Feature Article:

DOI. No. 10.1109/MAES.2023.3289928

Radar Challenges, Current Solutions, and Future Advancements for the Counter Unmanned Aerial Systems Mission

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INTRODUCTION

The advancement of unmanned aerial systems (UAS) has elevated them to be highly relied upon assets for commercial and military applications. For the commercial/civilian sectors, UAS provide the ability to execute dangerous or difficult tasks safely and efficiently, saving time, money, and lives [1]. They support multiple applications such as public safety (e.g., police, firefighters, and other first responders), disaster mitigation, environmental protection, scientific research, and agriculture [1]. For military applications, a principal advantage of UAS is their ability to reduce the risk to humans, and thus to provide cost-effective military options that can be used when political or environmental conditions prohibit the use of manned systems [2]. Drones are also increasingly becoming a weapon of choice for nonstate groups that employ the technology for surveillance, battlespace management, propaganda, and aerial strike attacks, often to considerable effect [3]. The proliferation of UAS technology has made counter-drone systems a ubiquitous weapon in UAS conflicts.

Although UAS have been a phenomenal technology advancement, their benefits have also been leveraged and implemented by adversaries with nefarious intent. Some of the key advantages nonstate actors take advantage of are listed below.

1) **Affordability**—For small UAS, such as a DJI phantom, the cost for entry is low. These UAS are readily available worldwide with internet purchase accessibility. Many of these can be bought and deployed for low cost, individually or in swarms, with minimal sustainment. For larger UAS in the Group 2 to 3 category (see Table 1), nonstate actors can purchase these from other countries for far less than fighter or surveillance aircraft. An unmanned air force capability becomes achievable with UAS. Michael Kofman, a military analyst at the Center for Naval Analyses, points out, "An air force is a very expensive thing...and they permit the utility of air power to smaller, much poorer nations [4]." At least 95 countries possess drones, which can potentially furnish even poorly funded state actors with an aerial command of the battlespace that was previously unavailable [3].

2) **Precision Navigation**—UAS use GPS for navigation. This enables them to be operated autonomously without the requirement of an operator. Smaller UAS can be programmed with waypoints, flying precise routes to do surveillance or cause damage critical infrastructure [5]. Additionally, UAS can be flown in GPS-denied environments using onboard video cameras.

3) **Payload Capacity**—UAS can carry varying types of payloads, including multispectral imaging systems for surveillance and intelligence gathering, nonkinetic effectors for electronic attack, and kinetic effectors for hard kill destruction [5].

4) **Networked Lethality**—UAS can provide real-time monitoring of geographical areas and provide real-time dissemination to other networked sensors and systems. With a group of UAS, a battlefield network can be employed for timely intelligence information and precision strike of valued assets and infrastructure.

Over the years there have been various incidents involving nonfriendly drone attacks that have caused severe damage and heightened security concern.

- 2013—A small quadcopter flew within feet of the German Chancellor and Defense Minister. The small UAS hovered briefly and then landed at

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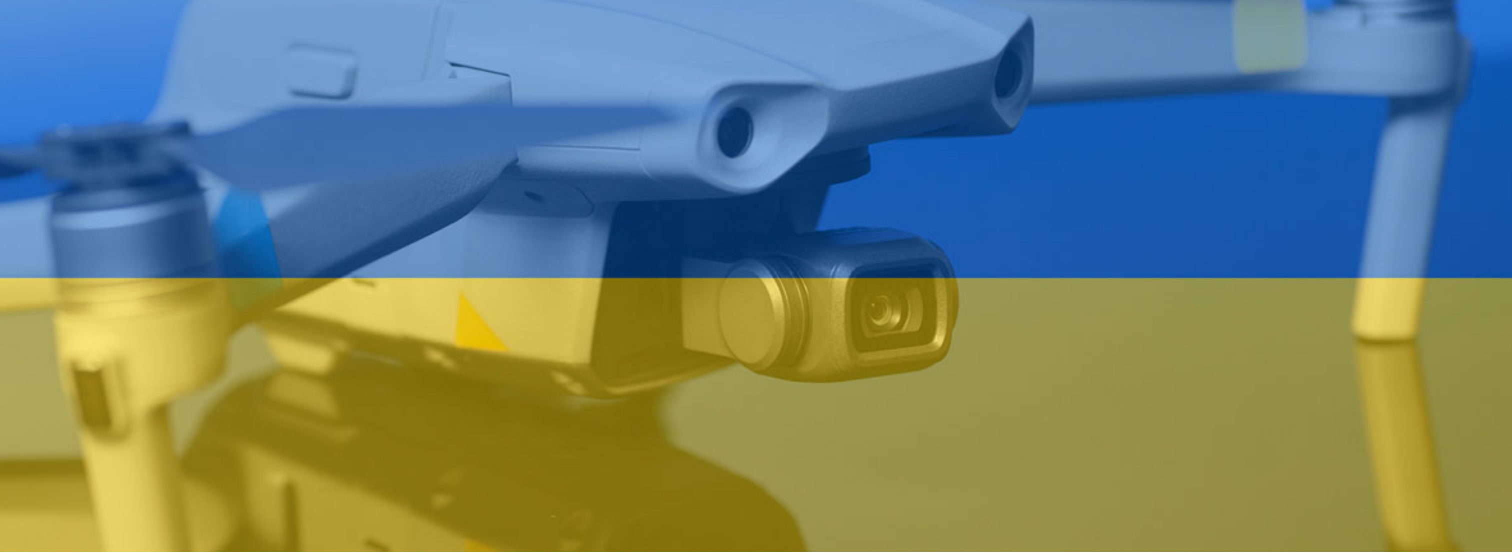
Manuscript received 29 August 2022, revised 11 May 2023; accepted 23 June 2023, and ready for publication 27 June 2023.
Review handled by Daniel O'Hagan.
0885-8985/23/$26.00



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Chancellor Merkel’s feet. Although the drone was harmless, it was an early sign of the potential for drone attacks [6].

