Bistatic UAV Radar for Ship Self-Defence

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ABSTRACT

In naval operations there is a requirement for increased warning time against low-altitude threats that originate from beyond the horizon of the shipborne radar. The use of UAV-based radar is a promising solution, because an airborne platform has a longer horizon than that of the shipborne radar. However, the potential benefits and drawbacks of UAV radar are not well understood. This paper considers several monostatic and bistatic UAV concepts and analyses their performance against threats that are representative of cruise missiles and anti-ship missiles. It is shown that the most promising concept is a bistatic configuration where the transmitter is deployed in the direction of the expected threat and has a reflector antenna with azimuthal steering. The required size of the antenna is quantified as a function of receiver ground range and target radar cross section.

1.0 INTRODUCTION

In naval operations there is a requirement for increased warning time against low-altitude threats that originate from beyond the horizon. Such threats are particularly dangerous when they operate at high velocities and thus result in very short reaction times for a vessel's surveillance system once the threats appear on the horizon. When operating in the littoral, naval vessels may also encounter threats launched from land-based vehicles. The aim of this work is to develop an affordable UAV-based radar system that will provide over-the-horizon detection and tracking capability for ship self-defence.

There are two general scenarios of interest for ship self-defence, the blue water scenario and the littoral scenario. In the blue water scenario, a vessel is located in the middle of open ocean. Land-based threats are not present, and in general there is not a lot of naval traffic in these areas. The primary source of interference for radar detection is sea clutter at various sea states. In the littoral scenario, a vessel is up to 100 km from shore. Threats may originate from other naval vessels or land vessels. Significant amounts of coastal traffic may be present. Both sea and land clutter may provide sources of interference for radar detection. One example of a littoral scenario occurs when a vessel is travelling through a strait. In this case, land based threats may be present on either side of the strait.

In either the blue water or littoral scenarios, a vessel may encounter multiple threats. As a first step, this study will consider single threat scenarios. If radar system performance against single threats is acceptable, multiple threat scenarios will then be considered.

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An early detection system could have several potential functionalities. It could be used as a trip-wire detection scheme, which would cue a shipborne radar regarding an imminent threat. It could also provide tracking capability or be used to provide illumination for missile guidance.

The shipborne radar horizon for a Canadian Patrol Frigate is approximately 25 km. In this study, monostatic and bistatic UAV radar systems will be designed to detect threats at a range of 25 km and beyond.

Figure 1 illustrates generic monostatic and bistatic UAV radar concepts. In the monostatic system, the radar only requires one line-of-sight to the target and may be designed to have a multifunction capability. In the bistatic system, a UAV transmitter is deployed beyond the horizon, in the proximity of the anticipated threat. The UAV receiver would be located directly above the ship. One advantage of such a bistatic system is that the closer proximity of the transmitter to the target enhances signal-to-noise ratio. Another advantage is that such a system may allow for simpler and cheaper UAV payloads, especially at the transmitter. However, such a bistatic system would require synchronization between the transmitter and receiver to achieve coherent processing gains. Furthermore, a bistatic system requires multiple lines-of-sight to the target.

Section 2 of this paper presents the threats considered in this study. Section 3 outlines the method that will be used to analyze various monostatic and bistatic UAV radar concepts. The results of this analysis are then presented in Section 4. Conclusions are given in Section 5.

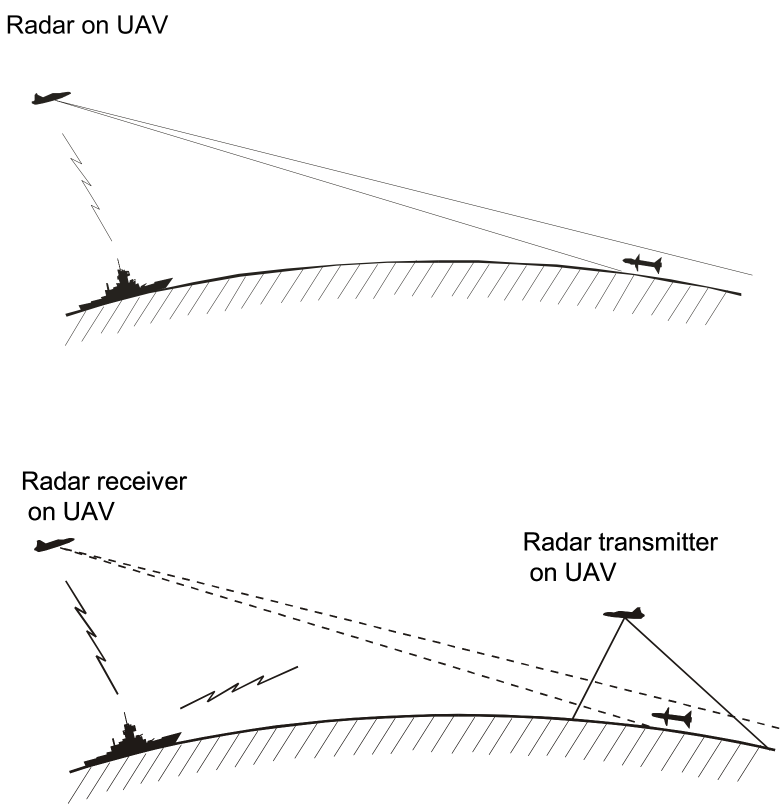

Figure 1: Illustration of monostatic and bistatic UAV radar concepts.

2.0 THREATS

In both the blue water and littoral scenarios, a naval vessel may encounter a number of low-altitude threats that originate from beyond the horizon, including, anti-ship missiles, cruise missiles and low-flying aircraft. This section describes these threats.

