Adaptive Active-Passive Radar Control for Low Probability of Intercept Operation

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ABSTRACT

Hybrid functionality offers a new paradigm of radar operation that combines active and passive radar sensing. In this paper the theory of hybrid radar is first introduced where some of the benefits of this type of radar are discussed. A brief review of experimental work conducted by University College London (UCL) on the topic of hybrid radar is then presented, before analysis of a simultaneous active and passive radar measurement of a quadcopter drone. This work then investigates how platforms that wish to operate covertly can use hybrid radar sensing to operate in a low probability of intercept (LPI) mode. In this mode, active radar emissions are minimised by fusing active and passive radar detections; with the objective of minimising the probability of detection by noncooperative Electronic Support Measures (ESM). Results from of a modelled hybrid radar scenario are then analysed to provide insight into the potential LPI benefits of hybrid radar.

1.0 INTRODUCTION

Conventional active radar systems rely on transmitting energy to form detections of targets. In contrast, passive radar systems use the illumination of targets from existing transmitters to form detections. Passive radar systems can use several types of existing transmitters (illuminators), these can be categorised into two groups, namely, cooperative and uncooperative. An example of a cooperative illuminator would be a friendly Airborne Early Warning and Control (AEW&C) radar, whereas examples of uncooperative sources include Terrestrial Digital Video Broadcast (DVB-T), FM Radio, or an adversary radar. Uncooperative illuminators are often referred to as Illuminators of Opportunity (IoO). Active and passive radars were first used during the Second World War [1]; however, a new paradigm of radar is now emerging that combines both sensing modalities into a single system, referred to as hybrid radar. Hybrid radar exploits both active radar and passive radar, capitalising on the strengths of each sensor. Unlike monostatic and bistatic radars, hybrid radars must fuse information originating from different transmitter-receiver pairs, and can therefore be viewed as a sub-category of multistatic radar. However, unlike conventional multistatic radar, a hybrid radar must use a mix of active radar and passive bistatic radar sensing, where emissions from existing transmitters are used for passive bistatic radar, rather than a dedicated cooperative transmitter.

Some of the theoretical benefits of combining active, passive and multistatic radar include:

- Low Probability of Intercept (LPI) – In the presence of a sufficiently strong and reliable IoO, target detections can be made using purely passive radar. In this case, active radar transmissions can be significantly lowered, or better ceased, reducing the probability of intercept by a non-cooperative Electronic Support Measures (ESM) or radar warning receivers.
- Enhanced Detection Performance – Stealth targets often have an intentionally low radar cross section for certain angles of incidence; hybrid radars will often receive target backscatter from a diversity of illumination angles, improving the ability of the radar system to detect such targets.

- Resilience to Electronic Counter Measures – It is likely that considerably different radio frequencies (RF) would be used for the active and passive radar sensing, therefore a radar jammer would either need to jam a very broad range of frequencies or multiple separate frequency bands, both challenging tasks. Additionally, the adversary would be unaware of which IoO the hybrid radar was using in order to jam the correct band.