- 2018—An assassination of Venezuelan President, Nicolas Maduro was attempted. The attack was done with a retail drone that was purchased online and armed with military grade explosives. The unsuccessful attack was a demonstration of the potential for drone attack lethality [7].
- 2018—The Gatwick Airport was shut down due to drone sightings at the airport. The incident took place at the travel period prior to Christmas. It led to the airport being closed for 30 h, disrupting 1000 flights. Thousands of travelers had their holiday plans disrupted [8].
- 2019—Aramco, the Saudi Aramco oil processing facility at Abqaiq, was attacked. A swarm of drones along with cruise missiles were used to strike the oil infrastructure. This caused the facility to be shut down due to large fires and voluminous damage [9].
- 2022—In Ethiopia’s Tigray region, 19 people were killed over two days with UAS air strikes and many more injured. The drones used hovered before dropping bombs [10].

In addition to incidents like these recent conflicts have shown how battlefields are being transformed by UAV technology. In the Nagorno–Karabakh War in 2020, the Azerbaijan forces, utilizing UAVs, had a decisive warfare advantage over Armenia. Confirmed losses via photographs or videos showed Armenian losses at 185 T-72 tanks, 90 armored fighting vehicles, 182 artillery pieces, 73 multiple rocket launchers, 26 surface-to-air missile systems, 14 radars or jammers, one SU-25 war plane, 4 drones, and 451 military vehicles [4]. The definitive UAV advantage of the Azerbaijan forces forced a cease-fire and ended the war in 44 days [4].

In the Ukraine and Russia conflict, UAVs have been used to varying degrees by both sides with Ukraine employing them the most. UAVs have been used for a variety of uses from carrying out strikes to guiding artillery and recording video that feeds directly into information operations [11]. The use of drones has given Ukraine an edge over Russia, which is impressive given Ukraine ranks fortieth in the world for defense spending [11]. Ukraine’s fleet of Bayraktar TB-2 s, Turkish-made military drones, have carried out numerous successful attacks against Russian forces, accounting for almost half of Russia’s surface-to-air missiles that have been destroyed and helping to sink the Moskva, the flagship in Russia’s Black Sea Fleet [11]. Additionally, the scale of small, commercial drone use in Ukraine is unprecedented enabling cheap airborne surveillance or even strike capability [12].

Table 1.

UAS Group Categories

UAS	Weight	Altitude	Speed
Group 1	< 20 lbs	< 1200 feet AGL	< 100 knots
Group 2	21–55 lbs	< 3500 feet AGL	< 250 knots
Group 3	< 1320 lbs	< 18,000 feet AGL	< 250 knots
Group 4	< 1320 lbs	< 18,000 feet AGL	any speed
Group 5	< 1320 lbs	< 18,000 feet AGL	any speed

Figure 1.
USMC's MADIS uses DRS RADA's multimission radars for 360° persistent coverage of UAS threats.

Due to the asymmetric nature of UAV threats technology solutions that are cost effective, high performing and size, weight, and power (SWaP) efficient are required to defend against small, medium, and large UAVs. The air defense systems that have traditionally been used to protect airspace are mostly designed with inhabited aircraft in mind and are optimized for detecting, tracking, and shooting down large fast-moving objects [3]. As a result, these traditional systems are challenged with small, slow, low flying drones [3]. As UAV threats have evolved, the U.S. Department of Defense (DoD) has developed a variety of detection and countermeasure systems to combat UAVs. These systems are called counter unmanned aerial systems (C-UAS). This has driven the market for C-UAS with over 537 systems on the market with varying levels of capability [3]. C-UAS are primarily composed of technologies that provide the following capabilities: detection/tracking, interdiction/mitigation, and command and control (C2).

C-UAS detection and tracking are done with radar, electrooptical sensors, acoustic sensors, and passive RF detection. An excellent summary of these different technologies is provided in [3] and [13]. These sensors are used to detect, identify, locate, and track UAVs. With the measurement of target tracks, classification processing is usually applied to provide additional threat information to the user [14], [15], [16], [17], [18], [19], [20], [21].

Mitigation technologies for interdiction can be divided into the following categories: soft kill (SK) and hard kill (HK).

SK mitigation does not physically destroy UAVs and disables them without collateral damage. These approaches span electronic attack (EA) via jamming (RF/GNSS) or spoofing, dazzling, and nets. HK mitigation involves physically destroying and/or damaging the threat UAV(s). HK approaches include directed energy [high energy lasers (HEL) and high-power microwave (HPM)], munitions and collision drones [3], [13], [22], and [23]. Although rarely mentioned the C2 in a C-UAS is very important. C-UAS typically employ heterogeneous combinations of detection/tracking and interdiction/mitigation subsystems. The C2 integrates the various subsystems to provide C-UAS capability. Examples of programs of record that employ C-UAS are the USMC's Marine Air Defense Integrated System (MADIS) (see Figure 1) and the U.S. Army's Maneuver Short Range Air Defense (M-SHORAD) (see Figure 2).

