NOISE JAMMING OF A FM BAND COMMENSAL RADAR

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***Abstract*—Commensal Radars (CRs) are a class of EM sensor that use the emissions of other systems to fulfill their function, without having any impact or collaboration with the emitter of opportunity. The jamming of Commensal Radar (CR) systems, and possible ECCM responses to such jamming have not received more than a passing reference in the open literature. We examine a specific case of an FM Band Commensal radar with a multi-receiver configuration (single transmit site, many spatially distributed receivers) and find that although modest jammer power can be very effective in jamming the CR, the unknown geometry and frequencies of operation of the Commensal Radar (CR) will make it difficult to jam in practice. Simple null steering by the CR receivers is very effective. We also note that the CR system requires excellent Electronic Support Measures (ESM) to be aware of electronic attack. The paper reviews the tactical situation, and the very sparse literature. This is followed by some analysis of the effect of noise jamming, followed by simulations of jamming, with and without receiver null steering, as well as some self-protection jamming.**

I. Introduction

A Commensal Radar (CR) has many forms, but requires a transmitter of opportunity to sense targets. It has no effect on the selected transmitter, and does not collaborate with it in any way. The architecture depends on how the system detects and tracks targets of interest. We thus have many examples called “Passive Bistatic Radar” (PBR), “Passive Coherent Location“(PCL), and so on [1], [2]. In addition, since there are a multitude of broadcast and communications systems (including other, active, radars) there are many options. To keep our analysis simple, we focus on a CR that uses a single transmit site combined with a multitude of spatially distributed receivers, thus fitting into the description, “Passive Multistatic Radar” (PMR) [1, Chapter 6]. However, we consider the effects of ECM on just one node of such a radar, together with its transmitter of opportunity, forming a PBR.

It is clear that CR is transitioning from a research topic to a serious contender as a sensor for civilian (Air Traffic Management)(ATM) and military applications. The latter use implies that it will be subject to Electronic Countermeasures (ECM), but this would also be in the former case for terrorist attacks on a country's ATM infrastructure, for example, or, inadvertent interference. We have carried out an extensive survey of the open literature, and did not find significant discussion of this topic. In fact, there is an optimistic view taken by the researchers in the field i.e. that CR will be robust against ECM [3]. This view must be treated with caution, as the CR systems must consider ECM and appropriate Counter-ECM (ECCM) measures to reduce the effect of ECM.

We have also investigated the possible Counter-countermeasures (ECCM) that a CR might deploy when an attack occurs. We note that the CR must be supported by excellent Electronic Support Measures (ESM) to assist it in the task of determining that an attack has occurred, and what countermeasures are required.

We begin the paper with a review of the sparse literature, a brief overview of the geometry and signal processing of a CR, especially the system that we shall investigate in depth. This is followed by calculations of the expected performance of an ECM system (specifically a noise jammer), with noise jamming simulation results.

The paper concludes with a brief discussion of ECCM that can be deployed, with an example in simulation.

II. Literature Review

The number of CR-related publications has grown substantially in recent years, particularly in relations to algorithmic refinement. RadarConf 2015 in Arlington had a track dedicated to CR for the duration of the conference. However, despite the intensity of CR research throughout the world, there are very few publications in the open literature that focus on ECM applied to CR.

Scholarly searches yield hits that mention various research programmes and suggestions for ECM against CR, however, there is little of technical rigour requiring review.

The NATO Advanced Modelling and Systems Applications for Passive Sensors group SET-164 has produced a comprehensive report on CR performance, particularly with regards to the impacts of clutter. Another NATO group, SCI-190 Electronic Countermeasures to Radar with High-Resolution and Extended Coherent Processing, has performed a small study of countermeasure against CR (SCI-190 was not exclusively focused on ECM against CR).

One of the main limiting aspects of jamming and deceiving CR is that the receiver location is unknown.

In [4] O'Hagan et al discuss an Active Fallback Component (AFC) that could be used along with CR with the intention of sustaining covert radar surveillance even in the event of broadcast infrastructure destruction. The AFC was discussed in terms of employing low-power, low probability of intercept, waveforms. The work was fundamentally a means of making CR robust and functional, even if their primary illumination source was disabled.