Ever-present threats to naval vessels are anti-ship missiles (ASM). Generally, ASM's are capable of cruising at low altitudes, travelling at subsonic or supersonic speeds, and can be launched from a ship, from a land vessel or from an aircraft. There are numerous types of ASM's in production, and they are used by almost every nation in the world. One example of an ASM is the Russian SS-N-22 'Sunburn', also called the '3M80' or 'Moskit' [1]. The Moskit is a surface-to-surface missile with inertial guidance, a dual mode active/passive radar terminal seeker, and an electronic protection measure (EPM) capability. With a launch weight of 4,500 kg, the Moskit has a length of 9.74 m, a body diameter of 0.76 m and a wingspan of 2.1 m. When cruising at low-altitudes, the Moskit has a range of approximately 150 km and a cruise speed of approximately Mach 2.1. Another example of an ASM is Boeing's AGM-84 Harpoon [2], which has an air-launched model and a surface and submarine-launched model. The Harpoon is lighter and smaller than the Moskit, with a weight of 519 kg, a length of 3.8 m, a body diameter of 0.34 m, and a wingspan of 0.83 m. At low altitudes, the Harpoon has a range of up to 124 km with a maximum speed of Mach 0.85.

Cruise missiles are surface-to-surface missiles that typically travel at subsonic speeds. One common example is the Tomahawk cruise missile, which has a length of 6.25 m, a diameter of 0.51 m, and a wing span of 2.62 m. The Tomahawk has a weight of 1,450 kg, a range of 1,300 km and a maximum speed of Mach 0.75 [3]. Previous work has been carried out on analyzing the monostatic and bistatic radar cross section (RCS) of a cruise missile [4].

Anti-ship missiles and cruise missiles are especially challenging threats because of their high velocity and low RCS. Low-flying aircraft are also threats of interest, because they can be used as vehicles for delivering cruise or anti-ship missiles.

This study focuses on the anti-ship missile and cruise missile threat. The radar concepts proposed will be evaluated against a generic missile target that has a RCS of 0.1 , 0.01, or 0.001 m^2. These RCS values are generally representative of the monostatic and bistatic RCS of anti-ship and cruise missiles. It is assumed that the missile is travelling in straight and level flight at a velocity between Mach 0.75 and Mach 2.1. This velocity range encompasses the top speeds of many cruise missiles and anti-ship missiles.

3.0 ANALYSIS METHOD

In this paper, the performance of various UAV radar concepts is assessed using simple models for signal and noise power. This type of analytical assessment allows various trade-offs to be easily quantified. Table 1 gives the bistatic radar system parameters used in this study.

Parameter	Definition	Value
P	peak power (W)	1,500
τ	duty cycle	0.4
G_T	transmitter antenna gain	
σ	target RCS	
A_e	effective area of receiver antenna	
R_T	transmitter-to-target range, or transmitter range	
R_R	receiver-to-target range, or receiver range	
k	Boltzmann's constant (Ws/°K)	1.38×10^{-23}
T_0	noise temperature (°K)	290
F_n	noise figure (dB)	4.3
L_s	system losses (dB)	5.0
N_P	number of pulses	1,024
σ^0	clutter cross-section per unit area (m^2/m^2)	
A_C	area of clutter cell	
PRF	pulse repetition frequency (kHz)	100

Table 1: Radar system parameters.

The received signal power S with coherent integration of N_P pulses is given by

$$S = N_P \frac{P\tau G_T \sigma A_e}{(4\pi)^2 R_T{}^2 R_R{}^2}.$$

The received noise power N is given by $N = kT_0 BF_n L_s$. Therefore the signal-to-noise ratio (SNR) for coherent integration is given by the bistatic radar range equation.

$$SNR = N_P \frac{P\tau G_T \sigma A_e}{(4\pi)^2 R_T{}^2 R_R{}^2 kT_0 BF_n L_s}.$$

Figure 2 shows an Excel spreadsheet that lists the system parameters and computes SNR. For a specified scenario, detection barrier, probability of detection P_d and probability of false alarm P_{fa}, one can determine radar parameters that achieve the required SNR. In addition the radar footprint and integration time are computed, which allows for the calculation of the time required to scan the barrier.

SNR Calculations for Over-the-Horizon Cruise Missile Detection						
Parameters				**Quantities of interest**		
			Transmitter			
Altitude	3,000	m		Beamwidth	16.80	deg.
Antenna diameter	0.100	m		Footprint diameter	886.00	m
Power (peak)	1,500	W		Gain	13.4	dB
Wavelength	0.03	m				
Ground range to Rx	25,000	m				
			Receiver			
Altitude	1,000	m		Beamwidth	1.51	deg.
Antenna height	1.0	m		Footprint length on ground	16,527.36	m
Antenna width	3.0	m		Horizon	112,935	m
Aperture efficiency	0.70			Gain	44.67	dB
			Waveform			
PRF	100	kHz		Unambiguous bistatic Doppler	3,000.00	m/s
Duty cycle	0.4			Unambiguous bistatic range	3,000.00	m
CPI length	1,028	pulses		Pulse width	4.00	µs
				Integration time	10.28	ms
			Target			
Velocity	717.5	m/s		Tgt Doppler	23,897.56	Hz
RCS	0.01	m^2		Tgt-to-Rx range	25,019.99	m
				Tgt displacement during CPI	7.38	m
			Noise			
Noise Figure	4.3	dB				
System Losses	5.0	dB				
			Single-pulse SNR			
				Signal Power	-153.49	dB
				Noise Power	-140.70	dB
				Signal-to-Noise Ratio	-12.79	dB
			SNR with Coherent Integration			
				Signal-to-Noise Ratio	**17.33**	**dB**

Figure 2: Spreadsheet for signal-to-noise ratio calculations.

4.0 PERFORMANCE OF UAV RADAR CONCEPTS

This section outlines the estimated detection performance of several UAV radar concepts. The list of concepts considered is not intended to be exhaustive. However the concepts considered place varying demands on the UAV payload.

For all concepts, it is assumed that the transmitter and receiver are stationary and that the receiver is located 1 km directly above the ship. The receive antenna is a rectangular phased array radar with a width of 3 meters and a height of 1 meter. It is assumed that probability of detection $P_d = 0.9$ and $P_{fa} = 10^{-5}$, so that a signal-to-noise ratio of 13 dB is required.

4.1 Monostatic Concept

In this concept, the radar antenna is a rectangular phased array and is located 1 km above the ship. The radar is modelled after the APG-66 multimode radar, with key specifications as shown in Table 2. The APG-66 has been used in the Small Aerostat Surveillance System (SASS) program to demonstrate the capabilities of UAV radar [5]. The SASS utilizes a helium-filled, tethered aerostat, the TCOM 32M. The radar is rack-mounted on the underside of the aerostat, and the data acquired by the radar is passed to an associated ground station via a fibre-optic link contained within the aerostat's tether. The APG-66 as specified in Table 2 is approximately 100 kg.

