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Airborne Ground Control Station Localization

Task Authorization No. 23

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TASK AUTHORIZATION NO. 23

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Abstract

The work conducted for this task was to provide literature review of applicable techniques and algorithms from industry and academia; including but not limited to foreign military research or demonstrations, journal articles, peer reviewed papers, credible conference publications and credible industry sources. These efforts were conducted for the DRDC Suffield Counter Unmanned Aerial System (CUAS) research program. Along with the literature review, Amtech Aeronautical Limited conducted a thorough market survey of applicable devices, instruments and products for the identification of Unmanned Air Vehicle (UAV) Radio Frequency (RF) signals, Direction Finding (DF) and geolocation of UAS and Ground Control Station (GCS), on-board data processing and signal analysis, UAV payload devices for precise geolocation, communications and computing payloads necessary for data processing and transmission, and cost effective UAS for such deployment. Recommendations of the most technically feasible approach for pursuing an airborne GCS localization system, potential equipment options and high-level refence designs containing electrical, software and mechanical aspects are made. This work was completed under contract W7702-145682/001/EDM.

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1 Introduction

The scope of this work performed is to provide research, technical and engineering support for the CUAS research being conducted at DRDC Suffield. The objective is to conduct research on a system that would allow the operator and/or user to locate a UAV and/or the UAV GCS from the air; creating a valuable asset for law enforcement or military personnel for threat elimination. The possibility of developing a system that could be mounted on a single UAV or on a constellation of UAVs is also explored; enabling better line-of-sight and mobility to locate the UAS operator. The research, along with engineering support is being conducted on a 'best level of effort' basis in accordance with the Statement of Work (SOW) as per the task authorization.

This report details the literature review of applicable techniques and algorithms, market survey of applicable devices, limitations and challenges associated with the explored techniques and recommendations of a feasible approach to develop an airborne GCS localization system. Further research and development options are also examined.

2 Background

Around the world, recent developments involving the use of small consumer grade UAVs by hostile actors have demonstrated that the threat posed by these increasingly commonplace devices to attack and disrupt operations is real. Airport operations have been halted, UAVs have been loaded with explosives and used in attacks against militaries and in assassination attempts. The requirement for an ability to deploy CUAS systems (Counter Unmanned Air System) to protect people, facilities, and operations is becoming increasingly critical.

Various technologies and techniques are currently available to help address the challenge of rogue UAV detection, localization, tracking, and interception. Rogue UAV's have signatures in the Radio Frequency (RF), visual, audio, and radar domains. These signatures can all be exploited by modern sensors to counter the threats posed by these devices.

Existing CUAS systems have typically used fixed sensors, or mobile sensors based in manned vehicles[ref]. With new developments in sensor and UAV technology, many sensors are now small and light weight enough to be successfully deployed on unmanned UAV platforms.

This paper will look at some currently available CUAS systems as well as examining some of the area of UAV based RF signal localization for future research and development work.

3 General Concepts for CUAS Systems

3.1 Overview

A vast multitude of small UAV's are easily attainable by private consumers today. The first step in countering developing threats posed by bad actors employing these UAV's is to recognize that they are part of a larger system. An Unmanned Air System (UAS) consists of multiple components in addition to a UAV, with these small commercial systems typically including a pilot, a Ground Control Station, and a communications signal between the UAV and the GCS. Each of these components is critical to the success of a UAV's mission. To counter the threat of a hostile UAS, it is necessary is to disrupt at least one of these links.

This report will focus primarily on the RF communications signal between the UAV and the GCS, which can be key to exposing the other UAS components.

3.2 Detecting and Tracking UASs

In order to counter a rogue UAS threat, the first step is detecting that a UAS is present. There has been significant research into a variety of ways that unmanned air systems can be detected. This section presents some of the common methods and sensors currently employed in CUAS systems.

3.2.1 Relevant Sensors and Technologies

RF Signals

Most consumer UASs rely on some sort of RF link between the UAV and a ground control station. This link can consist of command from the GCS, and telemetry and video signals transmitted back from the UAV. The monitoring (and potential manipulation) of RF signals is an invaluable capability for a CUAS system.

RF signals can be passively monitored, without any indication to the rogue UAS operator that the signal has been intercepted.

While it is increasingly easy for custom control signals to potentially be employed with the advent of Software Defined Radio (SDR) technology, to date most small consumer UASs have relied on unlicenced frequency bands and often WiFi signaling[10]. RF signals for these systems have distinctive "signatures" based on the frequencies and protocols that they use. A CUAV system can continuously scan the frequency ranges for signals matching the characteristics of a database of known signatures and use it as a basis for detection and to begin gathering information about the rogue UAS.

Some RF signal types can be decoded. For unencrypted traffic, and for known protocols this can reveal a significant amount of information about the rogue UAS, including GPS coordinates of the UAV and or GCS, to live video feeds from the UAV's cameras.

Some types of RF signals can be manipulated. GPS signals can be hijacked to force a UAV down, commands can be issued to cause the UAV to return to its takeoff coordinates. There are several commercial CUAS systems which support these capabilities. Common UAV communications protocols can have security vulnerabilities that can be exploited [12][13].

A good overall breakdown of the characteristics of RF signals for small UASs is given in the paper "Analysis and Decoding of Radio Signals for Remote Control of Drones" [9].

Once the UAS is detected, radio direction finding (RDF) techniques can be employed to localize the positions of RF emitters, which can include both rogue UAVs and the rogue UAV's GCS.

RF Sensors and components

In this section we will outline some of the sensors and system components that can be used for detecting and gathering information from RF signals.

Software Defined Radio (SDR)

Software Defined Radio (SDR) is a relatively recent development in radio communications technology where the analog hardware components previously required for radio communication are instead implemented by means of software running on a computer or an embedded system. Initially, the concept of SDR was strictly theoretical, however, the advances in the capabilities of digital electronics has allowed for practical implementation of SDR with significant applications in the military services, along with civilian and hobby driven applications.

SDR systems can receive transmissions from broadcast stations, aircraft communications, Digital Audio Broadcasting DAB radio stations, emergency services and many more platforms. On a high-level, the hardware required to implement an SDR system is an antenna, SDR receiver/transmitter and a computer running SDR software. The radio signals are received through an antenna, which are then passed through a Radio Frequency (RF) amplifier and/or filter, to an analog to digital (A/D) converter, into the software processor which employs modern error correction, encryption and network routing, before passing along the transmission to the user [1]. Radio transmission through SDR works in a similar manner; the input is processed by the software, the digital signals are converted to analog signals via a digital to analog converter, and then amplified/filtered and finally, transmitted from an antenna.

SDRs can cover a wide range of frequencies, as well as rapidly switch frequency ranges, which would allow reception and processing of multiple channels and signals from devices that hop frequencies; common to most UAVs and ground stations. SDR is frequently used by CUAS systems to scan known frequencies that are used by commonplace commercial and hobbyist UAVs.

Due to relative accessibility, SDRs are an excellent tool for implementing sensors for RF direction finding techniques. The software-based processing of the radio signals makes it easier to obtain the signal information required for RF DF techniques and algorithms.

Radio Direction Finding Techniques

RF direction finding is the determination of the position, velocity and/or other characteristics of an object or a transmitter, or the obtaining of information relating to these parameters, by the means of the propagation properties of radio waves [2]. Common RF direction finding techniques are the angle of arrival (AOA), frequency difference of arrival (FDOA), the time of arrival (TOA), time difference of arrival (TDOA), and received signal strength (RSS). Common data processing techniques involve the application of Kalman filtering, particle filtering, Multiple Signal Classifications (MUSIC) and phase interferometer algorithms [3].