III. Calculations of Jammer Effectiveness

Willis' book contains a comprehensive set of calculations of the effectiveness of noise jamming on a bistatic radar [1, Chapter 6, section 6.7]. We will not repeat the results here. The approach taken is to consider the noise present in the bistatic receiver as an increase in receiver noise temperature. The coverage of a bistatic radar without directional antennas is predicted with closed form solutions, and the area covered by a system with "benchmark range" ($\sqrt{R_1 R_2}$ can be calculated. R_1, R_2 are the transmitter to target and target to receiver ranges where the signal to noise ratio is considered adequate for detection.

The presence of jammer noise reduces the SNR and hence, "benchmark range", and also, coverage area. The ratio of area with and without jamming is a measure of effectiveness of the jamming. The calculations presented in the reference [1, Chapter 6, section 6.7] show the sharp reduction in performance due to jamming. The approach does not take into account antenna directionality, and the non-linear processing of a real system. We decided to use simulation (FERS [5], [6]) to investigate a number of scenarios. FERS is a powerful simulator allowing for an arbitrary number of transmitters, targets and receivers to be assessed in complex scenarios.

IV. Simulation Results

For simplicity, we analyse a CR in the form of a PBR in the FM Broadcast Band (88 to 108 MHz). The geometry is given in Figure 1. The parameters are typical of this type of system, of which the example is just one bistatic pair. To achieve tracking, a number of transmitters or receivers is required [7]. The planning of such a system is also complex, to obtain optimum performance [8].

A. Simulation overview

Referring to the figure, a receiver is located at the North most region of map labelled Malmesbury Rx. This receiver exploits an FM band transmitter labelled Constantiaberg Tx in the South West corner of the map. A jammer is positioned at a well known high site overlooking the entire region. This is located in the middle of the map. An aircraft flies from the North East which mimics the typical Johannesburg / Cape Town flight path of this region. The aircraft heads towards the Cape Town International Airport, labelled as CPT Airport. The simulation runs for 3 minutes during which time, the aircraft descends from 10000 to 5000 m, travel at a constant straight line velocity of 200 m/s.

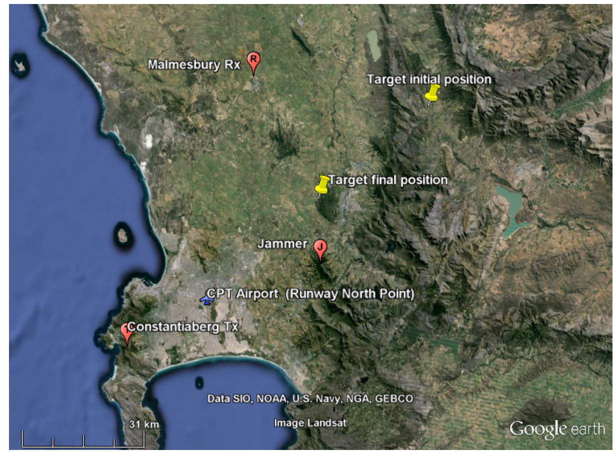

Fig. 1. An overview of the geometry for jamming simulations. North is upwards. The lateral scale in approximately 120 km by 100 km north-south.

The Constantiaberg transmitter radiates isotropically for simplicity. The radar receiver has a pair of 60 degree beam-width, 7.2 dBi antennas with a sinc function based response as shown in Figure 2 for both vertical and horizontal planes. This is very similar to the Yagi antennas used in the prototype FM band radar at UCT [9]. At the receiver site, the reference antenna points towards the Contastantiaberg transmitter. The surveillance antenna points towards the centre of the target flight path, i.e. between the 2 thumbtacks. The jammer has the same 7.2 dBi antenna as the receiver and points directly towards the receiver. Further details are given in Table IV-A.