Antenna size	1 x 3 meters
Antenna gain	42 dB
Antenna pointing accuracy	5 mrad
Antenna sidelobes	>40 dB (azimuth)
Frequency	9.7-9.9 GHz
Power	200 W (average), 17.5 kW (peak)
Beamwidth	0.75 (azimuth), 2.25 (elevation)

Table 2: Key parameters of APG-66 radar**.**

Figure 3 shows an illustration of the monostatic concept. The detection barrier has an annular shape, with the inner edge of the annulus at the shipborne radar horizon of 25 km, and the outer edge at the maximum detection range. The antenna is electronically steered in azimuth, and in elevation if necessary, so that a sequence of antenna footprints covers the entire detection barrier. For this study, it will be assumed that the radar operates at a frequency of 10 GHz, with a peak power of 1.5 kW. This lower power level, compared to the APG-66, will reduce the weight of the UAV payload. Note that a peak power of 1.5 kW will also be used in the bistatic concepts considered in this section.

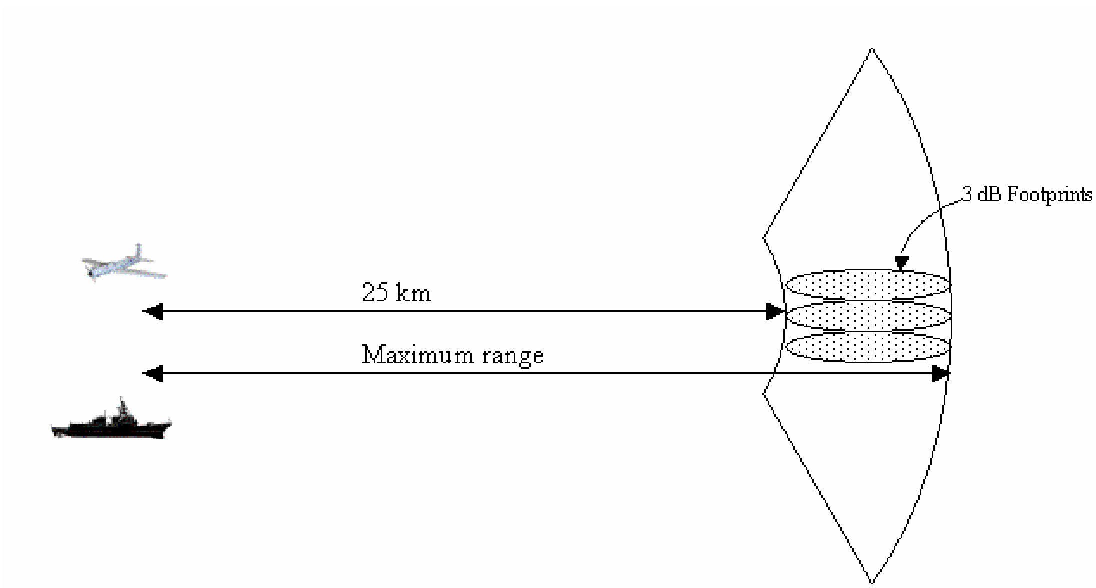

Figure 3: Illustration of monostatic concept.

Advantages of a monostatic radar concept include the requirement of only one line-of-sight to the target. A monostatic radar may also have multifunction capability and thus may make more efficient use of a single platform. However, cruise missile RCS values are typically very small, and a bistatic radar may be able to increase received signal power by locating the transmitter or receiver closer to the target. Thus the main disadvantage of a monostatic radar is that the SNR decreases as R^{-4}, whereas a bistatic radar may achieve higher SNR, depending on its geometry.

It is assumed that the inner edge of annular detection barrier has a ground range of 25 km. The maximum range is given by

$$R_{\max} = \sqrt[4]{N_P \frac{P\tau G_T \sigma A_e}{(4\pi)^2 10^{1.3} k T_0 B F_n L_s}}$$

The value of $R_{\max}$ as a function of target RCS is shown in Figure 4. The phased array antenna steers to ±60° electronically in azimuth. For an antenna of width w and at a look angle of α the 3-dB beamwidth in azimuth is given by $\theta_{3dB} = \dfrac{0.88\lambda}{w\cos\alpha}$. This equation can be used to compute the number of footprints required to scan the barrier.

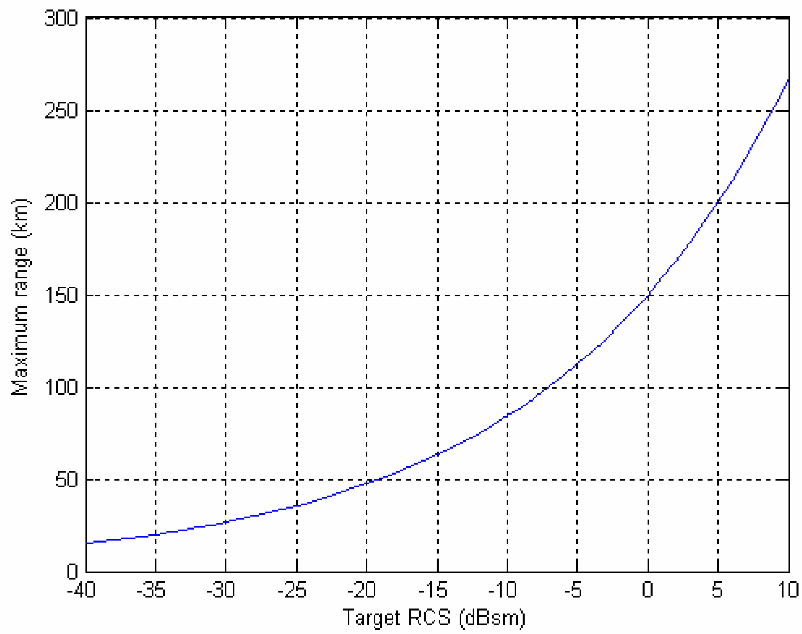

Figure 4: Maximum detection range vs. target RCS for the monostatic radar concept.