The primary payload for effective C-UAS is a radar. It is the only detection/tracking system that provides target range, velocity, and angular location in a single sensor. Electro-optical and infrared (EO/IR) sensors as an example do not provide range with a single sensor. Additionally, radars are able to provide day and night operation in all-weather environments. For C-UAS, other integrated payloads such as EO/IR cameras, EA sensors, and HK mitigation systems are cued based on the track information made available by the radar. Table 2 highlights key radar parameters for C-UAS.

The parameters listed provide the performance needed for a radar system that will give the warfighter the required C-UAS battlefield capability. Table 3 highlights why radars are the most robust sensor for detection and tracking with a comparison against alternate technologies.

Figure 2.
U.S. Army's M-SHORAD is a program of record that uses C-UAS technology.

Table 2.

Key C-UAS Radar Parameters That Ensure Maximum Radar Performance	
Parameters	**Description**
Maximum detection range	Maximizing the detection range increases the decision-making reaction time for threat neutralization.
Minimum detection range	Providing coverage for close-in engagements is key for providing satisfactory coverage.
Elevation coverage	Radars with limited elevation angle coverage will have a coverage gap near zenith around the radar. This poses a danger for C-UAS targets.
Azimuth coverage	360° AZ spatial coverage provides full capability for situational awareness.
Angle accuracy and resolution (range/azimuth)	Directly impacts target tracking for C-UAS.
Number of simultaneous tracks	To protect against dynamic attacks from multiple angles, being able to track multiple targets per 90° sector is advantageous.
Operational capability - OTM	On the move (OTM) capability provides greater benefit than being only transportable. OTM means the radar is fully operational while the platform is moving.
Day and night operation	Radars detect and track with the same performance in day or night conditions providing 24/7 availability.
All-weather operation	Radars are able to operate in various weather conditions such as rain and fog providing persistent capability.

Table 3.

Detection/Tracking Technologies				
Key Performance Parameters	**Radar**	**EO/ IR**	**Audio**	**Passive Detection**
Maximum detection range	Blue	Green	Red	Yellow
Minimum detection range	Green	Blue	Green	Blue
Elevation coverage	Blue	Blue	Green	Blue
Azimuth coverage	Blue	Blue	Blue	Blue
Angle accuracy	Green	Blue	Green	Green
Number of simultaneous tracks	Blue	Blue	Green	Blue
Operational capability - OTM	Blue	Yellow	Red	Green
Day and night operation	Blue	Green	Blue	Blue
All-weather operation	Blue	Yellow	Yellow	Blue

The colors in the table represent level of performance [blue (best) ⇒ green ⇒ yellow ⇒ red (worst)].

As C-UAS capabilities have advanced, more insight is understood relative to the existing challenges specific to the C-UAS mission. An overview of these challenges will be expounded upon to provide an understanding of how they affect radar performance. Existing radar solutions will also be discussed providing insight into how C-UAS radar challenges are being solved today. Finally, future advancements for C-UAS will be discussed, providing insight into what is on the technological horizon for C-UAS radars.

RADAR CHALLENGES AND EXISTING SOLUTIONS FOR C-UAS

SWaP

CHALLENGES

C-UAS radars for defense applications must support both base protection and mobile installations. For base protection, detection and tracking of UAS targets is required to protect critical infrastructure such as government facilities, airports, and military bases. For these type of fixed installations, SWaP is not tightly restricted. For mobile installations, this is not the case.

Force expedition applications normally require 360° coverage on a vehicle. Examples of this include the U.S. Army's M-SHORAD [24] and mobile-low, slow, small unmanned aircraft integrated defeat system (M-LIDS) [25], and also the

MADIS [26]. M-SHORAD uses the Styrker, M-LIDS uses a mine-resistant all-terrain (M-ATV) vehicle, and the MADIS platform is a joint light tactical vehicle (JLTV). For these vehicles and others, SWaP is restricted for the radar while at the same time requiring maximum detection range.

Size is challenging because the radar must provide 360° coverage, but not obstruct the view of other payloads on the vehicle. Additionally, for lightweight vehicles like the JLTV, there is limited space to mount a radar system. This forces the radar system employed to have a small footprint for the installation options of being mounted on the top of the vehicle or distributed around the vehicle.

Weight has similar limitations as size. For vehicles like the Stryker, the C-UAS radar is not the only system on the platform. Other systems such as effectors, jammers, comms, etc., share space with the radar, in addition to making sure there is enough room for the crew to operate the vehicle. Because of this the weight of each individual vehicle payload has to be minimized to meet the overall weight requirements. This is a challenge for radars that must provide enough effective radiated power (ERP) to meet maximum detection range requirements in a small form factor.2

For any vehicle platform, power is limited. Although the radar is important, there are many other critical vehicle systems that require power also. This means that the radar must be efficient in terms of power dissipation to not require a large amount of cooling or require no cooling. In extreme heat environments where the radar must operate continuously for long time durations, this becomes critical relative to reliability and maintainability of the radar. Additionally, the power required by the radar must fit into the overall power budget of the vehicle. Existing solutions to these SWaP challenges will be described next.

EXISTING SOLUTIONS

For a monostatic radar, detection SNR is a function of G^2, where G is the antenna gain. G can also be expressed by the equation:

$$G = \frac{4\pi A f^2}{c^2}. \tag{1}$$

In (1), A is the antenna area, f is the radar operational frequency, and c is the speed of light. (1) shows that the antenna gain can be maximized by increasing the antenna size A, and/or operational frequency f. Selecting an operational bandwidth at higher frequencies enables achieving optimal antenna gain while minimizing antenna size (see Figure 3).