Angle of Arrival

The angle of arrival technique uses the directional angle of the signal to locate the signal position. The AOA technique generates the angle of tracking, also known as the line of bearing (LOB) to estimate the position of the RF transmitter. This technique is the most effective when the UAV, or the receiver is pointing directly at the transmitter. Using a phased array of antennas, and a signal processing device, which could be SDR, the angle at which the received signal is located relative to the receiver could be estimated. The time or frequency difference between the array of antennas could be used to make an estimation of the angle at which the signal came from. Using the angle estimations provided by the multiple receivers, a line of bearing could be generated for the known location of the sensor to the estimated transmitter position [2]. The intersection of the LOBs would provide the estimated geolocation of the transmitter, which could be a ground station or a UAV.

Pseudo-doppler techniques can also be applied to determine the LOB. For pure doppler shifts to work, the UAV would have to fly at speeds fast enough to detect shifts. Instead, pseudo-doppler or synthetic doppler technique could be used, where the received signal is switched rapidly between a constellation of antennas, and the phase differences are measured to determine the line of bearing (LOB). Multiple UAVs that are independently generating LOBs can create angular diversity to determine the geolocation proximity. By mapping the intersecting LOBs between the UAVs, a region of uncertainty can be obtained, which can be simplified as a trapezoid. Further automation of the UAVs through cooperative auto-piloting could narrow the uncertainty region of the target; this would allow faster determination of the RF transmitter, which could be a ground station or a UAV [2].

Frequency Difference of Arrival

The frequency difference of arrival (FDOA) method uses the difference in frequency of the signal measured between two receivers to determine the signal position. If either the transmitter or the receiver is moving, a phase shift that is induced in the signal could be used to determine the position of the transmitter. In search for a ground station, the movement of the UAV, which would be the receiver, would allow the geolocation to occur. Given the location of the observation points, velocity of the UAVs and the observed phase shift, curves of possible locations for the transmitter can be generated [2]. An advantage of the FDOA technique is that the location error estimates are often in a different direction, which allows combining different techniques to narrow down the search. For instance, combing FDOA with LOB and observing the intersection points would narrow the estimated geolocation. A disadvantage of the FDOA technique is that it is difficult to implement for low power systems and the velocity of the receiver has to be sufficiently high to produce a large enough shift to overcome the error and noise in measurements. Combing FDOA with pseudo-doppler techniques may counteract this high velocity requirement.

Time of Arrival

The time of arrival (TOA) method locates the signal by measuring the precise time at which the signal arrives at multiple receivers. Since RF waves propagate at the speed of light, an accurate measurement of the time at which the receiver detects the signals would yield a circle of possible locations for each sensor. A drawback of this approach is that an extremely precise time estimate for which the signal originated is also required, which requires careful time synchronization by all emitters and receivers in order to be achieved [2]. The method calculates how far away from the receiver the transmitter is located by measuring the time difference between transmission and reception and multiplying by the speed of light. By taking readings at multiple locations with multiple UAVs and plotting the circles of possible locations; the intersection pints of those circles can determine the geolocation of the transmitter. Due to the difficulties in determining the time at which the signal was transmitted, the TOA technique lacks real world applications for tracking non-cooperative emitters.

Time Difference of Arrival

The time difference of arrival (TDOA) method locates the signal position from the time difference in the detection of the signal from multiple receivers. The TDOA is a variation of the TOA method; the difference being that the emitter does not have to be time synched with the receiver [2]. Instead, the method measures the time difference between the detection of the signal by multiple receivers to generate curves of possible target locations [3]. By taking multiple measurements via multiple receivers on multiple UAVs; the resulting intersections of the hyperbolic curves could determine the transmitter location. A disadvantage of this method is that a minimum of three UAVs would be required to generate a target location. An additional fourth UAV might be required if the altitude of the transmitter is unknown. This approach would not be as cost effective as the other methods. Moreover, all of the UAVs have to be precisely time synched with each other for proper geolocation.

Received Signal Strength

The Received Signal Strength (RSS) method measures the strength of the received signal to determine the geolocation. As the receiver moves and the received signal strength grows stronger or weaker, it can be determined whether the receiver is moving towards the location of the emitter or farther away from it. An advantage of the RSS method is that it is simple and easy to implement. It can also be used in combination with other methods to improve accuracy. The drawbacks of RSS are that its position estimates are not as accurate as other methods and RSS sensors work best in relatively close proximity to the transmitter in order to distinguish sufficient variation in signal power levels, which is required to track the emitter [2]. Combining the RSS methodology with the angle of arrival, frequency different of arrival or time difference of arrival techniques would yield better results.

RF Receiving Equipment

Directional antennas produce the highest signal when the receiver is pointing towards the transmitter. Common directional antennas are Yagi and Quad antennas [2]. When mounted on a UAV, directional antennas would quickly lose the signal if they are pointing away from the general direction of the transmitter and show strong signals strengths when pointing in the direction of the transmitter. Combining directional antennas with SDR for measuring a wide frequency range, the general direction of the transmitter could be determined.

Dipole Antenna

Dipole Antennas are the simplest antennas; they measure the wavelength of the received signal. If the dipole antenna is positioned where a null signal is obtained, it would indicate the direction of the transmitter. This is due to the wavelength difference across the dipoles being zero. Even though it is simple to utilize dipole antennas, the antennas are not suitable for a wide range of frequencies. When solving problems involving unknown frequencies, an array of diploe antennas would have to be used. An SDR could act as a central signal processor amongst the array of antennas.

Dual Dipole DF System

Dual dipole DF system, also known as the homing DF system, gives a left-right, front-back or null indication of the emitter signal. The system utilizes four antenna elements; two passive and two active elements. A pair of active and passive antennas are mounted on each side of the system, measuring the phase difference between the two incoming signals. This system can determine where the transmitter is located to the left or to the right of the respective position. A null indication determines that the transmitter is either to the front or the rear of the respective position.

Pseudo Doppler Direction Finding

Pseudo Doppler DF technique has an array of four (omni-directional) dipole antennas oriented in a circular formation that observe the change in frequency of the incoming signal. Each antenna is switched or sampled sequentially to simulate the effect of a single antenna being rotated in a circular trajectory [3]. The pseudo-doppler system would require an antenna controller or an antenna switch circuit to connect one antenna at a time to the receiver input; allowing to measure the phase difference [7]. Pseudo doppler direction finding may be most suited for UAV applications; it is low cost, light weight and requires minimal mounting space on the UAV.

Watson-Watt Method

Watson-Watt (WW) DF is a direction finding technique that is based on an amplitude-based method that uses the relative amplitude of the output of two antenna arrays arranged according to the Adcock Antenna Array design [6]. A WW implementation makes angle of arrival estimations by determining the arctangent of the magnitude of the east-west/north-south signal ratio. The Adcock design consists of four antenna elements in a perpendicular, crossed-baseline configuration. The antenna array was originally used to find the azimuthal direction of a radio signal to find the location of the radio transmitter. The Adcock antenna array replaces the loop antennas with symmetrically inter-connected pairs of vertical monopole or dipole antennas, which eliminates horizontally polarized distortion. The perpendicular configuration, typically labeled as North – N, South – S, East – E and West – W, with element spacing of less than one half the wavelength at the highest operating frequency [7]. The azimuth gain pattern from each antenna array are obtained by a vector difference of signals from each of the two antennas. The N and S antenna pair creates the Y-axis voltage and would have the maximum gain along the Y-axis. The E and W antenna pair creates the X-axis voltage, which has the maximum gain along the X-axis. An omni-directional antenna is placed centrally to eliminate the 180° phase ambiguity, providing basic directional sensing.

An advantage of using the Watson-Watt method is that the Adcock Antenna Array diameter could be small is size, making it ideal for UAV, mobile and transportable DF applications. Low cost receivers can also be used with the application, hence, making it a low-cost application.

There are certain disadvantages with the Watson-Watt method; if the center antenna is not used, the algorithm has an 180° phase ambiguity. The system is also susceptible to multipath and reflection errors.

A discussion of the merits of Watson-Watt over Pseudo-Doppler DF techniques has been published by RDF Products [14].