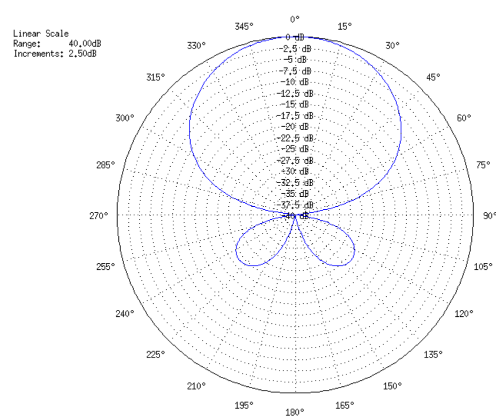

Fig. 2. Antenna beam used for the radar receiver and jammer. This pattern applies to both the horizontal and vertical. 0 dB boresight is equivalent to 7.2 dBi gain.

B. Illuminating Signal of Opportunity

The illuminating signal of opportunity used in the simulation is real FM data recorded at the actual site on which the simulation is based. This site has a favourable interference environment and is relatively free of multipath. The data is stored as a complex baseband stream of IQ data sampled at

TABLE I
NOISE JAMMER SIMULATION PARAMETERS.

Item	Parameter
Transmitter	
Antenna beam pattern	Isotropic
Antenna gain	0 dB
Antenna altitude	400 m
Power	16.4 kW (EIRP for 10 kW dipole)
Carrier frequency	89 MHz
Waveform	Real recorded FM data 204.8 kSps complex sampled
Receiver	
Antenna beam pattern	Sinc
Antenna gain	7.2 dBi (see Figure 2)
Antenna altitude	240 m
LO error	50 ppb (std. dev. of 0.01 Hz @ 204.8 kSps)
Noise figure	4 dB
Digitisation	204.8 kSps complex, 16 bit quantisation
Target	
Initial altitude	10000 m
Final altitude	5000 m
Velocity	Constant 200 m/s
RCS @ 89 MHz	46 dBsqm (200 m^2, a large airliner)
Jammer	
Antenna beam pattern	Sinc
Antenna gain	7.2 dBi (see Figure 2)
Transmit power	1, 5 and 10 W before antenna gain
Carrier frequency	89 MHz
Waveform	204.8 kSps complex, random noise
Radar Signal Processing	
DPI cancellation	5 range, 5 Doppler bins
DPI cancellation CPI	102400 samples (0.5 s)
Range/Doppler processing	120 range, 1601 Doppler bins
Range/Doppler CPI	819200 samples (4 s)
CFAR algorithm	GOCA-CFAR
CFAR window	4 guards, 8 reference cells (per side of CUT)
CFAR dimension	Doppler (robust against bandwidth fluctuations)
CFAR threshold	$P_{fa} = 10^{-5}$ (exponential noise model)

204.8 kSps, and this is used for all our simulations. It is fed into the simulator in this form. The simulator software mixes the baseband data up to a carrier frequency of interest. This way the simulation will produce realistic bandwidth functions in the FM band signal as well as a realistic FM signal ambiguity function. The spectrum of the FM signal is shown in Figure 3.

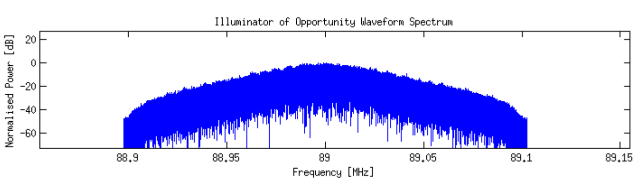

Fig. 3. The spectrum of the illuminator of opportunity (FM) signal shown at its RF frequency.

The equation for processing gain as shown in Equation 1, for a 204.8 kSps complex data block would allow for an integration gain of around 60 dB assuming a 4 second integration time, as is consistent with such an FM band radar. We have found that the range walk for passenger aircraft in 4 seconds is small enough.

$$\begin{aligned} G_{int} &= t_{int}\beta && (1)\\ &= 10\log\left(4\ s \times 204.8\ \text{kHz}\right) && (2)\\ &= 59.13\ \text{dB}, && (3)\end{aligned}$$

where G_{int} is integration gain, t_{int} is the integration time and β is the bandwidth of the signal.