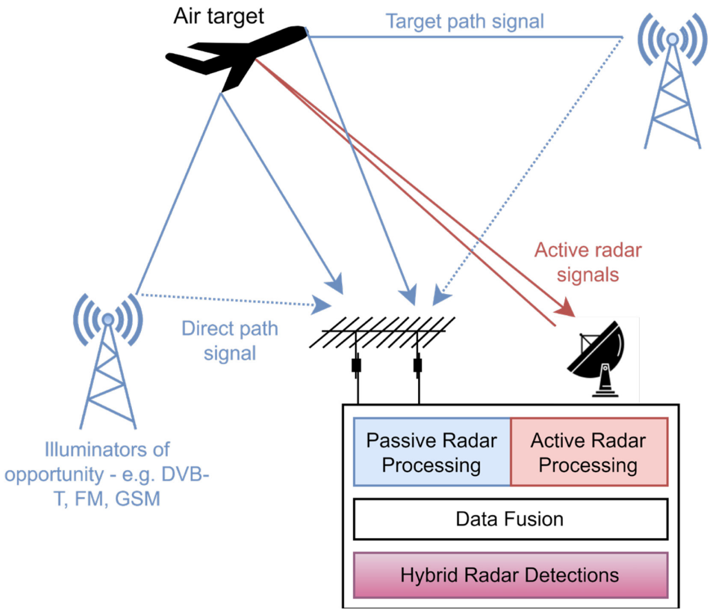


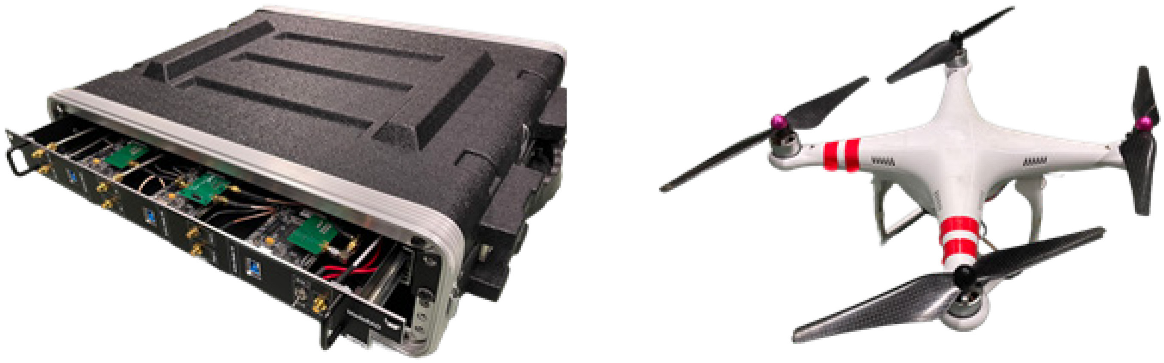
Figure 1: An example of hybrid radar scenario geometry.

2.0 HYBRID RADAR RESEARCH

A low-cost Software Defined Radio (SDR) based experimental radar system, bladeRAD [2], [3], has been developed at University College London (UCL) in collaboration with Dstl. This project aimed to deploy an experimental hybrid radar to collect data in a variety of targets and geometries. bladeRAD is a multifunctional system that has been used for joint active and passive sensing of targets using S-band Wi-Fi IoO [2] or UHF DVB-T [3] IoO, in combination with an active S-band Frequency-Modulated-Continuous-Wave (FMCW) sensor. Figure 2-1a is a photograph of a single node of the bladeRAD system, capable of multistatic/networked operation through use of an external GPS Disciplined Oscillator based synchronisation system [4]. In this section a brief overview of some active and passive measurements of a quadcopter drone will be presented before comment is made on some of the data fusion strategies available to hybrid radar systems.

2.1 Experimental Scenario

During a recent hybrid radar trial, several measurements of a DJI Phantom quadcopter were captured using an S-band FMCW active radar mode and DVB-T-based passive radar mode. These experiments were conducted in order to empirically investigate the advantages and challenges of hybrid radar sensing. A pseudo-monostatic passive radar geometry was used during the measurements, to reduce the effect of bistatic geometry on target range and velocity estimation, allowing direct comparison of the active and passive radar data, illustrated in Figure 3. The quadcopter moved over a range of 25-100 meters, though greater ranges will be possible in future experiments.



(a) (b)

Figure 2: (a) UCL bladeRAD experimental radar system; (b) DJI Phantom quadcopter.

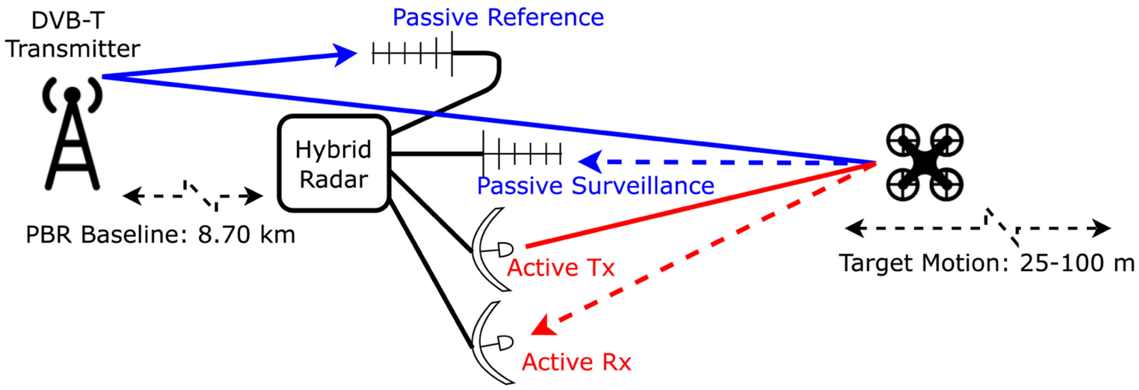


Figure 3: Experimental hybrid radar scenario.