Direction Finding Algorithms

Kalman Filters

Kalman Filters (KF) are commonly applied in direction finding applications. Kalman filters are good for combining information in the presence of uncertainty. Kalman filters can be used where there is uncertain information about some dynamic system, and educated guesses have to be made about what the system is going to do next. Advantages are that they are light on memory; they do not need to keep extensive information about pervious states; only the most recent previous state is required. Kalman filters work best with linear systems [4].

Extended Kalman Filter

Extended Kalman Filters (EKF) are applied in the presence of nonlinear systems, which work by linearizing the predictions and measurements about the mean. RF waves and target motion analysis consist of non-linear data sets, which yield better results under the extended Kalman filter [4].

Unscented Kalman Filter

Unscented Kalman Filters (UKF) take the extended Kalman filter one step further. The unscented Kalman filter linearizes the predictions and measurements about the mean, and looks at multiple other points, known as the sigma points. The filter considers a few points from the source gaussian and maps them on the target gaussian after passing points through a non-linear function. It then calculates the new mean and variance of transformed gaussian; having greater number of points allows for a more precise approximation.

Particle Filters or Sequential Monte Carlo

Particle Filters or Sequential Monte Carlo (SMC) methods are a set of Monte Carlo algorithms used for signal processing. In the case of transmitter location, the probability distribution of the transmitter position given by a collection of RDF readings can be leveraged through Bayesian reasoning, which states that based on the prior knowledge of the RF readings, a probable location of the transmitter can be estimated recursively. Particle Filters can combine RF readings and system noise to generate a probability for true location of the transmitter [4].

Multiple Signal Classification (MUSIC)

MUSIC conducts characteristic decomposition for the covariance matrix of any array output data, resulting in a signal subspace orthogonal with a noise subspace corresponding to the signal components. Then these two orthogonal subspaces are used to constitute a spectrum function to detect DOA signals [5].

Estimation of Signal Parameters via Rotational Invariance Technique (ESPRIT)

ESPRIT is a high-resolution signal parameter estimation technique based on the translational invariance structure of a sensor array. The ESPRIT algorithm is an attractive solution to many parameter estimation problems due to its low computational cost. By exploiting invariances designed into the sensor array, parameter estimates are obtained directly, without knowledge of the array response and without computation or search of some spectral measure. The exact number of samples and elements used is the most important parameter in the algorithms in order to sustain the accuracy of the direction of arrival of the incident signals. This algorithm is more robust with respect to array imperfections than MUSIC

4 Commercial CUAS System Survey

4.1 Overview

There is a large and growing number of CUAS systems to choose from in the marketplace today. Both military and commercial systems exist and are available in a multitude of configurations as diverse as the problems they attempt to resolve. They can incorporate a wide variety of sensor types for detection and tracking including radar, machine vision, acoustic, and RF sensors.

4.2 Military Systems

Military systems come in a wide variety of configurations, to meet a wide variety of situations. There are systems intended for fixed installation to protect facilities, vehicle portable systems for deployment in the field, systems to protect vehicles, and even man portable systems to protect squads of troops.

Military systems will typically offer a “capture or kill” capability as an option, or sometimes as a primary focus. Active countermeasures can include RF signal hijackers, RF signal jammers, guns, missiles, or even lasers.

4.3 Commercial Systems

Commercial systems have tended to be more passive with concentration on the detection and identification of a UAV threat, as frequently active countermeasures have regulatory or safety issues in the commercial space.

The problems they are designed to address include prevention of unauthorized UAVs posing safety hazards to operations including at airports and over wildfires, where risk of collision with aircraft is a major concern. Other areas include controlling airspace over prisons where UAVs can deliver contraband. Facilities such as stadiums, power plants and factories have also been targeted by rogue UAV operations. Law enforcement agencies are also starting to take interest as these systems can also be used to help insure compliance with current UAV operation regulations.

4.4 System Survey

Table 1 presents a brief, non-exhaustive overview of some of the many CUAS systems that exist in the market today. Source materials used in preparation of this summary are included in the Appendix.

SYSTEM	REPORTED FEATURES
Aaronia AARTOS	- RF signal detection - can detect and track both the drone and the operator - can detect multiple drones at once - modular - offers RF jammer, radar, EO camera integration (website datasheet "Aaronia_AARTOS_Drone_Detection_System.pdf"
ApolloShield	- RF signal detection - can detect and track both the drone and the operator - modular - offers RF jammer integration (March 2019 website http://www.apolloshield.com/)
Aselsan IHTAR	- radar detection - electro-optic (EO) thermal and daylight camera for identification - RF jammer (Jane's "IDEF 2017 Aselsan unveils anti-UAV systems.PDF")
Avnon Skylock	- radar and RF detection - offers RF jammer, EO camera, directed energy laser integration (Jane's "Skylock counter-UAV system books new orders.PDF"
Battelle DroneDefender	- RF hijacker/jammer (Jane's "Xponential 2016 Battelle updates, sells DroneDefender counter-UAS device.PDF"
Black Sage UAVX	- radar detection - EO daylight and infrared cameras - AI for target classification (Jane's "AI technology leveraged for C-UAV system.PDF")
CACI SkyTracker	- RF signal detection - can detect and track both the drone and the operator - modular - offers RF jammer integration (website datasheet "F387_1901_CORIAN_SkyTracker Suite.pdf")
Dedrone DroneTracker	- RF signal, acoustic, optical, infrared detection and identification - can detect and track both the drone and the operator - modular (website datasheet "dedrone-rf-300-product-brief.pdf") (Jane's "Drone Defence launches new counter-UAV concept.PDF")

DJI Aeroscope	- RF signal detection - can detect and track drones - currently only support for DJI drones (March 2019 website https://www.dji.com/ca/aeroscope) (March 2019 website https://www.theverge.com/2017/11/14/16634572/dji-aeroscope-drone-detection-interception-tech-next-level-lauren-goode)
DroneDefence AeroSentry	- RF signal detection - can detect and track both the drone and the operator (March 2019 website https://www.dronedefence.co.uk/products/drone-detection/)
DroneShield DroneSentry	- radar, RF signal, camera detection - can detect and track drones - modular - anti-swarming capability - offers RF jammer integration (March 2019 website https://www.droneshield.com/sentry)
Dynetics GroundAware	- radar detection - can detect and track drones (Jane's "GroundAware addresses UAV intrusions.PDF")
Elbit ReDrone	- RF signal detection - can detect and track both the drone and the operator - can detect multiple drones and operators at once - modular - anti-swarming capability - offers RF jammer, acoustic sensor, EO daylight and IR camera integration (website datasheet "ReDrones.pdf")
Liteye ADIS/AUDS	- radar detection - can detect and track both the drone and the operator - EO daylight and thermal camera tracking - offers RF jammer, optical disruptor integration (March 2019 website https://liteye.com/products/counter-uas/auds/)
Lockheed Martin Icarus	- RF, radar detection - appears to offer RF jammer, laser disruptor integration (March 2019 website https://www.lockheedmartin.com/en-us/news/features/2016/webt-laser-swarms-drones.html)