Also related to the modulation bandwidth is the range resolution: this relation is governed by Equation 4. For the simulation frequency (complex) signal and a carrier frequency of 89 MHz, the bin resolutions will be 1463.83 m and 0.25 Hz for bistatic range and bistatic Doppler resolutions respectively. 0.25 Hz is equivalent to 0.84 m/s bistatic range rate at 89 MHz.

$$\Delta R = \frac{c}{\beta \cos(\theta/2)}, \qquad (4)$$

where ΔR is the attainable bistatic range resolution in metres (which applies to the same dimension as bistatic range), c is the speed of light in metres per second, β is the instantaneous modulation bandwidth of the signal that is being exploited in Hertz and θ is the bistatic angle, that is, the angle formed by the transmitter-target and target-receiver line segments in radians.

C. *Jamming Signal*

The jamming signal is generated as a complex random sequence, which, as such occupies the full bandwidth of the target FM channel. The flat frequency response is characteristic of the noise like time domain signal, occupying 204.8 kHz of bandwidth. In practice the response of the RF frontend would attenuate the edge of the frequency pedestal.

The auto ambiguity function function of the jammer signal, which is the cross-ambiguity function of the jamming signal with itself, is a “thumbtack” response which can be attributed to the critically sampled noise signal that the jammer emits.

A passive radar receiver receiving such a jamming signal on both its surveillance and reference channel would therefore suffer integrated interference across its range/Doppler plane. The peak level would be scaled according to the received signal strength at the receiver input.

D. *Simulation Runs*

The following runs are performed with the FERS simulator to gauge the effect of the jammer on the radar. The important plots that we show are the Amplitude Range Doppler (ARD) and Constant False Alarm Rate (CFAR). The former is, after clutter cancellation, bistatic range from left to right, and measured doppler shift vertically, with colour indicating the strength of the return after processing. The latter is the same plot, except that an area based filter is moved over the data to average out false signals, essentially converting the plot to two values target or no target. A number of CFAR plots are then overlaid, and signals that exceed the threshold are repeated, thereby showing a history of targets that exceed the threshold. For all the simulations presented here, the signal level of the plot has been normalised to the level of the target at the beginning of the first clean simulation run as shown in Figure 4 of the simulation without jamming. This way the noise and interference floor level can be compared directly to the signal level of the target return.

1) No Jamming: To establish a performance baseline a simulation with the target flying its specified trajectory with no interfering signal present.

The target displays a signal to noise ratio in the range of 25 to 30 dB for the duration of manoeuvre. This is consistent with actual measurements taken at the site [8], [9] exploiting the same transmitter and observing large commercial airliners flying along a similar trajectory. Figure 4 shows the range/Doppler map at the beginning of the target manoeuvre, Figure 5 shows the range/Doppler map at the end of the target manoeuvre and Figure 6 shows the CFAR filter detection history for all frames of the target manoeuvre.

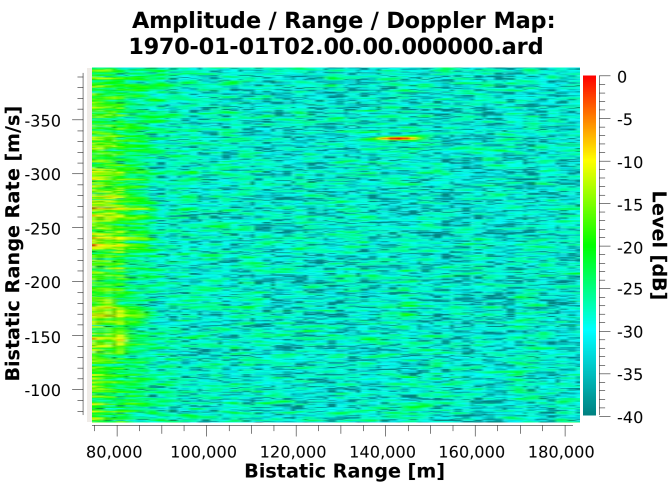

Fig. 4. ARD at the beginning of the flight trajectory when no jamming is present.