For a target RCS of -10 dBsm, the maximum detection range is 84 km. The inner ring of footprints extend from 25 km ground range to 74 km ground range. The radar forms 198 footprints in this ring using azimuth steering and scans the entire ring in 2 seconds. Elevation steering is then used to scan a second ring of footprints that extend from 74 km ground range to beyond the maximum detection range of 84 km. In total, the radar forms 396 footprints in the annular detection region and scans the entire region in 4 seconds.

For a target RCS of -20 dBsm, the maximum detection range is 47 km. For a target RCS of -30 dBsm, the maximum detection range is 27 km. In each case, the radar forms a single ring of 198 footprints that extend from 25 km range to beyond the maximum detection range. Electronic steering in elevation is not required. The entire barrier is scanned in 2 seconds.

4.2 Bistatic Concept with High-Gain Transmitter

This bistatic concept uses an APG-66 antenna as the transmitter and another as the receiver. The transmitter is deployed in the direction of the expected threat. Figure 5 illustrates this concept. The rectangular detection region is perpendicular to the receiver line-of-sight. The transmitter and receiver operate at approximately a 90-degree bistatic angle. The transmitter antenna is steered in azimuth and elevation so that a sequence of transmit footprints covers the rectangular barrier.

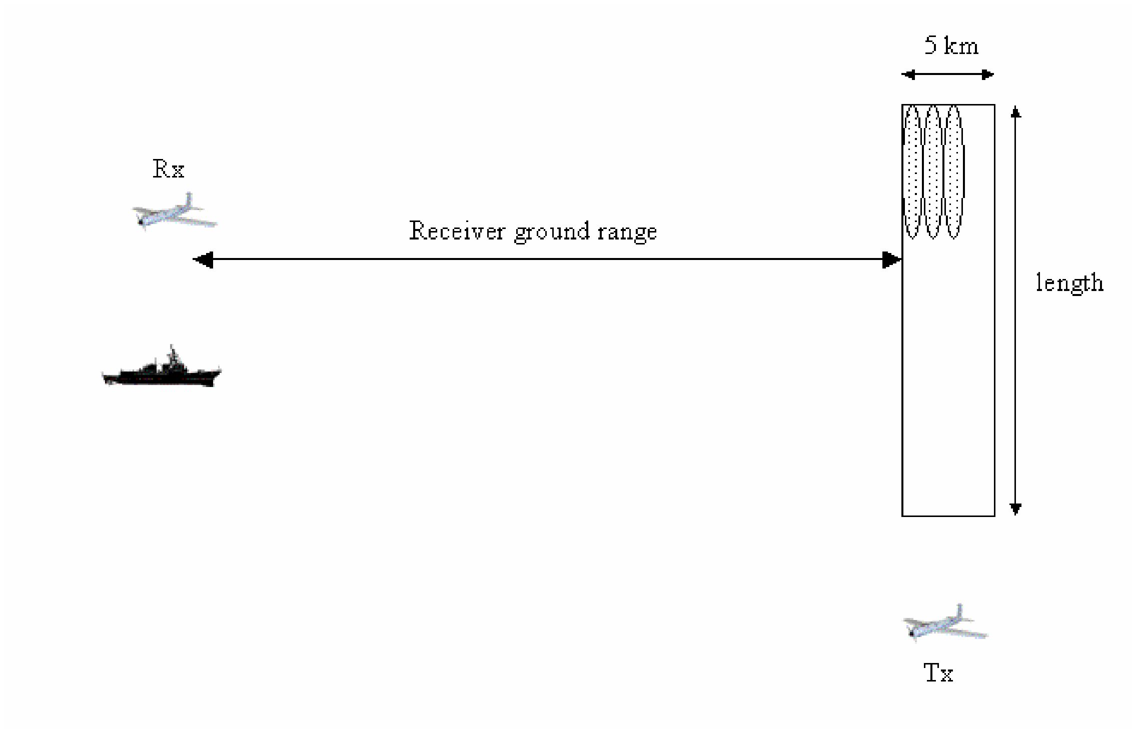

Figure 5: Illustration of Bistatic Concept with a High-Gain Transmitter.

Compared to the monostatic concept, this concept has reduces the transmitter range and thus increases SNR. However, this concept introduces the disadvantages of bistatic radar. In particular, two lines-of-sight to the target are required, and synchronization and timing must be maintained between the transmitter and target to carry out coherent processing.

The transmitter will scan the barrier from left to right and from top to bottom, subject to a specified revisit time, which is defined as the maximum length of time between scans for any point in the barrier. The revisit time is determined from the speed of the expected threat as follows. A Tomahawk cruise missile has a top speed of 256.25 m/s and will cross the 5 km wide barrier in 20 seconds. Thus a revisit time of 6 seconds will ensure three target detections within the barrier and allow for the formation of an initial track, which could then be handed off to the shipborne radar or another sensor. A Sunburn anti-ship missile has a top speed of 717 m/s and will cross the barrier in 7 seconds. In this case, a revisit time of 2 seconds ensures three detections within the barrier. Using SNR calculations, the maximum barrier length can be determined for a given target RCS and revisit time.

For a target RCS of -10 dBsm, Figure 6 shows the maximum barrier length for a revisit time of 6 seconds and 2 seconds. At 30 km ground range, the maximum barrier length is 229 km. Decreasing the revisit time from 6 seconds to 2 seconds results in a maximum barrier length of 220 km. Maximum barrier length for a target RCS of -20 dBsm is shown in Figure 7. Compared to the maximum barrier length for a –10 dBsm target, the maximum barrier length for a -20 dBsm target decreases by a factor of 4. The maximum barrier length for a target RCS of -30 dBsm, as shown in Figure 8, also decreases by a factor of 4, compared to the maximum barrier length for a target RCS of -20 dBsm.