2.1.1 Active Passive Radar Comparison

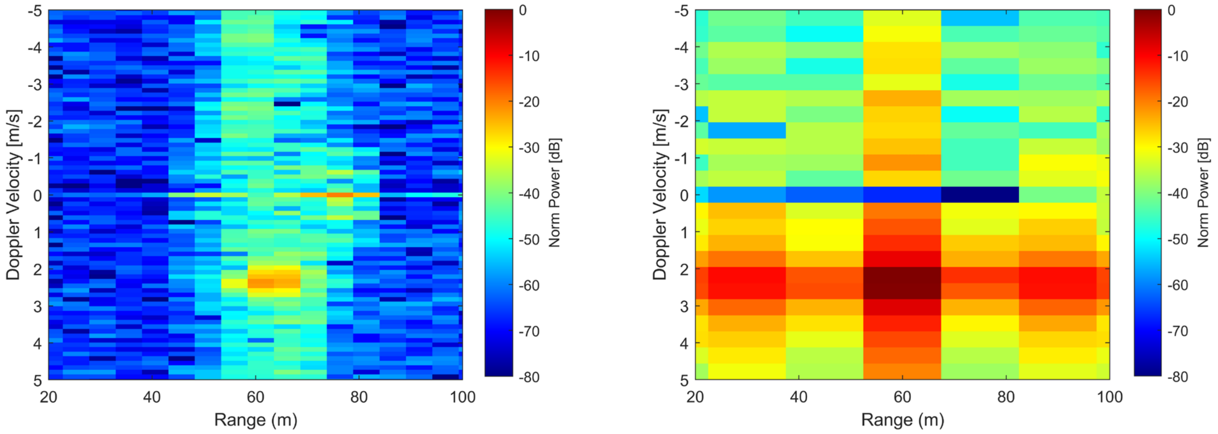
A key performance metric for a radar is its ability to resolve two closely spaced targets. This metric is referred to as range resolution and is dependent on the radar's waveform bandwidth *B*, namely,

$$\delta_r = \frac{c}{2B} \tag{1}$$

where *C* is the speed of light, and δ_r is the radar range resolution. Many high power IoO, suitable for long range detections, have relatively narrow bandwidths, e.g. FM radio (20 kHz), DAB radio (220 kHz), resulting in poor range resolution. DVB-T channels have a considerably larger 7.61 MHz bandwidth, providing an equivalent monostatic range resolution of 20 meters. Though one should note, range resolution of a passive radar is target geometry dependent, thus (1) represents a lower-bound. Many modern active radar systems have comparatively higher bandwidths of tens or even several hundreds of MHz, resulting in much higher range resolutions. The parameters of the active and passive radars used in the UCL hybrid radar experiments are summarised in Table 1. An active radar bandwidth of 30 MHz was used for the experiment. Example range-Doppler surfaces produced from the active and passive radar measurement of the quadcopter are shown in Figure 4. The higher range resolution of the active radar is evident when comparing the two surfaces, resulting from active radar having more than three times the waveform bandwidth. In active radar signal processing, and batched passive radar signal processing [5], the Doppler velocity resolution, δ_D, is a product of the radar's Pulse-Repetition-Frequency, *PRF*, central RF, *Fc,* and Discrete-Fourier-Transform (DFT) length, *nfft*, used is Doppler processing.

$$\delta_D = \frac{PRF}{2\,nfft}\,\frac{C}{Fc} \qquad (2)$$

In the results presented in this paper, the active radar has a larger *Fc,* thus for the same *nfft* and *PRF* the active radar provides a finer resolution in Doppler, though a lower un-ambiguous Doppler limit. If a conventional matched filter bank approach [6] is used to carry out passive radar signal processing, the Doppler resolution is entirely dependant on the signal processing.