MyDefence Eagle/Watchdog/Wolfpack	- radar, RF detection - can detect and track drones - modular (MyDefence Sep. 2018 Product Catalog)
Northrop Grumman MAUI/DRAKE	- acoustic detection - RF jammer (Jane’s “AUSA 2016 Northrop Grumman leverages C-IED technology for non-kinetic C-UAS.PDF”)
Optix Anti-Drone System	- RF detection and tracking - RF jammer (March 2019 website https://www.optixco.com/en/security-and-monitoring-systemss-166/optix-anti-drone-system-196/optix-anti-drone-system-111)
Poly Technologies	- RF jammer (Jane’s “Poly Technologies showcases C-UAV system.PDF”)
Rafael Drone Dome	- radar detection and tracking - offers RF jammer, EO/IR daylight and thermal cameras, and laser disruptor integration (Jane’s “Parting Shot Rafael Drone Dome.PDF”)
RS ARDRONIS	- RF detection - can detect and track both the drone and the operator - video interception - modular - RF jammer integration (Product brochure “R&S ARDRONIS Countering RC drones – every second counts”)
Sky Net	- RF jammer (Jane’s “Sky Net counter droneUAVUAS jamming systems.PDF”)
SkySafe	- RF Jammer (March 2019 website https://www.skysafe.io/)
SRC Silent Archer/Gryphon Skylight	- radar, RF signal detection - offers RF jammer, camera integration (March 2019 website https://www.srcinc.com/what-we-do/counter-uas/index.html)
Thales Gecko	- radar, acoustic, RF signal, laser scanner detection - kinetic disruptor, laser disruptor, RF signal jammer, UAV based jamming methods discussed (Jane’s “Paris Air Show 2015 Thales developing the means to neutralise unauthorised UAVs.PDF”)

Table 1: Market Survey of CUAS systems

5 UAV Based Localization

A novel approach to performing localization that has been proposed is the employment of "hunter" UAVs to quickly find and get eyes on the rogue UAV and/or its ground control station and pilot.

Most of the commercial offerings listed in the previous section do not employ UAVs to help perform localization but typically rely on ground-based or mast-mounted sensors. There has been research into this topic however, and through a literature survey we have examined current findings and recommendations to help determine the feasibility of this approach.

5.1 Advantages and Disadvantages

A UAV based signal localization system would have several advantages over traditional ground-based CUAS systems.

Airborne sensors could provide increased detection ranges, due to their altitude they would have increased range for line of sight visibility. They also would enable for increased precision in localization, as for mobile sensors the direction finding sensitivity increases as the RDF sensor approaches the target.

As the UAVs close in during localization, they would put eyes on the target Ground Control Station sooner, reducing the chances for the pilot to evade detection.

UAV systems may also be more flexible in different scenarios. Mobile sensors would reduce or eliminate the need to carefully deploy ground-based sensors in the best locations for the area of interest.

As for disadvantages, target localization may not be as instantaneous as for a fixed installation, as UAVs take time to travel and reach the target. The hunter UAV(s) require maintenance and preparation in order to be ready to deploy or to fly regular patrols, increasing overall system complexity.

5.2 Multi-UAV Systems

For multi-UAV systems versus single UAV systems, it has been shown that localization accuracy and performance increases with the number of hunter UAVs [3], but it has been suggested that 3-4 UAVs is optimal with diminishing returns thereafter.

Another paper [17] indicates that using three UAVs may result in a higher variability for position estimate with a higher error than for a two UAV system over time, however the average error for the initial position estimate is lower for a three UAV system, which would prove helpful for localizing a moving emitter or in cases where the target's RF signals are intermittent.

Regardless of these conflicting results, as the number of UAVs increases, so does the system cost, complexity and logistics of fielding the system.

5.3 UAV Augmented RF Based Tracking Overview

Although system size, weight, power consumption, antenna sensitivity band, and computational load must all be considered when selecting a suitable RF sensor technology for a UAV platform, various techniques have been successfully used to localize RF emitters from UAVs.

Pseudo-Doppler DF sensors are relatively easily adapted to a variety of UAV platforms. We have found examples of their use in several papers [2][15][16].

Watson-Watt DF sensors are also possible thanks to recent technological advances which make it possible to reduce the size and cost of multiple receiver banks. We have not found any papers using this technique on a UAV but it should be achievable, especially with the advent of multi-channel SDR systems available today.

Received Signal Strength sensors are based on signal measurements taken with a single receiver and are relatively simple in their operation. They have been used successfully in a number of papers [21][22][23][24][25] and they appear to be a viable alternative to strategies employing direction finding sensors.

5.4 Hunter UAV Path Planning

It is anticipated that the path planning techniques used are heavily dependant on the localization technique to be used, the UAV platform used, and the number of UAVs to be employed. Due to processing burden for some localization and path planning algorithms, it is likely that the best place to do localization and path planning is on the CAUSs ground station, with CAUS UAVs reporting their RF sensor signal and position telemetry information to the ground station and the ground station uploading new coordinates and waypoints to the UAVs dynamically.

It is anticipated that UAVs with Pseudo-Doppler and Watson-Watt based sensors would be able to take continuous direction finding readings without stopping, a UAV augmented with a directional antenna (such as a Yagi) have to perform special manoeuvres or stop and rotate periodically in order to take direction finding readings [1].

Some UAV based RSS search algorithms have used “lawnmower” style search patterns, flying over a target area (ref here). This technique is time consuming but may be adequate if the general location of the target emitter is already known. A cooperative swarm technique is proposed [24] that attempts to anticipate the motion of the target emitter to increase performance.

6 Recommendations for UAV CUAS Concept Design

6.1 Design assumptions and expected limitations

In the literature, several constraints have typically been made to bound the problem of localizing an RF signal with help from hunter UAVs. These limitations must be considered in order to understand the context of the research conclusions.

Often the target emitter (GCS) is constrained to be stationary for purposes of testing. This makes the localization task easier but there are no real world limitations preventing a GCS from being mobile, as long as the UAV remains in range.

The signal link from the target GCS to the UAV typically has a known signature and is constantly present and active. Each of these factors could be changed in a real scenario. If custom frequencies and protocols are used it would be significantly more challenging to detect and track the signal [10].

The hunter UAVs are confined to fly at low altitude. This helps to reduce the problem of target localization from 3 dimensions down to 2 dimensions, as their tracking receiver antennas can remain in a horizontal orientation. This may be difficult to achieve in urban environments, where obstacles could necessitate higher altitude operation.

Workarounds to these constraints should considered in the design of the final CUAS system, or the effectiveness of the localization techniques may not be as flexible as they could be in real scenarios.

6.2 System Components

UAV COMPONENTS

UAV Platform

The suitability of a hunter UAV platform is dependant on the expected required payload configuration and the search algorithms employed.

It should be large enough to house the payload components which may be sizeable depending on the selected RF sensor configuration. It should have enough lifting capacity to lift the payload and have enough dwell time and range to complete the localization search pattern.

Speed can be an asset in order to execute the search swiftly, but platform manoeuvrability can also be an important factor. The platform should be flexible enough to perform any special manoeuvres required for the selected localization technique, (i.e. rotary wing UAVs may be more suited to dwelling at waypoints and performing rotation manoeuvres to obtain direction-finding estimates)

Minimizing the platform's noise signature should also be considered, as avoiding or delaying detection by the target operator may give the UAV platforms more time to execute their search.

RF Sensor Configuration

Based on the results of the literature survey, it appears that the RF sensor configurations with the most promise have been based on the Pseudo Doppler technique. It was most notably successfully employed in the trials of (ref. "Radio Determination on Mini-UAV Platforms_ Tracking and Locating_low.pdf") and less successfully employed in (ref. "Geolocation of RF Emitters Using A Low-Cost UAV-Based Approach").

Flight controller/autopilot modules

Flight controllers are used extensively in quadrotor platforms and can be used to automate the control of the navigation of any UAV platform. There is a large and increasing number of flight controller boards and associated software used, for a wide variety of applications.

ArduPilot (http://ardupilot.org/) is an open source software platform that can run on a variety of small microprocessor and microcontroller platforms. It implements the low-level controls required to automate flight and GPS based navigation for a number of different types of unmanned platform including both rotary and fixed wing UAVs. It was successfully employed in some of the research papers [1][11]. As the software is open source, it is possible to modify it to support custom sensors, which would be a good way to integrate the RF sensor into the UAV platform.

PX4 (http://px4.io) is another open source autopilot system. It supports ROS (Robot Operating System) interfacing through a ROS node that supports the MAVLink protocol (MAVROS), and has been successfully employed in a UAV system directed using ground based radar sensor telemetry [8].