Although operating at higher frequencies allows decreased antenna area for lower SWaP, the loss due to environmental effects such as rain increases, requiring increased transmit power. This is highlighted in Figure 4. As an example, if 20 dBi of antenna gain is required, looking at Figure 3, Ku-band might be selected to minimize the antenna area. However, Figure 4 shows that at Ku-band there is a detection range performance reduction of greater than 10% for ranges greater than a kilometer. This would cause the required transmit power to be increased to account for the loss.

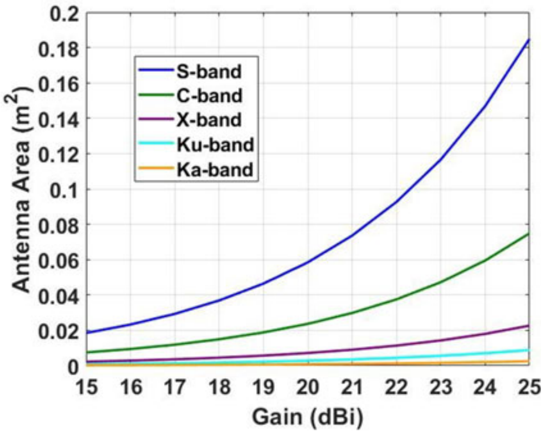

Figure 3.
The antenna gain is selected based on maximum detection range requirements. Once the desired gain is determined, the operating frequency can be traded to minimize the antenna area as required based on size requirements.

Size and weight are balanced with performance in the radar design by trading antenna area and frequency to achieve the required detection range performance. Table 4 shows a subset of companies that build and manufacture radars for C-UAS and the frequency bands of operation that are employed. Each company's radars will have its own strengths and weaknesses based on the frequency selected.

MULTIPATH AT LOW ELEVATION ANGLES

CHALLENGES

Ground-based radars must contend with multipath for targets that are at low altitudes (small elevation angle relative to the radar). The IEEE radar definition for multipath is "the propagation of a wave from one point to another by more than one path" [35]. For radars, this occurs when the energy reflected from a target has more than one path to return back to the radar as shown in Figure 5. The direct path is the desired return; however the indirect path simultaneously provides a path for the signal to return with a different amplitude and phase than the direct path. The direct and indirect returns add together causing performance degradation in angle accuracy and loss of signal. Multipath returns can be categorized as main beam (MB) or sidelobe (SL). SL multipath can be mitigated by weighting of the antenna SLs [36], however MB multipath mitigation is more challenging since it cannot be mitigated with sidelobe weighting.

UAS are categorized into five different groups [37]. The groups are highlighted in Table 1 [38]. Radar systems

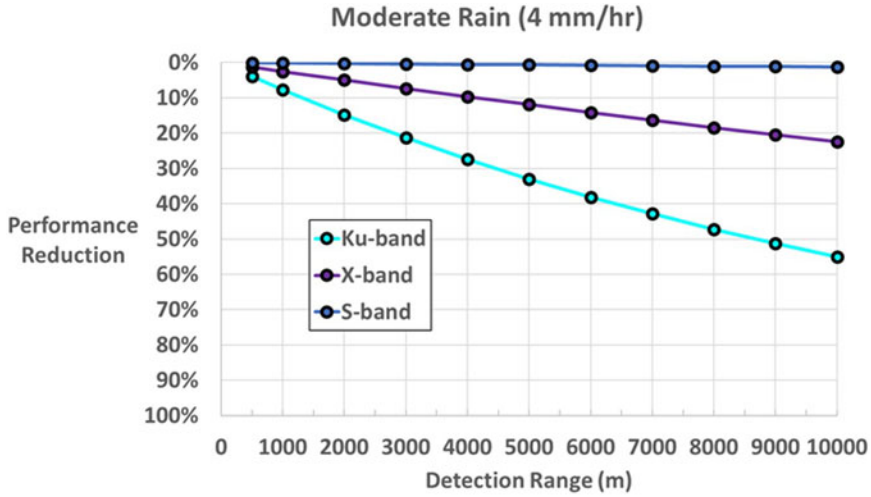

Figure 4.
Operating at higher frequencies increases loss due to rain. This is accounted for by transmitting more power, which can impact the radar power system design.

employed for C-UAS can target subsets of the groups shown or all the groups. For UAS that fly above 1200 ft, SL multipath is dominant and can be mitigated as mentioned previously with SL weighting. For small UAS (sUAS) in the Group 1 (Figure 6) and two categories that fly at altitudes below 1200 ft MB multipath is dominant. The radar beam must be scanned near the ground for low altitude coverage.

EXISTING SOLUTIONS

An approach to multipath mitigation is to decrease the beamwidth of the radar antenna beam. The beamwidth of an antenna is a function of the largest length of the antenna in the dimension of interest D and the operating frequency f. This is expressed as

$$Beamwidth = k \cdot \frac{c}{f \cdot D}. \tag{2}$$

Table 4.

Companies That Manufacture Radars for C-UAS and Their Operational Frequencies	
Company	**Operational Frequency Band**
DRS RADA	S-band [27]/X-band [28]
Echodyne	Ku-band/K-band [29]
Thales	X-band [30]
SRC	L-band [31]/S-band [32]/X-band [33]
Blighter	Ku-band [34]

Frequency is one of the primary design variables that drives performance of C-UAs radars.