(a) **(b)**

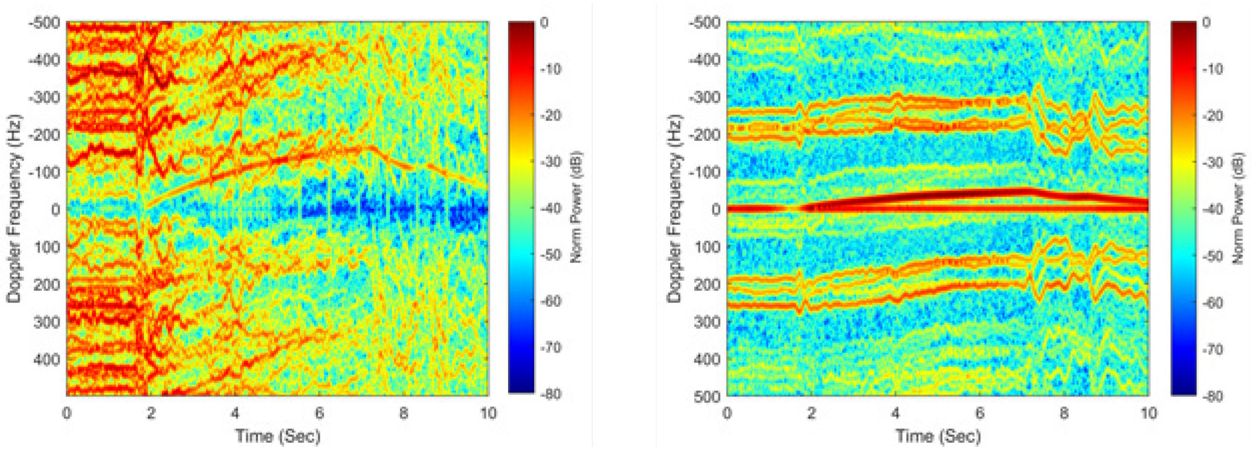
Figure 4: Example simultaneously captured range-Doppler surfaces of quadcopter using (a) active 2.45 GHz FMCW radar; (b) 690 MHz DVB-T passive radar. Captured using the UCL bladeRAD radar.

Table 1: Radar parameters.

Parameter	Active Radar	Passive DVB-T Radar
RF (MHz)	2440	690
Sample Rate (MSPS)	60	20
Waveform Bandwidth (MHz)	30	7.61
Waveform Modulation	LFM	OFDM
PRF (kHz)	1	1

2.1.2 Hybrid Radar Micro-Doppler

The greater the number of radar sensors, the greater the potential information available to the user/system to make decisions on both the presence and classification of the target. Hybrid radars require a minimum of two channels of radar data, one passive and one active. These are typically at different central frequencies to avoid interference between channels and provide frequency diversity. Figure 5 shows spectrograms of the Doppler signature from a quadcopter measured simultaneously with the active and passive radar modes. In both spectrograms the bulk Doppler of the quadcopter is visible from approx. 2 seconds into the capture and, as expected, the Doppler shift is more extreme in the case of the active sensor, due to the higher central frequency. The target's micro-Doppler signature is clearly observable in both plots, as side bands around the drone's bulk Doppler. These horizontal lines are caused by the rotating propeller blades, commonly referred to as Helicopter-Rotor-Modulation (HERM) lines. In the active radar plot, there appears to be considerably more HERM lines. This is a result of aliasing of HERM lines at frequencies exceeding the un-ambiguous Doppler limit of the active radar. This result demonstrates the benefit of observing the same target in two different modes simultaneously via the diversity of signature.



(a) (b)

Figure 5: Example simultaneously captured quadcopter Doppler signatures using (a) active 2.45 GHz FMCW radar; (b) 690 MHz DVB-T passive radar. Captured using the UCL bladeRAD radar.

2.2 Hybrid Radar Data Fusion

As discussed in the introduction, hybrid radar is a sub-category of multistatic radar. As such, the data fusion strategies available to hybrid radar are identical to those available to multistatic radar. Multistatic radar fusion is commonly split in to two categories dependant on the level of radar data that are fused. One category is centralised, in which raw data is fused pre-thresholding and detection, the other is decentralised fusion, where individual receivers share detections or tracks with a central fusion centre (FC).

When determining the appropriate fusion level, both the coherence of the signals arriving at the receivers and the coherence of the hybrid radar system's equipment should be considered [7]. In the case of hybrid radars, the passive IoO will typically operate at a different central frequency to the active radar component. As such, the signals transmitted by the active and passive radar will be incoherent, making the overall hybrid system noncoherent. Noncoherent multistatic systems must fuse data post envelope detection, where the phase information is first eliminated. Fusion strategies available to noncoherent multistatic radars are limited to, video fusion, when using a centralised approach, or fusion of plots or tracks when using the decentralised approach. Video fusion removes the phase information before incoherent summation of radar data in the FC. The practical implementation of video fusion presents some considerable challenges in hybrid radar systems, not least due to the considerably different sensor resolutions, as illustrated in Section 2.1.2. Additionally, centralised fusion strategies share data at a considerably lower level of abstraction and thus requires high-bandwidth communication links between receivers, challenging in systems with distributed receivers. Therefore, in practice video fusion is rarely implemented in multistatic radar, instead a designer will often opt for a considerably less complex decentralised approach [7].