UAV processor

It is anticipated that an on-board microcontroller would be required to perform any on-board processing tasks such as obtaining data from the RF sensor, interfacing with the autopilot system, implementing autonomous behaviours, and managing communications with the ground station and other members of the hunter UAV team.

ArduPilot natively supports the concept of secondary "companion computers" which can access the MAVLink data that the autopilot receives and can use it to make intelligent decisions during flight.

UAV communications and protocol

Based on the results of the literature survey, it is recommended that the adoption of a communications protocol such as MAVLink be adopted. MAVLink is compatible with ArduPilot flight controllers and Mission Planner ground control station software and should provide for flexibility if a requirement arises for some of the components to be changed out. MAVLink can be routed to and from subunits on the UAV and can also support inter-UAV communications. It was successfully employed in a number of research papers.

Other onboard sensors

Other sensors on the hunter UAV(s) such as cameras would prove useful once localization of the target is complete. Cameras could be automatically directed by platform software to focus on the estimated target position and would enable the CUAS system operator to view the target at the earliest opportunity.

GROUND CONTROL STATION COMPONENTS

Localization software

Due to the expected limitations to available processing power on a hunter UAV, it is anticipated that the Ground Control Station would have the most resources available to perform target localization and coordinate path planning for the UAVs. Custom software will have to be developed to perform these tasks.

Flight Control software

Mission Planner (http://ardupilot.org/planner/) is a Windows-based open source ground control station platform that is compatible with ArduPilot. It can be used as a testbed for guiding the UAVs for preliminary trials and the localization/path planning software may be able to use scripts for Mission Planner to as an intermediary to communicate with the hunter UAVs and direct their flight paths.

APM Planner (http://ardupilot.org/planner2/) is an alternative GCS platform that is also compatible with ArduPilot and can run on Windows, Linux or Mac computers. It is currently less fully featured than Mission Planner but is in development to achieve feature parity.

RF SENSING AND DIRECTION FINDING EQUIPMENT

SDR Platforms

A wide array of SDR platforms exist on the market today. These range from equipment originally developed to implement receivers for digital TV to software running on Raspberry Pis.

In this section we present some of the hardware we have found through our literature survey.

FUNcube Dongle Pro+

The FUNcube Dongle Pro+ is a wide band, high performance SDR developed to provide simple and inexpensive means of receiving RF signals. The dongle connects directly between the antenna feed and the PC USB port. The FCD has a microcontroller to store and run the firmware which manages its internal functionality and interface with the controlling PC, allowing for firmware upgrades as improvements are made.

The advantage of using the FUNcube is that it is small in size with a direct antenna feed, it is powered through the USB port and works on multiple operating systems, such as Linux®, OSX® and Windows®. The FUNcube could be connected to a Raspberry Pi® and mounted on a UAV as a light weight solution.

General specifications of the FUNCube Dongle Pro+ are listed in Table 2.

Characteristic	Specification
Operating frequency range	150 kHz to 240MHz and 420MHz to 1.9GHz
Typical frequency coverage	150kHz to 260MHz and 410MHz to 2.05GHz
Sampling rate	192 kHz
TCXO	0.5 ppm (theoretical 1.5 ppm)
Antenna port	Standard SMA female antenna port
USB port	USB 1.x type A male connection
Noise figures	50MHz 2.5dB 145MHz 3.5dB 435MHz 3.5dB 1296MHz 5.5dB
Compatible OS	Linux®, OSX®, Windows®
Power supply	USB-powered

Table 2: Specifications of the FUNCube Dongle Pro+

HackRF One

The HackRF One is an SDR from Great Scott Gadgets® capable of transmitting and receiving radio signals from 1 MHz to 6 GHz. The HackRF One is an open source hardware platform that can be used as a USB peripheral or programmed for stand-alone operation.

The receiver has a slim design with the dimensions of 124mm x 80mm x 18mm and with a weight of 100g or 0.22lbs., making it a compact and light weight SDR that could be mounted on a UAV. The SDR is compatible with various SDR software such as GNU Radio and SDR#, making it compatible with any operating system capable of running the SDR software. HackRF One has a clock synchronization input which may be helpful for a multi-UAV system. An antenna switch is available for the HackRF for pseudo-doppler DF applications.

General specifications of the HackRF One are listed in Table 3.

Characteristic	**Specification**
Operating frequency range	1 MHz to 6 GHz
Transceiver	half-duplex
Sampling Rate	up to 20 million samples per second
Compatibility	OS running GNU Radio, SDR#, or other software
Filtering	software-configurable RX and TX gain and baseband filter
Antenna port power	50 mA at 3.3 V software-controlled
Antenna connector	SMA female
Clock synchronization	SMA female clock input and output for synchronization
Communication	Hi-Speed USB 2.0
Power supply	USB-powered
Dimensions	124mm x 80mm x 18mm

Table 3: Specifications of the HackRF One SDR

HackRF Opera Cake – Antenna Switch

Opera Cake is an antenna switch that connects to HackRF One, providing several switchable RF ports that can be controlled from software. It consists of two primary ports, each connected to any of the eight secondary ports, and could be optimized for use as a pair of 1x4 switches or as a single 1x8 switch. Users can control Antenna Switch for HackRF with command-line software or can configure HackRF One for automated switching based on frequency or time. Opera Cake could also be used to test pseudo-doppler direction finding technique, connecting multiple antennas for different frequency bands or to construct switchable filter banks. For techniques other than pseudo-doppler DF, Opera Cake could be used to connect antennas of different frequency bands to receive a wider spectrum.

The RTL-SDR Blog V3

The RTL-SDR Blog V3 dongles were originally designed for DVB-T HDTV reception, but they were found by hardware hackers to be useful as a general purpose SDR. The RTL-SDR Blog V3 was redesigned with SDR user needs in mind. The SDR is compatible with Windows®, Linux® and OSX® operating systems. It also supports single board PCs like the Raspberry Pi® and Odroid® with command line apps. The SDR is USB powered, with a direct antenna connection, making it very compact. The RTL-SDR Blog V3 could be connected to a Raspberry Pi® and mounted on a UAV as a light weight solution.

General specifications of the RTL-SDR Blog V3 are listed in Table 4.

Characteristic	**Specification**
Operating frequency range	500 kHz – 1766 MHz
Direct sampling mode frequency range	500 kHz – 24 MHz
Bandwidth	Up to 2.4 MHz stable
RF connection	2 SMA connectors
Power supply	Via PoE, external 5V DC connector, microUSB port
Compatible OS	Linux®, OSX®, Windows®
Typical input impedance	50 Ohms
Typical current draw	270-280 mA

Table 4: Specifications of the RTL-SDR Blog V3

N-Channel Scalable Coherent Receiver – Coherent-receiver.com

CR0x is an N-channel scalable coherent receiver that employs the RTL-SDR technology in order to create inexpensive multi-channel receiving systems. Reconfigurable design techniques deliver high system performance, flexibility and small board space requirements. All these factors enable the use of the CR0x in many applications, such as pseudo-doppler DF, Watson-Watt DF, coherent receiving, passive radar, synchronized receiving on different frequencies. The receivers could be expanded for unlimited number of channels with flexible open hardware extension interface (I2C).

General specifications of the N-Channel Scalable Coherent Receiver are listed in Table 5.