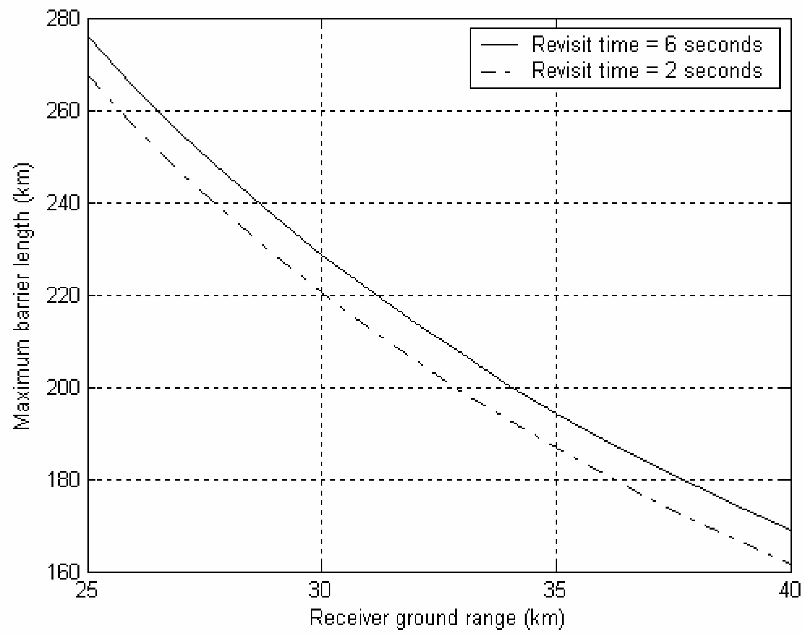

Figure 6: Maximum barrier length for a target RCS of -10 dBsm.

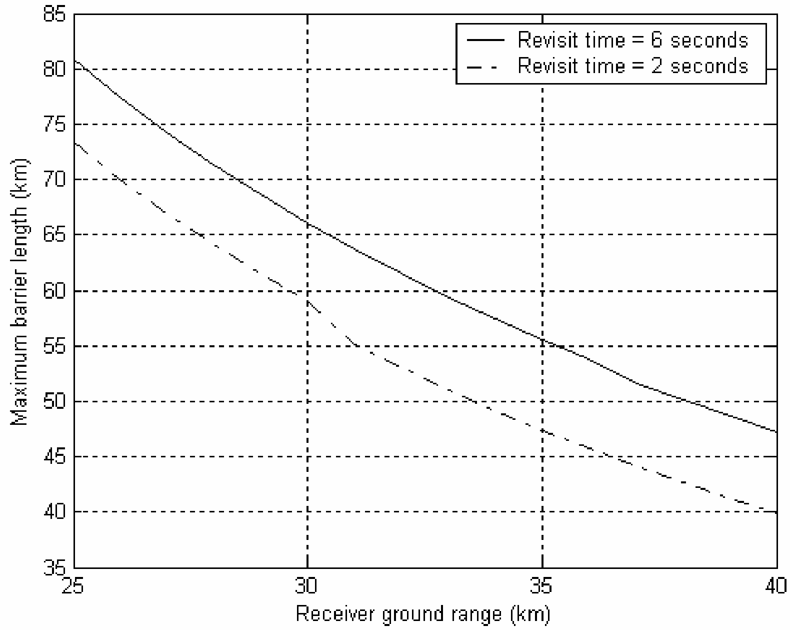

Figure 7: Maximum barrier length for a target RCS of -20 dBsm.

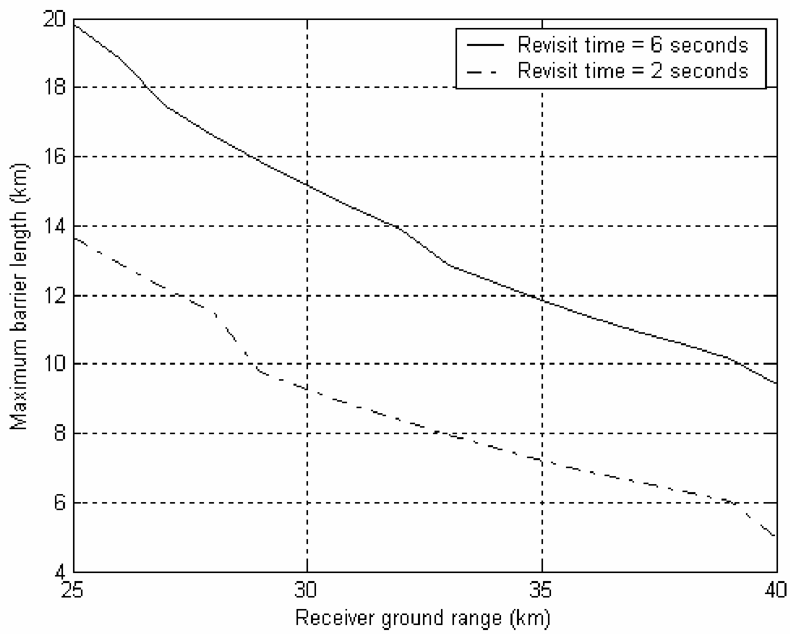

Figure 8: Maximum barrier length for a target RCS of -30 dBsm.

4.3 Bistatic Concept with Low-Gain Transmitter

In this concept, the transmitter is again deployed in the direction of the expected threat, and the transmitter and receiver operate at approximately a 90 degree bistatic angle. The key difference is that the transmitter antenna is a small, low-gain antenna that is fixed and staring, as illustrated in Figure 9. This concept requires a much smaller and simpler payload compared to a high-gain transmitter. On the other hand, the low-gain antenna results in decreased signal power at the receiver.