In both decentralised fusion strategies, matched filtering, thresholding and parameter estimation is conducted locally in each receiver. In the case of plot level fusion, the binary decisions from each receiver are then shared with the FC, where a final decision on the presence of a target is made by joint processing of a sequence of binary decisions in the FC. Comparatively, when implementing track level fusion, detections are made locally to allow tracks to be formed by individual receivers. Tracks are then fused allowing for false tracks to be eliminated and higher accuracy track parameter estimations. Decentralised fusion requires considerably lower-bandwidth communication links between receivers, thus is often preferable in practical implementations.

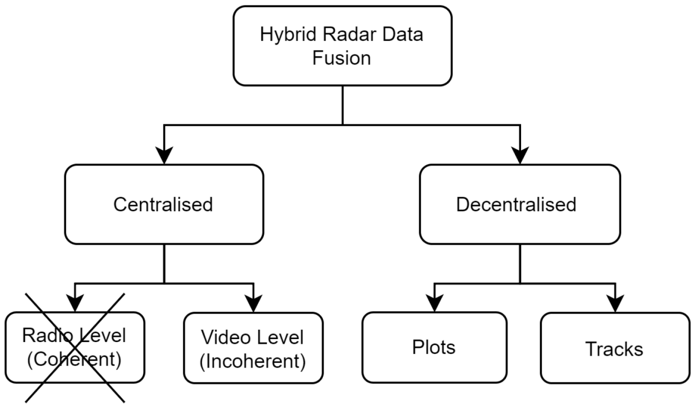


Figure 6: Multistatic radar fusion categories.

3.0 ADAPTIVE ACTIVE-PASSIVE RADAR

LPI radars usually employ a mixture of features focused on the antenna design and waveform to reduce the probability of interception by non-cooperative ESM receivers. Properties such as: long duty-cycle, spread spectrum, low sidelobe antennas and power management are common, but not exclusive, features of LPI radars. Fundamentally, the best LPI strategy is to not radiate at all, a strategy possible in hybrid radar, when relying purely on the passive radar sensing mode. That said, the availability, power, and bistatic geometry of the passive IoOs will vary, causing the detection performance of the passive sensor to be dynamic. This variability of detection performance is often unacceptable to users, limiting the practical exploitation of exclusively passive sensing systems. In order to address this challenge, hybrid radars combine active and passive sensing, such that in scenarios where the passive radar is unable to provide adequate detection performance, the active radar can be engaged to supplement the passive radar. For hybrid radars operating in an LPI mode, the active radar's power should additionally be controlled to minimise the transmit power necessary to complete the sensing task. This can be achieved through continuous evaluation of the performance of the passive radar, to determine if passive sensing alone can meet the required detection performance of the platform. If the passive sensor alone cannot provide adequate detection performance, the required active radar performance can be evaluated and engaged to maintain the minimum detection performance required.

The number, power, and directions of active radar transmissions will directly impact the probability of a non-cooperative ESM receiver detetcting the presence of the platform. Therefore, if the platform wishes to minimise the probability of its transmissions being intercepted, these three parameters should be minimised through the exploitation of passive sensing. That said, when using purely passive sensing, suboptimal performance will be observed due to the lower bandwidth waveforms and target geometry-based performance, as discussed in Section 2.1.1. Additionally, by minimising active radar transmit power, and thus the SNR of target backscatter, the accuracy of target parameter estimation (e.g. range and velocity) will be degraded, as will the ability to detect specific target features, such as those from micro-Doppler signatures. If the user desires the best possible track and/or classification accuracy, maximum transmit power in the direction of the target would likely be opted for – this may be done briefly to classify a target, or for a sustained period prior to engaging a target.