We have included the signal and some of the data processing in our simulations, and Figure 6 thus represents to plot extraction level, the output of a realistic CR. The analysis based only on SNR reduction [1, Chapter 6, section 6.7] does not include the highly non-linear effect of the clutter reduction and CFAR processing [9]

2) 1W Jamming: The jammer is now activated (see Figure 1) with 1W of power feeding into the 7.2 dBi antenna which is directed at the radar receiver site. There is a noticeable rise in the noise floor and accordingly a drop in SINR, of approximately 10 dB. The CFAR filter is still able to detect the target through the manoeuvre. Figure 7 shows the range/Doppler map at the beginning of the target manoeuvre, and Figure 8 shows the CFAR filter detection history for all frames of the target manoeuvre.

3) 10W Jamming: The noise jammer power is then increased to 10W. The target is no longer discernible in a single stationary ARD map. The interference floor is raised.

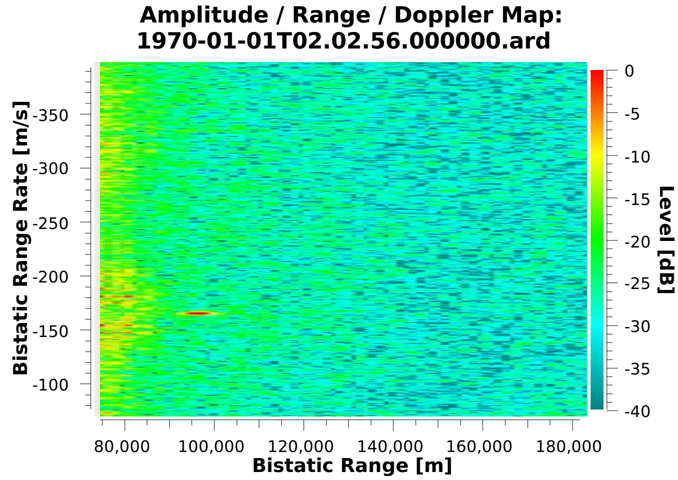

Fig. 5. ARD at the end of the flight trajectory when no jamming is present.

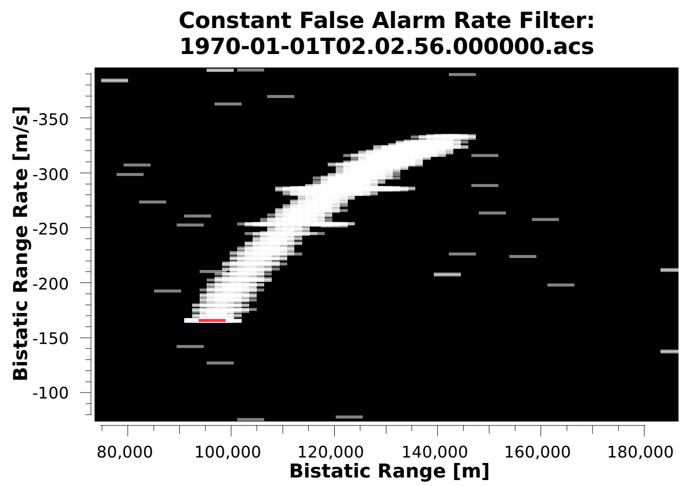

Fig. 6. CFAR history for the duration of the flight trajectory when no jamming is present.

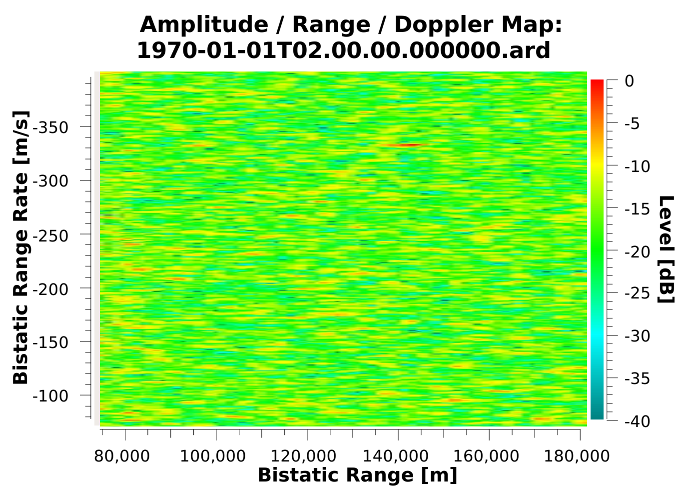

Fig. 7. ARD at the beginning of the flight trajectory when 1 W jamming is present.