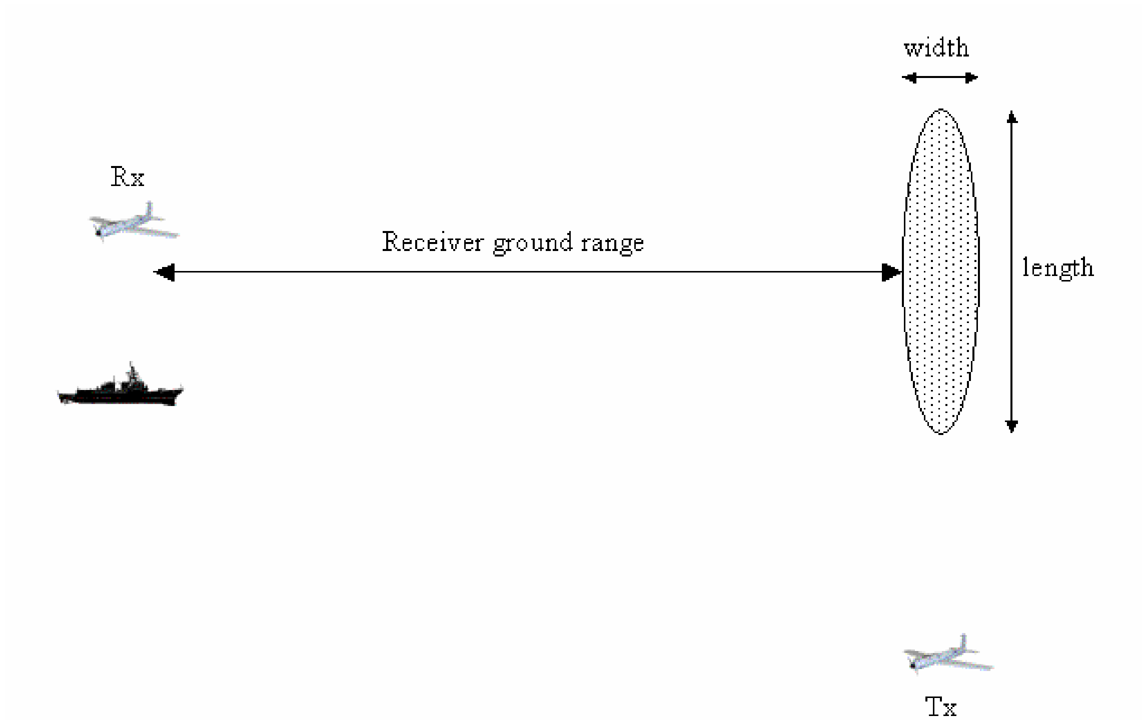

Figure 9: Illustration of Bistatic Concept with Low-Gain Transmitter.

The transmitter antenna is assumed to be a 10-cm reflector. For target RCS values of -10 dBsm and -20 dBsm, the transmitter altitude is 1 km, while for a target RCS of -30 dBsm, the transmitter altitude is 500 m. It is desired that the transmitter footprint be as large as possible, under the constraint that all targets are detected within the footprint. Figures 10-12 show the maximum size of the antenna footprint for target RCS values of -10 dBsm, -20 dBsm, and -30 dBsm. It is seen that at a receiver ground range of 30 km, the radar detects -10 dBsm targets in a 9 km by 4 km footprint. However, -20 dBsm targets are detected within a 2 km by 1.2 km footprint, and -10 dBsm targets are detected with in 500 m by 400 m footprint. For the two smallest RCS targets, this concept provides unacceptably poor coverage.

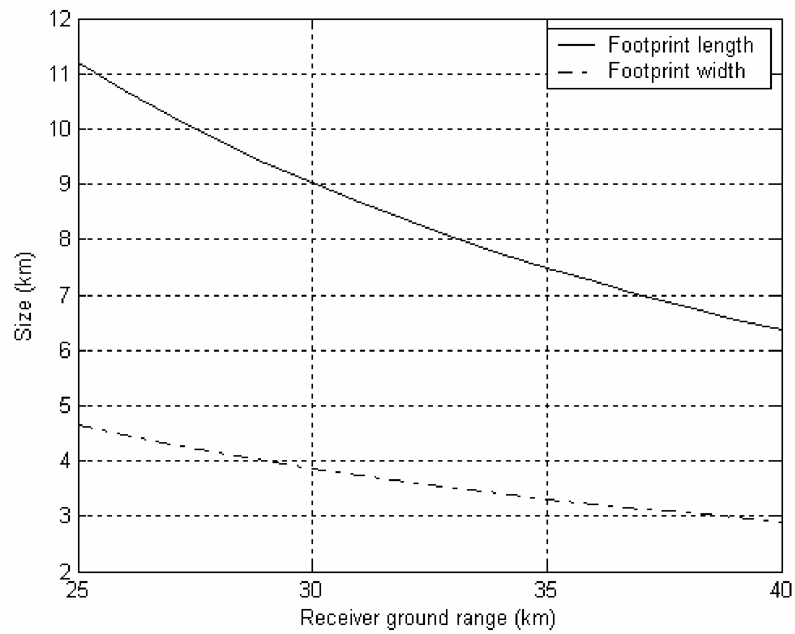

Figure 10: Maximum footprint size for a target RCS of -10 dBsm.

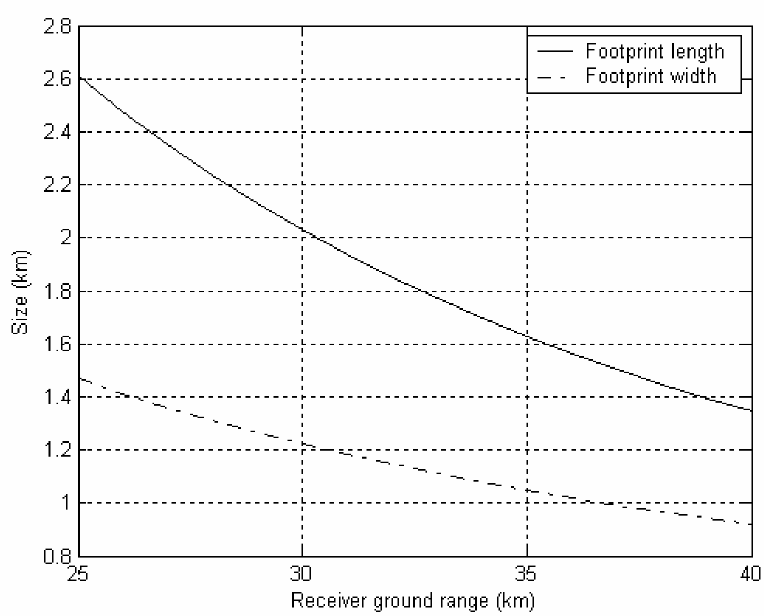

Figure 11: Maximum footprint size for a target RCS of -20 dBsm.