3.1 Modelled LPI Scenario

Modern military airborne platforms commonly use Active Electronically Scanned Arrays (AESA) for search and tracking of targets. These arrays will have instrumented scan angles of approximately ± 60°, limited by the scan losses increasing with angle [8]. A passive radar's performance is geometry dependent and determined by the relative locations of the target, IoO and radar. The detection performance of the passive radar must therefore be evaluated for all locations in the field of coverage of the active radar. In regions of poor passive radar coverage, the active radar should direct energy to supplement the passive sensing. In this example scenario, an example of a hybrid radar platform adapting its active radar's performance, in order to account for the varying passive radar performance, is investigated. The objective of the platform is to minimise both the number and relative strengths of active radar transmissions, whilst sustaining a minimum detection performance in the active radar's field of coverage. In this example, a platform is assumed to have an S-band active AESA with transmit and receive beamforming capable of resolving targets in azimuth. The platform is additionally assumed to have an UHF passive radar receive array, also capable of resolving targets in azimuth. The active radar has a 120º field of view and can vary the power of transmitted beams in order to gap-fill regions of poor passive radar performance and minimise emissions in regions of good passive coverage.

3.1.1 Scenario Parameters

The hybrid radar must sustain a minimum probability of detection (P_D) of 0.9, for a hypothetical Swerling 1 type target with an RCS of 5 m^2. It must maintain this detection performance in 120º field of view and up to a range of 50 km from the radar. The performance of the passive radar is estimated using the bistatic range equation and Swerling 1 receiver operating curves to determine an estimated P_D for each point in the surveillance area. Two real-world DVB-T IoO are modelled in the scenario. These are named DVB-T IoO 1, corresponding to the 200 kW Crystal Palace transmitter in south London, and DVB-T IoO 2 corresponding to the Sandy Heath transmitter located in Bedfordshire, 78.91 km to the North-East of DVB-T IoO 1. The passive radar is capable of detecting and resolving the location of targets using a single IoO. Figure 7 illustrates a top-down view of the modelled two-dimensional scenario.

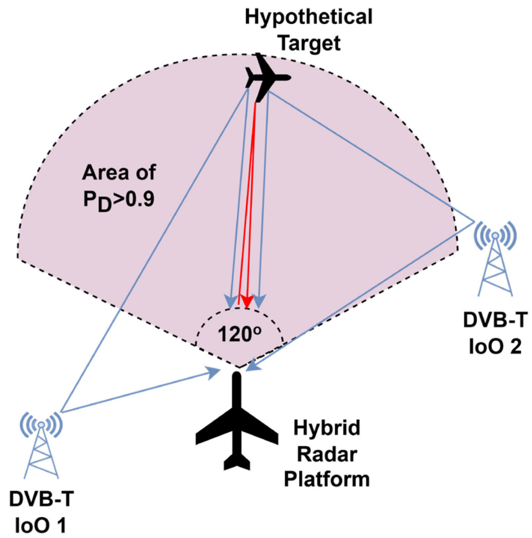


Figure 7: Hybrid platform geometry.

3.1.2 Sensor Fusion Method

Active and passive radar data are fused at the detection level using OR logic. The joint probability of detection can be estimated using,

$$P_O^D = 1 - \prod_{i=1}^{n}\left(1 - P_i^D\right) \quad i = 1,2 \dots, n \tag{3}$$

Where P_O^D is the joint P_D of the combined sensors, P_i^D is the *i*th individual sensor P_D, and *n* is the number of fused sensors. The probability of false alarm (P_{FA}) of the overall hybrid system can be calculated by summing the individual sensors detector's P_{FA},

$$P_o^{FA} = \sum_{i=1}^{n}(P_i^{FA}) \quad i = 1,2 \dots, n \tag{4}$$

where P_o^{FA} is the joint P_{FA}, and P_i^{FA} is the P_{FA} of *i*th individual sensor. In order to control P_o^{FA}, the individual sensors detector's P_{FA} can be can be calculated using,

$$P_i^{FA} = P_o^{FA}/n \tag{5}$$

In this scenario, three channels of radar detections are fused, one from the active radar and two from the passive radar - one for each IoO. The overall system P_{FA} was chosen to be 10^{-6}. Using (5), it is possible to determine that the detectors for the individual sensors should each have P_{FA} values equal to a third of the overall system P_{FA}.