In (2), k is the beamwidth factor and is equal to 0.886 for uniform illumination (no SL weighting) [36]. By designing the radar at higher frequencies, the radar beamwidth is decreased. This reduces the MB multipath discussed previously, while also improving the angle accuracy. This does not come for free because decreasing the radar beamwidth increases the time required to scan the FOV. This will be illustrated later when discussing maximizing detection range.

Another approach to multipath mitigation is to decrease the elevation MB beamwidth by increasing the length of the radar in the elevation dimension. Similar to increasing the frequency, this also decreases the antenna beamwidth and minimizes MB multipath and increases elevation (EL) angle accuracy. In many practical operational scenarios, multipath is most significant in the EL dimension, and the azimuth (AZ) dimension of the radar can be optimized to maintain a sufficient scan rate for performance. Figure 7 illustrates the dependence of the radar beamwidth on f and D.

A software approach for multipath mitigation in contrast to modifying the radar antenna is to use algorithms for multipath suppression. Many of these algorithms attempt to characterize the reflected ground bounce from the indirect path and optimize the received signal from the direct path. A combination of narrow beamwidth and software algorithms are typically the most favored approach.

BIOLOGICAL VERSUS MAN-MADE TARGET CLASSIFICATION

CHALLENGES

A challenge for all C-UAS is differentiating between biological targets (birds) and man-made targets (sUAS). Birds fly at

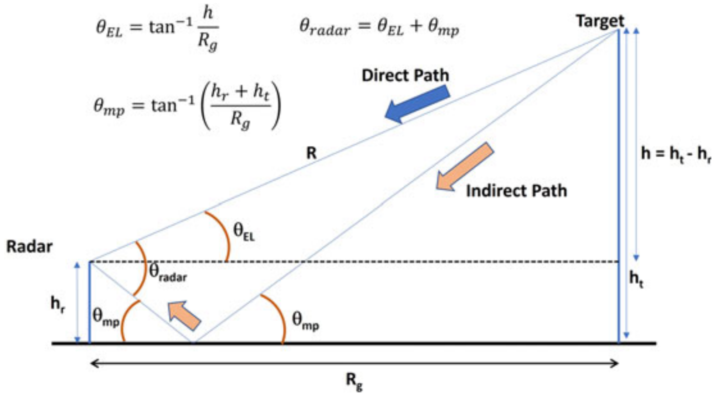

Figure 5.
Multipath illustration shows the direct and indirect paths for target reflections. The indirect path dynamically adds constructively and destructively altering the estimated elevation angle measurement of the target. For C-UAS radars, this is primarily main beam multipath at elevation angles relative to the radar of less than 10°.

max speeds similar to sUAS (20–100 m/s) and have a radar cross section (RCS) that is also comparable to drones (−25 to −20 dBsm). This creates a source of ambiguity for the radar tracker and can lead to false positive and negative classifications due to birds (see Figure 8). For C-UAS radar modes that simultaneously detect Group 1/2 and Group 3–5 UAS, this poses a problem. For larger targets that fly at speeds much greater than birds, classification is minimally impacted. However, if the requirements necessitate tracking slower moving Group 1 and 2 UAS, the improper classification of birds as UAS will clutter the air picture and degrade battlespace awareness. For C-UAS applications that focus only on Group 1/2 UAS, classification becomes a larger problem.

EXISTING SOLUTIONS

The most prevalent solution for mitigating false bird detections is to couple the radar with an EO/IR sensor. The radar generates target tracks that are passed to a multispectral camera. The camera is cued in the direction of the radar track, and visual confirmation is used to verify if the track is a valid drone detection or not. Additionally, artificial intelligence/machine learning (AI/ML) is used for target classification. AI/ML classification algorithms for imagery are well understood and mature [40], [41]. These algorithms are applied to the images captured by an EO/IR sensor that is coupled with a radar in C-UAS. Autotracking cameras with AI/ML classification capability are a powerful mitigation solution for false positive bird tracks.

Ideally, using only the radar track data is more beneficial enabling operation without a separate camera sensor. This would minimize the SWaP of the overall C-UAS system in addition to the system complexity. Microdoppler is a type of processing that uses the time varying doppler signature of target returns to determine if the track is a bird or drone. Microdoppler [16], [42] is effective but it requires a large SNR. This is because the returns of rotating blades on a quadcopter or any UAS with rotating blades are much

Figure 6.
The quadcopter DJI UAS is an example of a low-cost and easily accessible drone that can be retrofitted and weaponized [39].

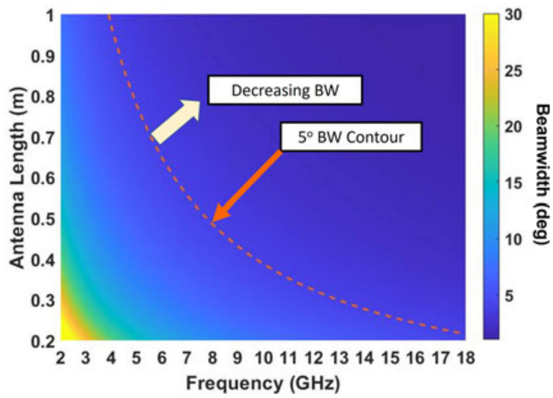

Figure 7.
The radar array beamwidth is proportional to the array size and operational frequency. The beamwidth can be reduced by either increasing the antenna length and/or the operational frequency. This is depicted by the yellow arrow showing the reduction in beamwidth to less than 5° is above the contour.