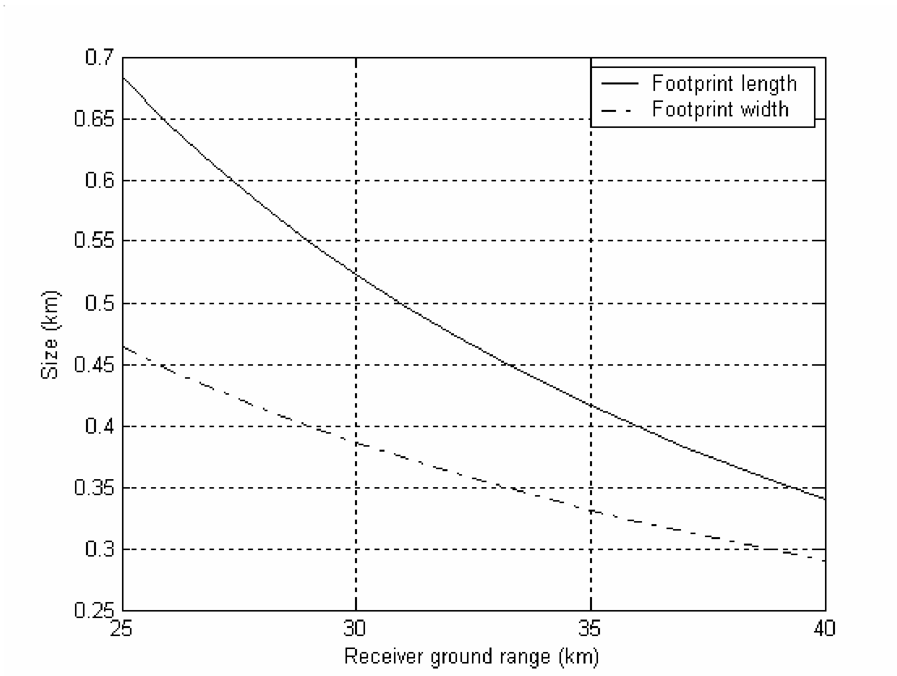

Figure 12: Maximum footprint size for a target RCS of -30 dBsm.

4.4 Pseudo-Monostatic Concept

In this concept, the transmitter is again deployed in the direction of the expected threat. The transmitter is a reflector antenna that scans, in azimuth only, an annular detection barrier, as shown in Figure 13. The inner edge of the barrier is 5 km in ground range from the transmitter, and the barrier has a width of 5 km. For this fixed barrier size, it is desired that the reflector antenna be as small as possible. This concept specifies a barrier with an effective length of approximately 20 km, while only requiring azimuthal steering.

Figures 14-16 show the minimum reflector diameter for target RCS values of -10 dBsm, -20 dBsm, and -30 dBsm. At a receiver ground range of 30 km, a 12-cm reflector will detect all -10 dBsm targets within the barrier, while a 38-cm reflector is required for -20 dBsm targets, and a 1.2 m reflector is required for -30 dBsm targets. Thus for targets with RCS of -20 dBsm or greater, a reflector antenna of 38 cm or less is required to establish a 20 km barrier. The antenna has a relatively small size and scans in azimuth only, which results in a modest UAV payload. Of the four concepts considered in this paper, the pseudo-monostatic concept has the best detection performance considering its modest UAV payload, based on an analysis of SNR. Instead of a reflector antenna, a rectangular phased-array antenna could be used as the transmitter. If electronic steering were employed the antenna could be steered up to 60 degrees from boresite.

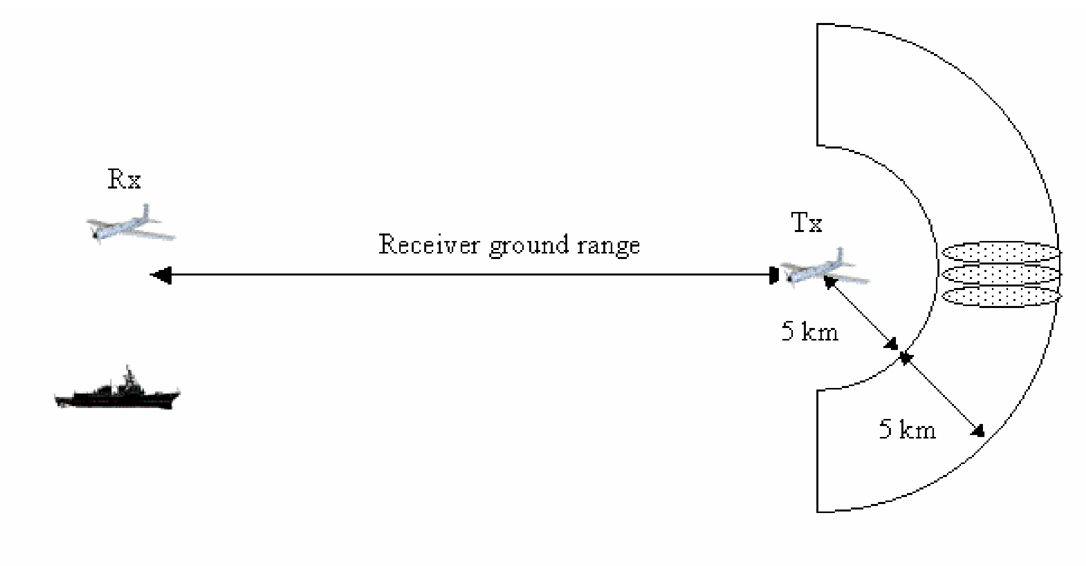

Figure 13: Illustration of pseudo-monostatic concept.