3.2 Model Results

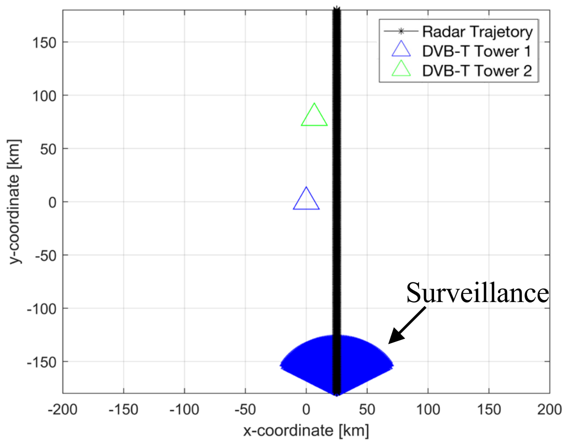
In the scenario, the hybrid radar platform travels along a 360 km trajectory past two DVB-T IoO, the path of the platform with respect to the IoOs is shown in Figure 8(a). For each increment in platform movement, the passive radar performance was evaluated for the entire surveillance region. If the passive radar could provide the minimum performance required, no active radar transmissions would occur. If there was a location in the surveillance region that the passive radar could not provide adequate coverage, the active radar would supplement the passive radar in that direction. Figure 8(b) shows the required active radar transmit power as a function of scan angle (azimuth) as the platform moves through the scene. It is assumed the passive radar can not detect targets in the forward scatter region, where the hypothetical target approaches the baseline between receiver and transmitter. As such, in these forward scatter regions, only the active radar is engaged to provide coverage. The forward scatter angle for each IoO is indicated by red lines in Figure 8(b). In this model, hypothetical target locations with bistatic angle of greater than 170° were considered in the forward scatter region.

In Figure 8(b) when the platform is located between the two IoO, at y-coordinate 0 km, it can be observed that the output of the active radar is 0 kW for the majority of scan angles, indicating that the passive radar is providing detection coverage for the bulk of the surveillance area. In this position, the peak output power of the active radar is 164 W, an 8.83 dB reduction compared to the 1.25 kW required to provide the same detection probability using purely active radar sensing. An 8.83 dB reduction in transmit power translates to a tactically significant 64% reduction in the intercept range of an ESM receiver operating within the illuminated region. Reductions in the intercept range of an ESM receiver can be calculated using the one-way radar equation. As the only parameter which is considered as a variable in this scenario is the radar transmit power, the percentage reduction in ESM intercept range can be calculated using,

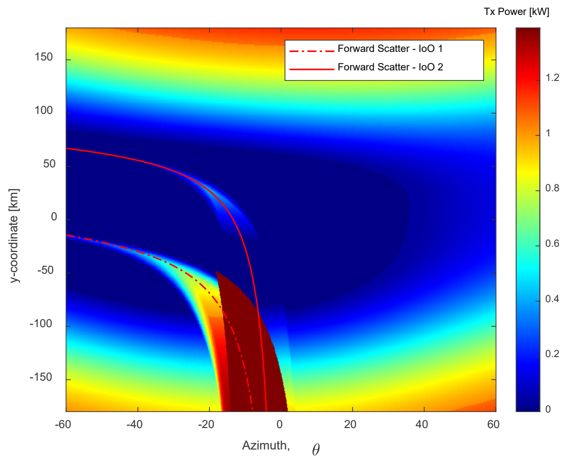
$$\% \, ESM \; Reduction = \left(1 - \sqrt[2]{P_{t2}/P_{t1}}\right) \times 100 \qquad (6)$$

where P_{t1} is the original radar transmit power and P_{t2} is the new transmit power. In Figure 8(b) there is a sizable region in which no active radar sensing is required to fulfil the platform's detection performance requirements, an obvious bias towards the regions close the IoOs is clearly shown. In these regions, where there is no intentional active radar illumination, sidelobes from the AESA may still be detectable whilst illuminating other regions of poorer passive radar coverage. That said, the power of these sidelobes will likely be orders of magnitude lower than the main beam of the AESA.

To provide comparison, when the platform is located at y-coordinate 180 km, the active radar provides the bulk of the detection coverage for the surveillance area. This is observable in the upper region of Figure 8(b), where the active transmit power is comparable to the active only radar power level. In this location, the largest reduction in transmit power was 1.06 dB, equivalent to an insignificant 11% reduction in ESM intercept range.



(a)



(b)

Figure 8: (a) Map of modelled scenario platform and IoO locations; (b) Active AESA radar transmit power as a function of scan angle for the evolving scenario.

In order to summarise the overall reduction in active radar emissions achieved through using hybrid sensing, the power of the active radar was averaged over all scan angles and calculated for each increment in the platform's movement. Figure 9 shows the average transmit power vs the platform position. To provide comparison, the active radar transmit power required to provide the minimum detection performance, when using only active sensing, is plotted in black on Figure 9. One can clearly observe a considerable saving in mean transmit power through using joint active and passive sensing.