Characteristic	Specification
ADC resolution	8 bit
Clock	28.8 MHz
Sample rates	0.240 MHz 0.288 MHz 0.960 MHz 1.200 MHz 1.440 MHz 2.016 MHz 2.208 MHz 2.400 MHz 2.880 MHz
TCXO	0.1 – 2 PPM
Female antenna port	SMA
R820T2 tuner	24 MHz – 1766 MHz
Power supply	USB powered 5 V
Noise figure	3.5 dB at RF_IN
Noise floor	-60 dBm
Operating temperature	-10° to 60° C
Compatible OS	Linux®, OSX®, Windows®

Table 5: Specifications of the N-Channel Scalable Coherent Receiver

LimeSDR – Lime Microsystems

LimeSDR is a low cost, open source SDR platform that can be used to support just about any type of wireless communication standard. The LimeSDR platform gives the user an intelligent and flexible device for manipulating wireless signals. The LimeSDR can be applied in drone command and control, RF DF techniques, as well as other applications. The LimeSDR could be combined with the LMS8001 Companion to extend the frequency range of the Lime SDR to 100 kHz to 10 GHz frequency range.

General specifications of the Lime SDR from Lime Microsystems are listed in Table 6.

Characteristic	Specification
RF transceiver	Lime Microsystems LMS7002M MIMO FPRF
FPGA	Altera Cyclone IV EP4CE40F23
Memory	256 MB DDR2 SDRAM
Communication	Cypress USB 3.0 CYUSB3014-BZXC
Continuous frequency range	100 kHz – 3.8 GHz
Bandwidth	61.44 MHz
Power supply	Micro USB or optional external power supply
Dimensions	100 mm x 60 mm

Table 6: Specifications of the Lime SDR

LMS8001 Companion – Lime Microsystems

The LMS8001 Companion board provides a highly integrated, highly configurable, four-channel frequency shifter platform. One of the typical applications of the LMS8001 Companion is extending LimeSDR frequency range up to 10 GHz. Extending the frequency range would allow for a broader spectrum search by the UAV to locate a transmitting ground station. The LMS8001 has the dimensions of 100 mm x 60 mm with a USB interface.

KerberosSDR: 4X Coherent RTL-SDR

The KerberosSDR is a low cost 4 tuner phase coherent RTL-SDR. It has applications in radio direction finding, passive radar, beam forming or it may be used as four convenient RTL-SDR dongles. A custom demo software is developed that illustrates direction finding and passive radar capabilities; its base DSP and phase synchronization code could be adapted to any coherent application. In a nutshell, the system is a phase coherent RTL-SDR made out of two or more RTL-SDR dongles that share a common clock and are synced together. KerberosSDR can also be extended to 8x receivers by daisy chaining two boards together, so that their clocks and noise sources are connected.

General specifications of the KerberosSDR: 4X Coherent RTL-SDR are listed below in Table 7.

Characteristic	**Specification**
Operating frequency range	24 MHz – 1.7 GHz
ADC sample rate	2.4 MSPS
Bit Depth	8 bits
Power supply	5V USB powered (micro USB)
Compatibility	Linux®

Table 7: Specifications of the KerberosSDR

The KerberosSDR board consists of four RTL_SDR R820T2 receivers, a wideband noise source that can be switched in software, a USB Hub, and a calibration board for synchronizing samples with the noise source. The user would have to provide a 5V USB power supply with a micro USB Cable, a Linux® based computing device such as a PC or a single board computer like Raspberry Pi®.

An open-source direction finding application has been developed by Tamas Peto, a PhD student at Budapest University of Technology and Economics by using DF algorithms like Bartlett, Capon, Maximum Entropy and MUSIC.

Crimson Software Defined Radio

Crimson is a wide band, high gain, direct conversion quadrature transceiver and signal processing platform. Using analog and digital conversion, it is capable of processing signal bandwidths up to 322MHz from approximately DC to 6 GHz. Crimson is compatible with GnuRadio, and includes source code for many of its drivers and peripherals.

General specifications of the Crimson Software Defined Radio are listed in Table 8.

Characteristic	Specification
Operating frequency	100 kHz – 6 GHz
Channels	Four RX and four TX channels, each with 322MHz of controllable RF bandwidth
Processor	On-board Arria V ST FPGA complete with dual ARM
FPGA	Altera Arria V ST FPGA SoC

Table 8: Specifications of the Crimson SDR

Quadrus SDR

The QUADRUS SDR platform is a phase-coherent multi-channel integrated platform for advanced SDR software implementation. It contains all the elements for a complete SDR receiver functionality; it is a multi-channel SDR software receiver with advanced signal processing and open programming and remote-control interface on TCP/IP. It can be used as a single element or as part of the higher-level integrated system, which could be used for direction finding.

General specifications of the Quadrus SDR are listed below in Table 9.

Characteristic	Specification
FPGA	Xilinx Spartan 3
Clock	10 MHz clock with sync input/output
Sampling rate	80 MSPS
Bandwidth	320 MHz analog bandwidth
Channels	4 phase-coherent SDR

Table 9: Specifications of Quadrus SDR

USRP B210 SDR Kit - Dual Channel Transceiver (70 MHz - 6GHz) - Ettus Research

The USRP B210 SDR kit provides a fully integrated, single-board, Universal Software Radio Peripheral USRP™ platform with continuous frequency coverage from 70 MHz – 6 GHz. Though it has not been used for DF applications, its frequency range and 56 MHz of bandwidth could make it a candidate.

General specifications of the USRP B210 SDR Kit - Dual Channel Transceiver are listed below in Table 10.

Characteristic	Specification
Operating frequency range	70 MHz – 6 GHz
Bandwidth	56 MHz
FPGA	Spartan6 FPGA
Communications	USB 3.0 with bus power

Table 10: Specifications of the USRP B210 SDR Kit

YARD Stick One SDR

YARD Stick One (Yet Another Radio Dongle) can transmit or receive digital wireless signals at frequencies below 1 GHz. The dongle connects directly between the antenna feed and the PC USB port. The YARD stick one is good for receiving transmission in the industrial, scientific and medical frequencies.

The advantage of using the YARD Stick One SDR is that it is small in size with a direct antenna feed, it is powered through the USB port and works on multiple operating systems, such as Linux®, OSX® and Windows®. The YARD Stick One SDR could be connected to a Raspberry Pi® and mounted on a UAV as a light weight solution.

General specifications of YARD Stick One SDR are listed in Table 11.

Characteristic	Specification
Operating frequency	300-348 MHz, 391-464 MHz, and 782-928 MHz
Typical operating frequency	281-361 MHz, 378-481 MHz, and 749-962 MHz
Antenna port	Standard SMA female antenna port
Communication	USB 2.0
Compatible OS	Linux®, OSX®, Windows®
Power supply	USB-powered

Table 11: Specifications of the YARD Stick One SDR

Airspy R2

Airspy R2 has application in RF DF, passive radar and coherent receiver array. It is designed for monitoring VHF and UHF frequencies. Airspy R2 supports multiple platforms such as Linux®, OSX®, and Windows® and has a clock synchronization input. Airspy R2 is small in size with a direct antenna feed, it is powered through the USB port. The Airspy R2 could be connected to a Raspberry Pi® and mounted on a UAV as a light weight solution.

General specifications of YARD Stick One SDR are listed in Table 12.

Characteristic	Specification
Operating Frequency	24 MHz – 1700 MHz
Antenna port	Standard SMA female antenna port
Bandwidth	10 MHz
Dimensions	53mm x 25mm x 4mm
Weight	65 g
Compatible OS	Linux®, OSX®, Windows®
Power supply	USB-powered

Table 12: Specifications of the Airspy R2 SDR

Analog Devices AD-FMCOMMS5-EBZ

The Analog Devices AD-FMCOMMS5-EBZ is a development board with 2 AD9361 RF Transceiver units synchronized with a common reference oscillator. Each AD9361 supports 2 direct conversion receive channels, so the board supports 4 receive channels by itself, which would potentially eliminate the need for switching between antennas in a direction finding application.

General specifications of this board are listed in Table 13.

Characteristic	Specification
Operating Frequency	70 MHz – 6 GHz
Antenna port	Standard SMA female antenna port
Bandwidth	200 kHz - 56 MHz

Table 13: Specifications of the Analog Devices AD-FMCOMMS5-EBZ SDR

Comparison of SDR platforms

Table 14 below compares some of the specifications of the various SDR platforms; the main focus being the frequency range of the SDR and the bandwidth. Larger bandwidth allows for more signals to be analyzed at once.