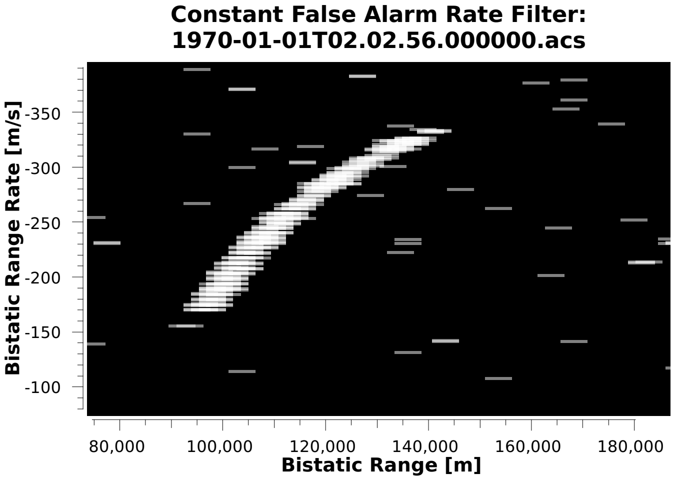

Fig. 8. CFAR history for the duration of the flight trajectory when 1 W jamming is present.

The CFAR detector begins to loose a significant number of detections during the target manoeuvre. Figure 9 shows the CFAR filter detection history for all frames of the target manoeuvre.

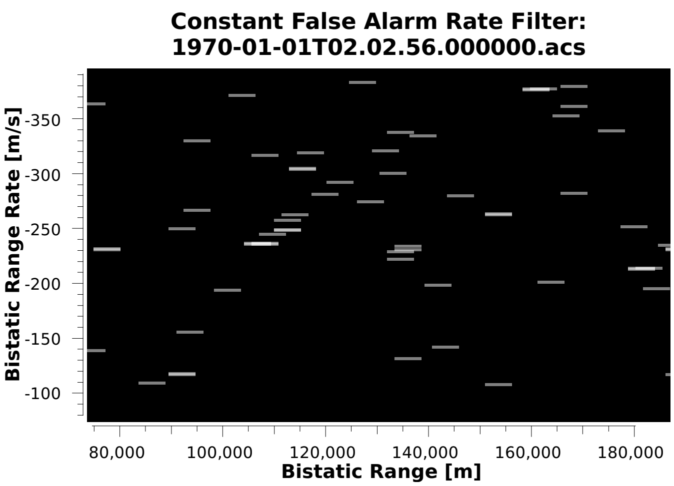

Fig. 9. CFAR history for the duration of the flight trajectory when 10 W jamming is present.

4) Target Self-protection: This section discussed the implications of the target radiating its own jamming signal. This is simulated with an omni-directional beam pattern. Only 1W of power is radiated given that airborne ECM platforms are likely to have power limitations. In effect the emitted signal is orders of magnitude larger than the target echo even at only 1 W and so masks the radar return effectively. Figure 10 shows the CFAR trail for the entire trajectory. The target trajectory is not identifiable in the output map.

To investigate the effect of the self protection jamming further, the ARD map shown at the beginning of the trajectory as in Figure 11, normalised to the level of the target return. The target return level is again derived as the jamming free interference simulation run as shown in Figure 4. The normalised version is shown in Figure 11. As can be observed the noise-plus-interference floor now sits some 20 dB above the level of the target so detection is highly unlikely.