One should note that when calculating the active radar transmit power required in each azimuth direction, scan loss of the active radar AESA has not been accounted for. For practical arrays, the off-boresight gain will reduce with scan angle; that said, scan loss could be easily incorporated by introducing an appropriate weighting vector. In this model, the performance of the passive radar is evaluated with each step of platform motion. However, in real-world scenarios, the passive radar performance could be evaluated as part of pre-mission planning. This would allow for an optimum flight path to be selected, in order to minimise the active radar emissions and probability of detection by non-cooperative ESMs whilst completing the mission. It should also be noted that for the proposed LPI mode, the individual performance of the active and passive radars would need to be calibrated accurately enough to allow reliable predictions of detection performance for a variety of targets and geometries. Without this calibration it is very unlikely this type of operation would provide a reliable or consistent level of detection performance.

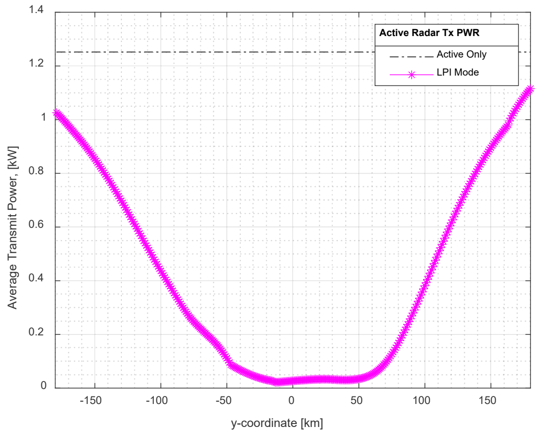


Figure 9: Average active radar transmit power as a function of platform y-coordinate location for the modelled hybrid radar scenario.

4.0 SUMMARY

In the past, relying on passive radar sensing alone would likely have been unacceptable in many applications, this is due to passive radar performance varying with target location and geometry. However, it has been shown that through combining active and passive sensing, hybrid radars allow for the shortfalls of passive sensing to be overcome by gap-filling with the active radar sensor. This allows the benefits of passive radar sensing to be exploited and the full active radar performance to be available when required. One of the theoretical benefits of hybrid radar, LPI, has been explored in Section 3.0. It was shown through adapting the active radar's configuration, in accordance to the availability of passive IoO, considerably fewer and lower power active radar emissions were required. These reductions in emissions will considerably reduce the probability of interception and thus detection by a non-cooperative ESM receiver. Without this, the LPI benefit of the hybrid radar may not be realisable. In scenarios, where LPI is not required, combining active and passive sensing will provide the radar operator with more information on the target and thus likely result in greater detection, parameter estimation and classification performance. Having to implement a secondary passive sensor on a platform would incur additional costs; however, such a modification would require only an additional receiver system – an inexpensive alternative to an additional active sensor.

5.0 ACKNOWLEDGMENTS

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6.0 REFERENCES

[1] Willis, N.J., *Bistatic Radar,* SciTech Publishing, 2005 ISBN: 0-9645923-0-4.

[2] P. J. Beasley and M. A. Ritchie, “bladerad: Development of an active and passive, multistatic enabled, radar system”, in *Proc. 2021 18th Eur. Radar Conf.*, 2022, pp. 98–101.

[3] P. J. Beasley and M. A. Ritchie, “Multi-Band hybrid active-passive radar sensor fusion”, *IEEE Radar Conf*, 2023, *In Press.*

[4] P. J. Beasley and M. A. Ritchie, “Multistatic radar synchronisation using COTS GPS disciplined oscillators” in *Proc. Int, Conf. on Radar Sys.*, 2022, pp. 429-434.

[5] B. Tan, K. Woodbridge, and K. Chetty, “A real-time high resolution passive WiFi Doppler-radar and its applications,” *in Proc. Int. Radar Conf.* IEEE, 2014, pp. 1–6.

[6] H. Kuschel, D. Cristallini, and K. E. Olsen, “Tutorial: Passive radar tutorial,” IEEE AES Mag., vol. 34, no. 2, pp. 2–19, 2019.

[7] V. Chernyak, *Fundamentals of Multisite Radar Systems*. Gordon and Breach Science Publishers, 1993, ISBN: 90-5699-165-5.

[8] R. J. Mailloux, *Phased Array Antenna Handbook*, Artech House, 2nd ed., 2005, ISBN 1-58053-689-1.