SDR Model	Freq. Range	Bandwidth	Antenna Port	Dimensions	Power supply
FUNcube Pro+	150 kHz to 240MHz and 420MHz to 1.9GHz	--	SMA female	--	USB 5V
HackRF One	1 MHz - 6 GHz	--	SMA female	124mm x 80mm x 18mm	USB 5V
RTL-SDR V3	500 kHz – 1766 MHz	2.4 MHz	SMA female	--	USB 5V
N-Channel Scalable Receiver	24 MHz – 1766 MHz	--	SMA female	--	USB 5V
Lime-SDR	100 kHz – 3.8 GHz	61.44 MHZ	SMA female	100 mm x 60 mm	USB 5V
Kerberos-SDR	24 MHz – 1.7 GHz	--	SMA female	--	USB 5V
Crimson	100 kHz – 6 GHz	322 MHz	SMA female	--	USB 5V
Quadrus	--	320 MHz	SMA female	--	USB 5V
USRP B210	70 MHz – 6 GHz	56 MHz	SMA female	--	USB 5V
Yardstick One	300 MHz – 928 MHz	--	SMA female	--	USB 5V
Airspy R2	24 MHz – 1700 MHz	10 MHz	SMA female	53mm x 25mm x 4mm	USB 5V
AD-FMCOMMS5-EBZ	70 MHz – 6 GHz	200 kHz - 56 MHz	SMA female	--	--

Table 14: Comparison of SDR platform specifications

Recommendations for an SDR System

The following three SDR systems appear promising for UAV deployment. The top criteria we used for selection are for ruggedness, compactness, weight minimization, capacity for employing multiple RF DF techniques, and whether they have already been demonstrated to work well in the literature survey.

FUNcube Dongle Pro+ SDR

The FUNcube Dongle Pro+ SDR was used on a UAS for RF DF application for wildlife tracking [1]. The FUNcube Dongle Pro+ was connected to a Raspberry Pi 2 running GNU Radio software for signal detection, processing and systems communication.

The SDR's system architecture consists of a high-speed ADC which samples the baseband signal after down conversion through an RF mixer; a critical component in the performance of the SDR. The FUNcube Dongle Pro+ has 16-bit ADC depth and adjustable front-end RF and IF filters, resulting in superior narrow band sensitivity if desired. The FUNcube Dongle Pro+ does not require any proprietary USB drivers and works with most SDR software.

HackRF One

HackRF One is being recommended due to its wide frequency band range of 1 MHz to 6 GHz. HackRF One is an open source hardware platform that can be used as a USB peripheral or programmed for stand-alone operation. The SDR is compatible with many SDR processing software such as GNU Radio, allowing it to be used on any operating system. Moreover, the SDR has a clock synchronization input, which may assist in multi-UAV systems. HackRF One has a slim design, weighing 100g with the dimensions of 124 mm x 80 mm x 18 mm. An antenna switch, Opera Cake, is available for the HackRF for pseudo-doppler DF applications or connecting multiple antennas for different frequency bands. The developers of HackRF One have used it to implement the pseudo-doppler DF method[20].

The KerberosSDR

By using the KerberosSDR board, an open-source direction finding application has been developed by Tamas Peto, a PhD student at Budapest University of Technology and Economics by using DF algorithms like Bartlett, Capon, Maximum Entropy and MUSIC.

The SDR consists of four RTL_SDR R820T2 receivers, a wideband noise source that can be switched in software, a USB Hub, and a calibration board for synchronizing samples with the noise source. A Linux® based computing device such as Raspberry Pi® could be used and mounted on a UAV along with an antenna array.

This system is small, lightweight, can support 4 channels at once, and has been demonstrated to work for a pseudo-doppler implementation [18].

Antenna Platforms

In this section we present a few of the commercial offerings for candidate antenna types that are currently available.

UltraWide Omnidirectional Antenna from Anritsu® LTD.

The UltraWide Omnidirectional Antenna from Anritsu® is maximized to give omni-directional sensitivity from low 20 MHz to well above 21 GHz. The nominal gain of the antenna is -7 to +0 dBi over 98% of the antenna. The ultrawide antenna offers the finest wideband sensor for receiving RF signals ideal for SIGINT and multiband communications applications. The antenna weighs 370 grams, with the dimensions of 40.64 cm x 15.24 cm x 2.54 cm, with operating temperatures of -35° C to 85° C.

Due to the height of the antenna, it may be challenging to mount four antennas on a UAV to execute the pseudo-doppler or Watson-Watt direction finding technique; a durable, but light weight apparatus would have to be constructed to mount the antennas for DF.

General specifications of UltraWide Omnidirectional Antenna from Anritsu® LTD are listed below in Table 15.

Characteristic	Specification
Type	Modified Bi-Conical
Frequency range	20 MHz to 21 GHz
Impedance	50 Ohms
VSWR	<2:1
Antenna gain	0 dBi or greater above 325 MHz
Polarization/pattern	Vertical/omni-directional
Maximum continuous power	10 watts
Dimensions	40.64 cm x 15.24 cm x 2.54 cm
Weight	370 g

Table 15: Specifications of the UltraWide Omnidirectional Antenna

Drone Mountable Directional Antenna (DF-A032) from Alaris Antennas®

The DF-A0132 is a drone mountable wideband antenna for direction finding, transmitter hunting and signal monitoring in the 20 to 8500 MHz band. The antenna makes use of an integrated low-noise, wideband amplifier that enhances system sensitivity when the antenna is used in active mode. The amplifier can be by-passed for passive mode operations in high field strength environments.

Several papers that have been explored used directional antennas to determine the geolocation of the transmitter. The antenna weighs less than one kilogram and is mechanically designed to reduce wind resistance. The dimensions of the antenna are 443 mm x 320 mm x 50 mm, which may cause difficulties in mounting the antenna on a UAV; an appropriate UAV would have to be selected to make use of this antenna. Multiple antennas may also be mounted on a single UAV.

General specifications of the Drone Mountable Directional Antenna (DF-A032) from Alaris Antennas are listed below in Table 16.

Characteristic	Specification
Type	Directional
Frequency range	20 – 8500 MHz
Impedance	50 Ohms
VSWR	< 3.5:1
Antenna gain	6 dBi above 600 MHz
Polarization/pattern	Vertical or horizontal
Power supply	15 V, via RF
Dimensions	44.3 cm x 32 cm x 5 cm
Weight	< 1 kg

Table 16: Specifications of the Directional Antenna DF-A032

Handheld Direction-Finding Antenna (DF-A0133) from Alaris Antennas®

The DF-A0133 is a handheld wideband antenna for direction finding and transmitter hunting in the 500 to 8500 MHz band. It uses a single wideband antenna in a neat housing, and some integrated electronics to make it more effective when used in conjunction with signal analyzers or SDR. A single RF output is provided, with the capability of choosing to connect or bypass the pre-amplifier. The amplifier is a low-noise wideband amplifier that enhances system sensitivity in active mode. In passive mode, the amplifier is bypassed so that the antenna can be used in the presence of strong signals.

Even though the antenna is designed as a handheld antenna, it could be modified such that it could be mounted on the UAS platform. Though the majority of the efforts would be made with either the Watson-Watt method or the pseudo-doppler method, if a strictly rotational direction-finding method is to be explored, the DF-A0133 antenna may be of interest.

General specifications of the Drone Mountable Directional Antenna (DF-A0133) from Alaris Antennas are listed in Table 17.