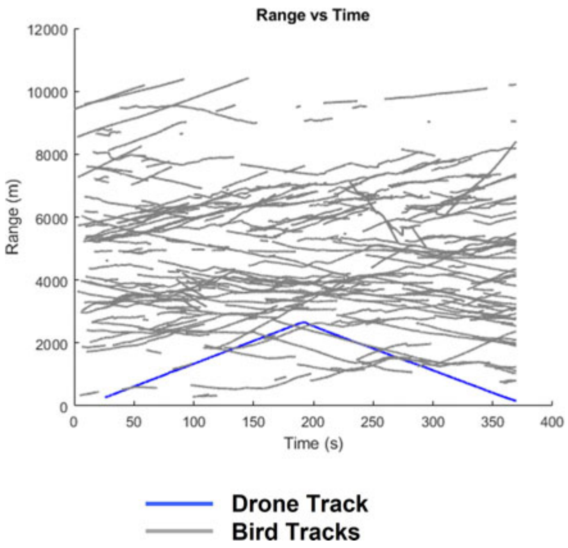

Figure 8.
Example scenario with a single UAS and multiple birds. The birds cause a cluttered air picture if not properly classified.

smaller than that of the UAS body that the radar is designed to detect. This limits the detection range for which micro-doppler is effective. Microdoppler also has limited capability for fixed wing drones that do not have a large number of propeller blades for doppler discrimination.

MAXIMIZING DETECTION RANGE

CHALLENGES

The average power form of the radar range equation is shown below:

$$SNR = \frac{T_{CPI} \cdot duty\,cycle \cdot P \cdot G^2 \cdot \sigma \cdot \lambda^2}{(4\pi)^3 \cdot R^4 \cdot k \cdot T_o \cdot F \cdot L}. \quad (3)$$

T_{CPI} is the coherent processing interval (CPI) time, *duty cycle* is the ratio of the pulsewidth to the pulse repetition interval (PRI), P is the peak transmitted power, G is the antenna gain, σ is the radar cross section (RCS), λ is the RF wavelength, R is the detection range, k is Boltzmann's constant, T_o is $290^o K$, F is the noise factor, and L represents system losses. To maximize R the following parameters are traded and optimized: P, G, T_{CPI}, and $duty\,cycle$. These parameters directly affect other radar performance parameters such as scan rate, and must be balanced accordingly. Rearranging (3) in terms of R better shows the dependencies of R on P, G, T_{CPI}, and $duty\,cycle$. This is highlighted in the following equation:

$$R = \left(\frac{T_{CPI} \cdot duty\,cycle \cdot P \cdot G^2 \cdot \sigma \cdot \lambda^2}{(4\pi)^3 \cdot SNR \cdot k \cdot T_o \cdot F \cdot L}\right)^{\frac{1}{4}}. \quad (4)$$

P and *G*

Detection range is proportional to the transmitted power P. Equation (4) shows that $R \propto P^{\frac{1}{4}}$. As an example, in order to improve the detection range (using transmit power only) by a factor of two (100% increase) requires an increase in power by a factor of 16 (see Figure 9). SWaP constraints limit the allowable P because increasing the power too much can lead to a need for liquid cooling, which also increases the system weight and reduces the reliability. These are undesirable for C-UAS.

Maximizing G also increases the radar detection range and can be used to minimize the required P. Increasing G provides a quadratic improvement in SNR [see (3)] and improves angle accuracy (σ_{BW}), which is directly proportional to the ratio of the antenna beamwidth and SNR $\left(\sigma_{BW} = \frac{BW}{\sqrt{(2 \cdot SNR)}}\right)$. At first glance, this appears optimal. To rapidly scan the field of view (FOV) a larger beamwidth is desired. However, increasing the beamwidth reduces the antenna gain and decreases the angle accuracy. This is highlighted in Figure 10. Since $G = \frac{4 \cdot \pi \cdot A \cdot f^2}{c^2}$, the antenna size A and the frequency f must be balanced to optimize G for both detection range, angle accuracy, scan rate, and radar size/weight (see Figure 11).

T_{CPI}

The coherent processing interval time when increased directly increases SNR and maximizes detection range [see (4)]. Increasing T_{CPI} also improves doppler/velocity resolution. Increasing T_{CPI}, though cannot be done without consideration of the scan rate. The scan rate can be defined as the inverse of the product of T_{CPI} and the number of beams required to scan the FOV (N_{beams}). For C-UAS, scan rates of 2 Hz or more and velocity resolution on the order of 0.5 m/s are typically desired to optimally maintain track continuity. This requires T_{CPI} to be selected carefully to balance detection performance, scan rate, and velocity resolution.

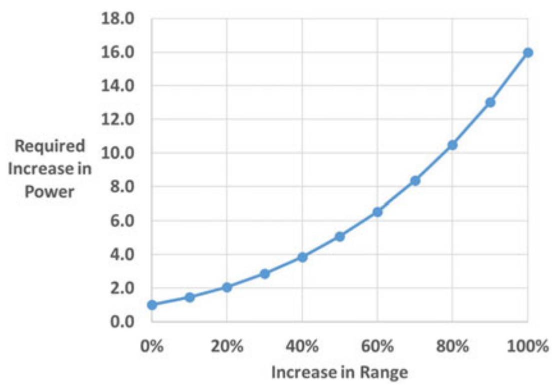

Figure 9.
The figure illustrates the required increase in power for improvement in detection range with constant antenna gain. Arbitrarily increasing the transmit power is not a viable option due to increased power dissipation and a potential need to require liquid cooling. The required transmit power must be balanced accordingly.

