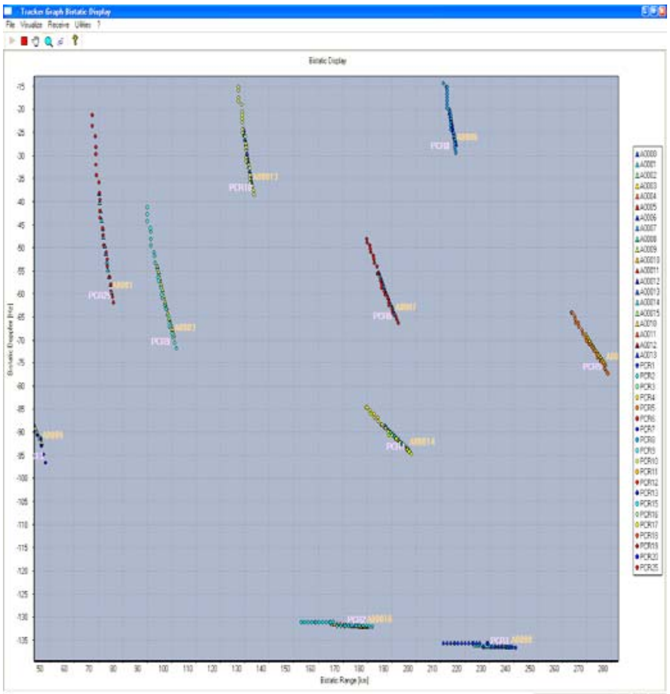

Figure 7: Range-Doppler tracks - zoom.

The most significant results are anyway related to Cartesian tracks. The comparison between Figure 8 and Figure 9 clearly states that the application of particle filtering to bistatic confirmed tracks greatly enhances the PCR tracking performance in the x-y domain. The simple trigonometrical transformation used in previous works [2] behaves acceptably well with those tracks that do not cross each other, but cannot compete with particle filtering when trajectories intersect.

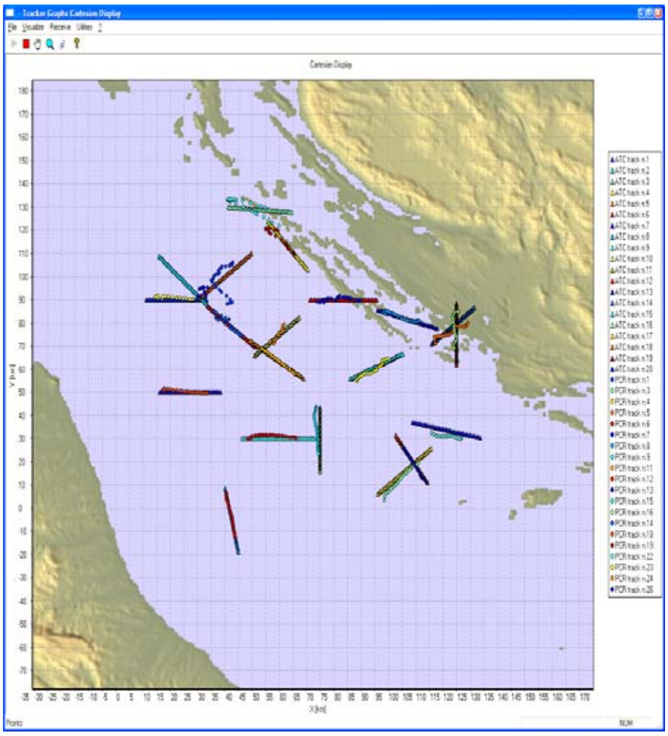

Figure 8: Cartesian tracks obtained via particle filtering.

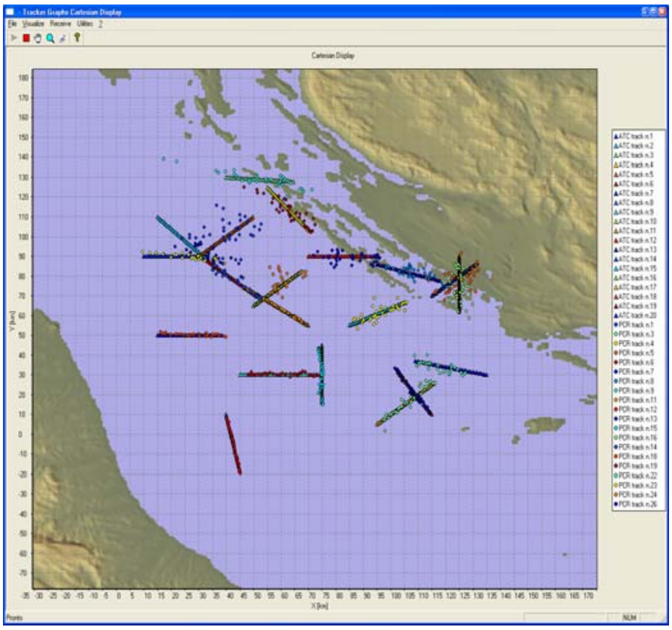

Figure 9: Cartesian tracks obtained via geometric transformation.

7 Conclusions

A real time signal and data processor test bed for a passive covert radar exploiting a single non co-operative FM radio transmitter is now available. The environment the radar is expected to work in is emulated via an exhaustive scenario generator, which reproduces the many electromagnetic contributes the antennas are supposed to receive and that may help modelling any working site. The signal and data processing algorithms have all been designed and developed according to radar coverage and real time requirements. This FM-band passive covert radar observes aircraft at ranges of up to 150 km in a 120° wide azimuth sector and refreshes target tracks every 3-4 seconds. The advanced tracking algorithm, which includes the application of particle filtering to confirmed bistatic tracks, is a noticeable step forward in the development of passive covert radars.

Acknowledgements

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