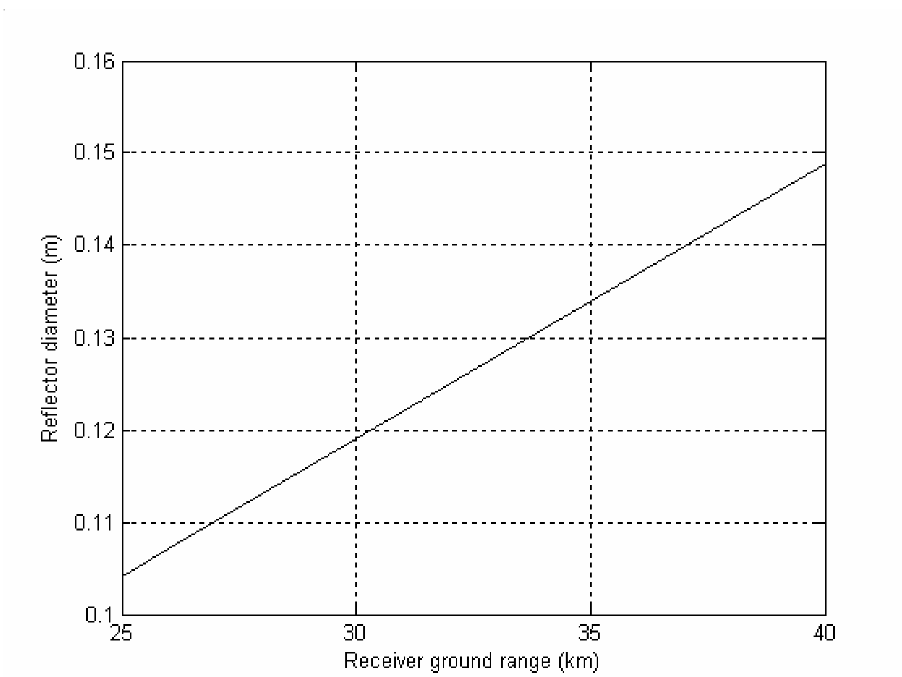

Figure 14: Minimum receiver diameter for a target RCS of -10 dBsm.

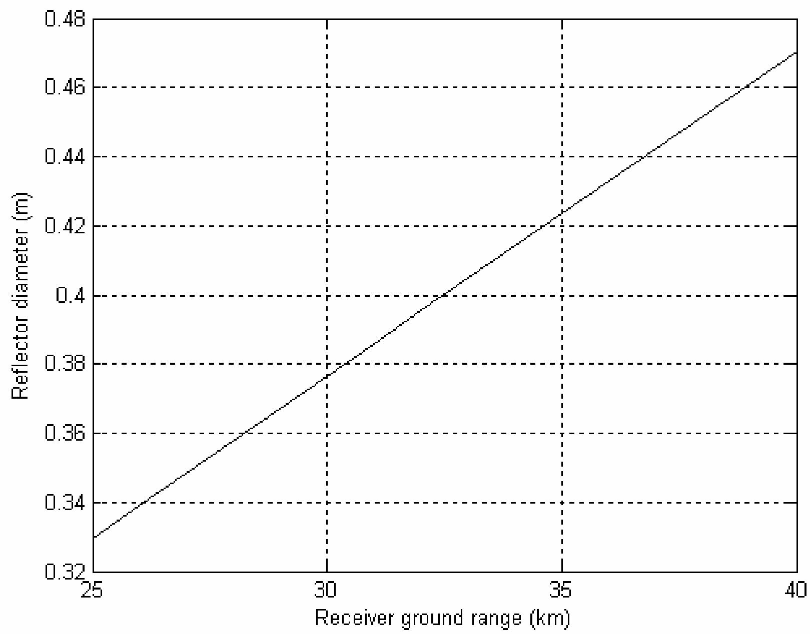

Figure 15: Minimum receiver diameter for a target RCS of -20 dBsm.

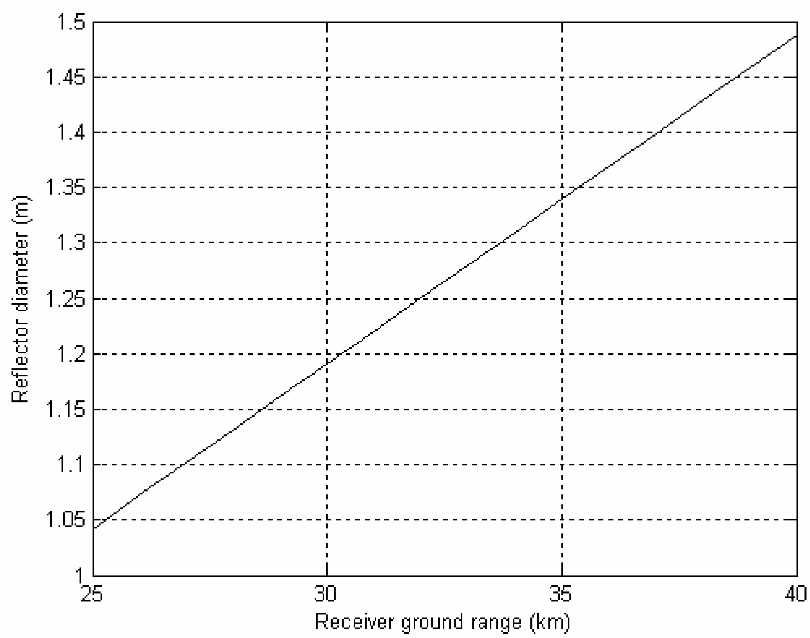

Figure 16: Minimum receiver diameter for a target RCS of -30 dBsm.

5.0 CONCLUSIONS

In summary, this paper considered various UAV radar concepts to enhance over-the-horizon detection of low-altitude threats. Targets such as cruise missiles and anti-ship missiles are the most challenging threats because of their high velocity and low RCS. This study used SNR calculations to analyze the detection performance of various concepts.

A monostatic concept utilizing an APG-66 radar was analysed. For a target RCS of –20 dBsm, it was shown that the radar has a maximum detection range of 47 km. However, this concept requires a large UAV payload. A bistatic concept with a high-gain transmitter was shown to achieve excellent detection performance, in this case with large UAV payload at the transmitter. A bistatic concept with a low-gain transmitter has a much lighter and cheaper payload, but was shown to provide inadequate area coverage.

The most promising concept was a pseudo-monostatic concept with a transmitter reflector antenna that rotates in azimuth only. This concept was shown to detect targets within a 20 km long barrier, with a reflector diameter that varies with receiver ground range and target RCS. The analysis showed that a fixed and staring transmitter antenna will not provide adequate area coverage, however the pseudo-monostatic concept provides good detection performance with a reasonable UAV payload.

6.0 REFERENCES

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