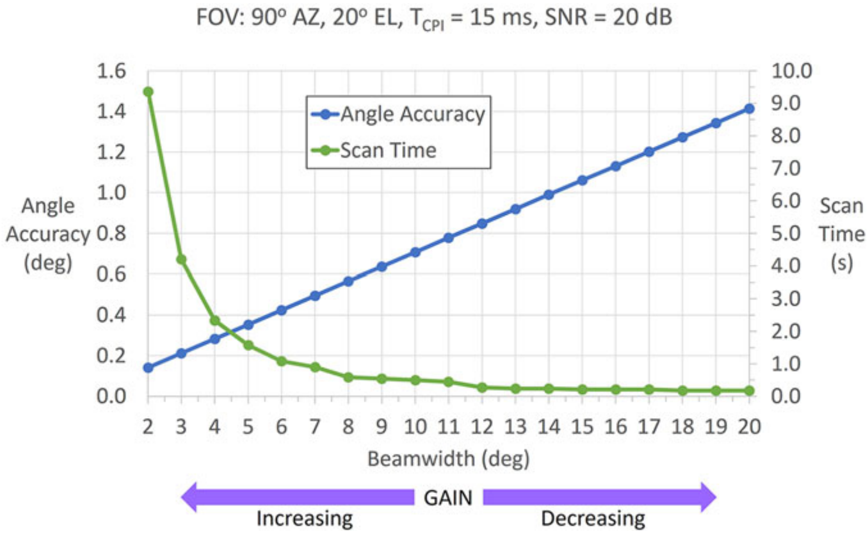

Figure 10.
Optimizing antenna gain to improve detection range requires a trade between scan rate of the FOV and angle accuracy. Increasing the gain decreases the antenna beamwidth for improved angle accuracy but at the cost of increased scan time. The radar beam in the figure is a pencil beam (equal beamwidths in AZ and EL).

Duty Cycle

Increasing the duty cycle also directly maximizes the detection range. This though must be traded with minimum detection range. Figure 12 show two waveforms with their coverage overlaid. The second waveform's duty cycle is increased by 50%. Correspondingly, the minimum detection range has been increased. This poses a challenge for C-UAS applications that require a maximum detection range greater than 5 km with a minimum detection range on the order of 100 m.

EXISTING SOLUTIONS

P* and *G

P is typically determined by the semiconductor technology used for the transmit high-power amplifiers (HPAs). In order to maximize transmit efficiency (minimizing power dissipation), a semiconductor material is chosen that will simultaneously maximize the allowable transmit power while maximizing the transmit efficiency. Gallium Nitride

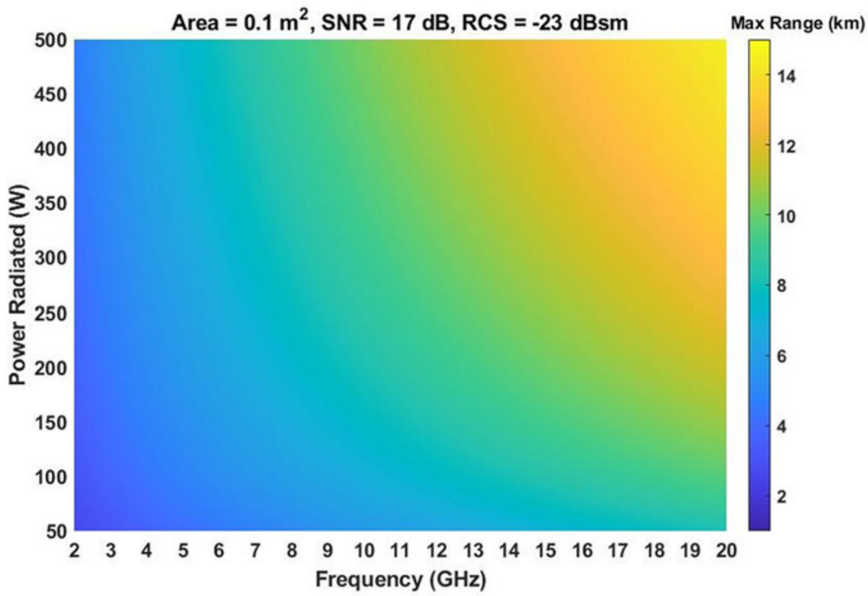

Figure 11.
Transmit power and frequency are traded to balance detection range as a function of power and antenna gain. Increasing the operational frequency increases the antenna gain and reduces the required transmit power and vice versa. The figure shows the max detection range as a function of frequency and transmit power for a 0.1 m^2 radar array.

(GaN) is typically the preferred choice for maximizing P. GaN-based amplifiers can provide a much higher output power in a smaller space [43], and transmit with better power efficiency at higher power levels than other semiconductors such as gallium arsenide (GaAs) [44]. Thus, for applications that require longer detections ranges without increasing the antenna size (and thereby gain), GaN is optimal because it is capable of transmitting high power with optimal power dissipation (maintaining SWaP).

T_{CPI}

As previously mentioned, increasing T_{CPI} maximizes SNR and thereby detection range but also decreases the scan rate. To counter this, T_{CPI} is shortened to improve/maintain the scan rate at the expense of velocity resolution, which is inversely proportional to T_{CPI}. The velocity resolution may be increased slightly, but can be balanced for maintaining adequate performance.