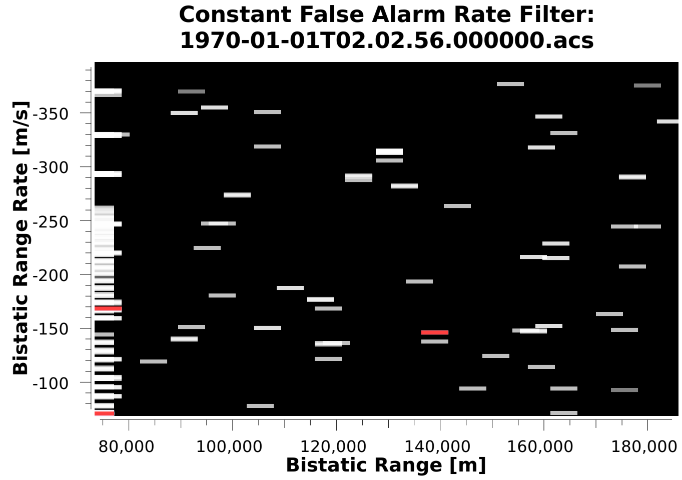

Fig. 10. CFAR history for the duration of the flight trajectory when 1 W self-protection jamming from the target is present.

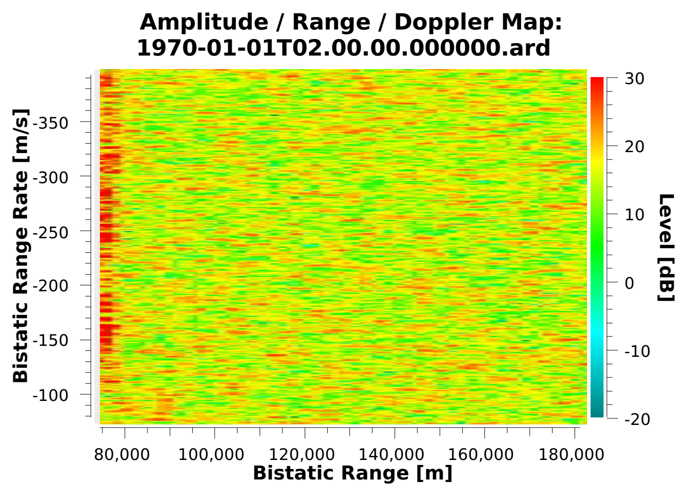

Fig. 11. ARD at the beginning of the flight trajectory when 1 W self-protection jamming from the target is present. The map is normalised to the level of the target return.

E. ECCM

Depending on the type of CR system, it should be possible to have an array type antenna, and then to have such an antenna steer a null toward the jamming source (assuming such a source's position or bearing is known). As shown in Willis [1], substantial improvement to CR system performance is possible, at the expense of having a *wedge* taken out of the coverage by the surveillance channel null. A conventional ESM with AoA capability would be very useful to find the bearing and presence of a jamming source.

This is illustrated by simulation. Figure 12 show the CFAR results repeating the 10 W jammer scenario described in Section IV-D3. All details are the same except that the surveillance antenna is rotated to the North such that a 7.5 dB null (relative to the 7.2 dBi main lobe) is steered towards the jammer. It is shown that this gives suitable isolation to allow for target detection. Again the plots have been normalised to the target level which is now slightly lower due the main beam of the surveillance antenna not being centred on the target for the duration of its flight path. While the target is not present in the initial ARD map, it soon becomes detectable as can be seen by the CFAR history in Figure 12.