Characteristic	Specification
Type	Directional
Frequency range	500 – 8500 MHz
Impedance	50 Ohms
VSWR	< 3.5:1
Antenna gain	3 dBi above 1000 MHz without amplification
Polarization/pattern	Vertical or horizontal
Power supply	5 V, via USB
Dimensions	370 mm x 310 mm x 60 mm
Weight	< 1 kg

Table 17: Specifications of the Directional Antenna DF-A0133

Advanced Telemetry Systems - 3 Element Folding Yagi

In tests where the 3-element folding Yagi antenna was used [1], it was demonstrated that the UAV mounted Yagi Rotation system was successfully implemented and tested. The paper recommended to narrow the azimuth beam width to optimize the antenna.

General specifications of the 3 Element Folding Yagi antenna are listed below in Table 18.

Characteristic	Specification
Type	Directional
Frequency range	141 – 220 MHz
Antenna gain	Isotropic 7.7 dBi, Dipole 5.6dBi
Polarization/pattern	Vertical or horizontal
Dimensions	106 cm x 86 cm x 4 cm
Weight	0.54 kg – 0.71 kg

Table 18: Specifications of the 3 Element Folding Yagi Antenna

Linksys® HGA7T High Gain Antenna

The Linksys® HGA7T is a high gain antenna providing gains of 7 dBi between 2.4 GHz to 2.5 GHz. Most UAVs operate in the 2.4 GHz or the 5 GHz range, which would make the antenna suitable for pseudo-doppler or Watson-Watt techniques. The antenna is light weight; an Adcock array would weight 200 grams, plus the weight of the apparatus holding the antennas.

General specifications of the Linksys® HGA7T antenna are listed in Table 19 below.

Characteristic	Specification
Type	Omni-directional
Frequency range	2.4 GHz to 2.5 GHz
Impedance	50 Ohms
VSWR	1.92
Antenna gain	7 dBi

Characteristic	Specification
Polarization/pattern	Linear Vertical
Maximum continuous power	10 watts
Dimensions	28.5 cm x 1.4 cm
Weight	40 g
Connector	Reverse TNC

Table 19: Specifications of the Linksys® HGA7T Antenna

Super Power Supply® High Gain Dual Band Antenna

The Super Power Supply® high gain dual band antenna is a high gain antenna providing gains of 9 dBi between 2.4 GHz to 5 GHz. Most UAVs operate in the 2.4 GHz or the 5 GHz range, which would make the antenna suitable for pseudo-doppler or Watson-Watt techniques. The antenna is light weight; an Adcock array would weight 270 grams, plus the weight of the apparatus holding the antennas. The antenna is available for purchase on Amazon® and is affordable, costing $20 CAD for three antennas. The manufacturer, Super Power Supply® is not a well-known company for manufacturing antennas or wireless gear.

General specifications of the Super Power Supply® antenna are listed in Table 20 below.

Characteristic	Specification
Type	Omni-directional
Frequency range	2.4 GHz and 5 GHz
Antenna gain	9 dBi
Polarization/pattern	Linear Vertical
Dimensions	38.6 cm x 4.6 cm x 1.5 cm
Weight	54 g
Connector	RP SMA

Table 20: Specifications of the Super Power Supply® Antenna

Linksys® WRT004ANT High Gain Antenna

The Linksys® WRT004ANT high gain dual band antenna is a high gain antenna providing gains of 4 dBi at 2.4 GHz and 7 dBi at 5 GHz. Most UAVs operate in the 2.4 GHz or the 5 GHz range, which would make the antenna suitable for pseudo-doppler or Watson-Watt techniques. The antenna is light weight; an Adcock array would weight 250 grams, plus the weight of the apparatus holding the antennas. The physical design of the antenna would not have as much resistance compared to the other antennas mentioned.

General specifications of the Linksys® WRT004ANT antenna are listed in Table 21 below.

Characteristic	Specification
Type	Omni-directional
Frequency range	2.4 GHz and 5 GHz
Antenna gain	4 dBi at 2.4 GHz and 7 dBi at 5GHz
Polarization/pattern	Linear Vertical
Dimensions	28.8 cm x 2.7 cm x 1.0 cm
Weight	~ 50 g
Connector	RP SMA

Table 21: Specifications of the Linksys® WRT004ANT Antenna

Antenna Catalog

An antenna catalog/technical data sheet from Anritsu® is included in the Appendix, which consists of various omnidirectional and directional antennas. Most UAVs operate in the 2.4 GHz frequency range and there are several antennas in the technical data sheet that would be small enough to be mounted on a light weight apparatus that could be mounted on the UAV.

Recommendations for Antenna

While considering the pseudo-doppler and Watson-Watt methods to be the prominent methods that would be employed for geolocation, a recommendation is being made for the Linksys® WRT004ANT high gain antenna and the UltraWide Omnidirectional Antenna from Anritsu® LTD.

Linksys® WRT004ANT High Gain Antenna

The Linksys® WRT004ANT high gain dual band antenna is being recommended due to its dual band capabilities of 2.4 GHz and 5 GHz, which is where most of the UAVs operate, along with its dimensions and weight. The antenna is light weight; an Adcock array would weigh 250 grams and a four antenna pseudo-doppler array would weigh 200 grams, plus the weight of the apparatus holding the antennas. The dimensions of 28.8 cm x 2.7 cm x 1.0 cm would make the antenna easier to work with compared to the UltraWide Omnidirectional Antenna from Anritsu®, which has the dimensions of 40.64 cm x 15.24 cm x 2.54 cm, where the width becomes of concern when creating a mounting apparatus. Also, the brand name of Linksys® is a known industry brand name, compared to Super Power Supply®.

UltraWide Omnidirectional Antenna from Anritsu® LTD

The height and width of the antenna would make it challenging to mount on an UAV and would require an apparatus to be constructed that would have to be attached to the UAV to hold the antennas in place. However, the antenna is sensitive to frequencies ranging from 20 MHz to 21 GHz, making it versatile to receive most transmissions of interest. The ultrawide antenna offers the finest wideband sensor for receiving RF signals ideal for SIGINT, multiband communications applications and devices that hop frequencies. The wide frequency range would allow one system to be utilized by filtering the frequencies of interest, rather than investing in multiple antenna arrays for different frequencies; combining the architecture with SDRs and digital filtering.

6.3 Other promising concepts of operations

Although we recommend investigating localization techniques based on a Pseudo Doppler direction finding sensor, it would be worthwhile to compare and evaluate the effectiveness of Watson-Watt and RSS techniques as well. This could be done in simulation to start, and most of the RF hardware is flexible enough to allow for alternate sensing techniques, which would make this possible with minimum system reconfiguration.

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List of symbols/abbreviations/acronyms/initialisms

ASOGG	Autonomous Systems Operation Group
CUE	Contested Urban Environment
DAS	Data Acquisition System
DF	Direction Finding
DND	Department of National Defence
DRDC	Defence Research and Development Canada
DSTKIM	Director Science and Technology Knowledge and Information Management
RDF	Radio Direction Finding
SEEC	Suffield Environmental Exposure Centre
TA	Technical Authority
UAS	Unmanned Air System
UAV	Unmanned Air Vehicle
WW	Watson-Watt

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The work conducted for this task was to provide literature review of applicable techniques and algorithms from industry and academia; including but not limited to foreign military research or demonstrations, journal articles, peer reviewed papers, credible conference publications and credible industry sources. These efforts were conducted for the DRDC Suffield Counter Unmanned Aerial System (CUAS) research program. Along with the literature review, Amtech Aeronautical Limited conducted a thorough market survey of applicable devices, instruments and products for the identification of Unmanned Air Vehicle (UAV) Radio Frequency (RF) signals, Direction Finding (DF) and geolocation of UAS and Ground Control Station (GCS), on-board data processing and signal analysis, UAV payload devices for precise geolocation, communications and computing payloads necessary for data processing and transmission, and cost effective UAS for such deployment. Recommendations of the most technically feasible approach for pursuing an airborne GCS localization system, potential equipment options and high-level refence designs containing electrical, software and mechanical aspects are made. This work was completed under contract W7702-145682/001/EDM.