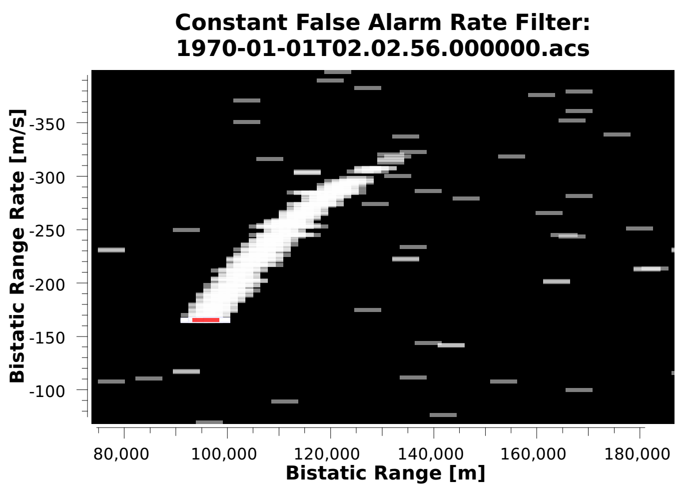

Fig. 12. CFAR history for the duration of the flight trajectory when 10 W jamming present and a 7.5 dB null relative to bore-site gain is steered towards the jamming.

CR systems that rely on a single receive station, and multiple transmitters will suffer most in terms of loss of angle coverage in utilising this sort of ECCM. However, a CR that uses multiple receive stations, spatially distributed, will have much more flexibility. This is somewhat difficult to quantify, as it is so specific to the actual installation of the CR. Arguing loosely, the wedge taken out from each system will point in a different direction for each receiver, leaving the aggregate performance of the system good.

F. The Importance of ESM

The presence of a noise jammer has an insidious effect on system performance, and it is clear that a CR system must be fitted with an ESM that is able to detect the presence of the jamming, frequency, and relative direction, so that ECCM can be triggered.

V. Conclusions

This paper has explored the effectiveness of ECM deployed again a CR. We demonstrate with a number of simulations the effectiveness of ECM when the CR System's positions are known. The effectiveness of a self-protection jammer is also shown. The simulations include typical signal processing, up to the plot extraction stage.

It is also clear that unless the jammer has prior knowledge of both frequency of operation, and the site of the CR system, mounting an ECM attach will be very difficult.

We point out the importance that a CR system is supported by excellent ESM, so that the presence, and bearing, of jamming can be detected. This will allow the CR to deploy ECCM null steering. It follows that a system with spatially diverse receivers will be very difficult to jam, as not all antennas will be exposed to the jammer. Simple null steering is an effective countermeasure to standoff jamming. However, self protection jamming cannot be mitigated. However, a platform carrying a jammer is in effect carrying a beacon, and DoA and other techniques can be used to find the target.

References

[1] Willis NJ, Griffiths H. Advances in bistatic radar. SciTech Publishing; 2007.

[2] Baugh KW, Benner R, Lodwig R. Civil aviation passive coherent location system and method. Google Patents; 2003. EP Patent App. EP20,010,979,880. Available from: https://www.google.com.tr/patents/EP1344083A2?cl=en.

[3] Villano M, Colone F, Lombardo P. Antenna Array for Passive Radar: Configuration Design and Adaptive Approaches to Disturbance Cancellation. International Journal of Antennas and Propagation. 2013;2013(Article ID 920639):16 pages.

[4] O'Hagan DW, Ummenhofer M, Kuschel H, Heckenbach J. A Passive/Active Dual Mode Radar Concept. Proceedings of the International Radar Symposium. 2013;p. 136 – 142.

[5] Inggs MR, Brooker MJ. Extensible Simulator for Waveform Diversity Testing. In: Proceedings of the 4th Waveform Diversity and Design Conference; 2009. .

[6] Brooker MJ. The Design and Implementation of a Simulator for Multistatic Radar Systems [Doctoral Thesis]. University of Cape Town. Rondebosch, 7701, South Africa; 2008.

[7] Maasdorp F, Nadjiasngar R, Inggs M. A Cramer Rao analysis on receiver placement in a FM band Commensal Radar system based on Doppler only measurements. In: Radar Conference (Radar), 2014 International. IEEE; 2014. p. 1–6.

[8] Inggs M, Tong C, Nadjiasngar R, Lange G, Mishra A, Maasdorp F. Planning and design phases of a commensal radar system in the FM broadcast band. Aerospace and Electronic Systems Magazine, IEEE. 2014;29(7):50–63.

[9] Tong C. A Scalable Real-time Processing Chain for Radar Exploiting Illuminators of Opportunity. University of Cape Town. Rondebosch, 7701, South Africa; 2014.