Duty Cycle

Increasing the duty cycle also directly maximizes the detection range as previously discussed. For applications where minimum detection range is important this is not favorable. Increasing the *duty cycle* by increasing the pulsewidth leads to an increase in the minimum detection range. Pulse compression [45] is nominally used to keep the pulsewidth the same while still increasing power on target for maximal detection range. However, in some instances a combination of both pulse compression and an increase in the pulsewidth is employed. The pulse compression gain offsets the amount of increase required by the pulsewidth and keeps the minimum detection range at a desirable level. Common pulse compression waveforms used are Barker codes [46] and linear frequency modulation (LFM) [47].

FOV COVERAGE

CHALLENGES

A standard approach for air defense applications is to create a scan fence with the radar. The maximum height of the scan fence is at the maximum detection range as shown in Figure 13. The number of beams required to cover the scan fence region is a function of the radar's antenna beamwidths and drives the scan rate as discussed previously. For C-UAS, UAS are detected in the search fence region and subsequently tracked. A vulnerability that exists is if a UAS target flies out of the search fence and the radar track is lost. When this occurs, the radar is unable to reacquire and establish a new track, and the UAS will be undetected by the radar. This is less of a problem for Group 3–5 UAS because the speeds at which they fly, dropping the track is very low probability. However, for Group 1–2 drones flying at speeds less than 100 m/s with RCS profiles like birds this is much more problematic. UAS target tracks can switch to bird tracks for birds in close proximity to the UAS, and at low speeds (< 30 m/s) with maneuvering flight profiles, maintaining track can be additionally challenging.

EXISTING SOLUTIONS

To maintain track outside of the search fence, the simplest solution is to add more search beams for increased elevation coverage. For mechanically steered radars this is challenging. The time required to scan the radar antenna with a gimbal is not feasible. This would decrease the scan rate for undesired performance. Active electronically scanned arrays (AESAs) enable an increased scan volume due to

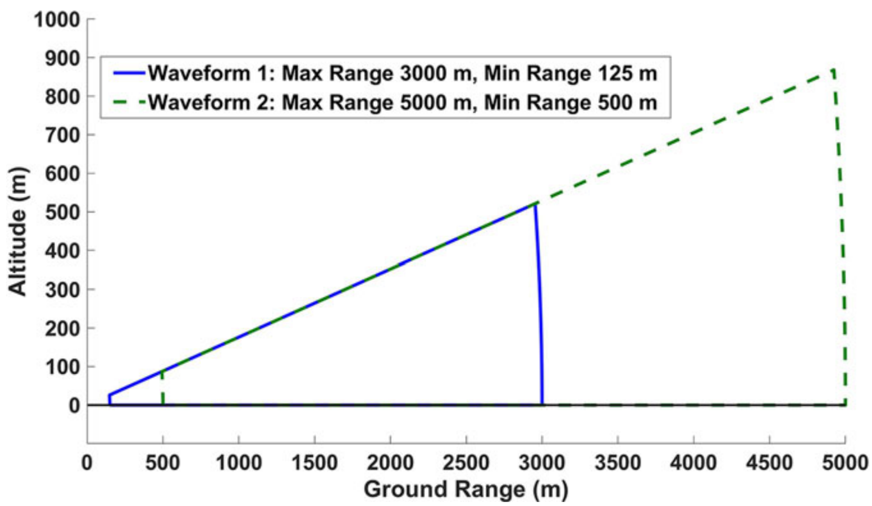

Figure 12.
Waveform 1 has a maximum range of 3000 m with a minimum range of 125 m. Increasing the pulsewidth of Waveform 1 results in Waveform 2. Waveform 2 has a longer pulsewidth and higher duty cycle for extended detection range, however the minimum range has been reduced to 500 m.

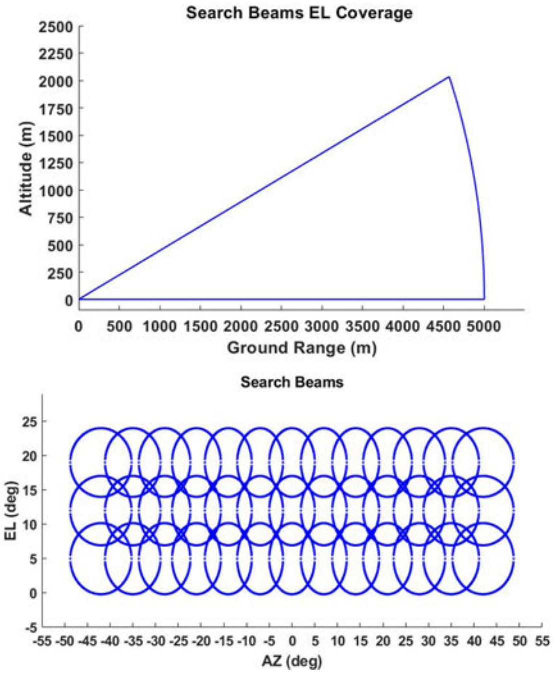

Figure 13.
Scan Fence example for air defense applications. C-UAS radars employ this approach.

their rapid scan capability [36]. AESA radars are therefore the preferred radar of choice for C-UAS applications.

If the scan rate degradation from adding more search beams is to great even for an AESA radar, another approach is to add dedicated track beams. When UAS targets that are being tracked leave the search fence coverage area, a dedicated track beam can be used for the UAS target while still executing track while scan (TWS). For this approach, an AESA is also required for operational implementation.

SIMULTANEOUS TRACKING OF MULTIPLE UAS GROUPS

CHALLENGES

Some C-UAS applications require simultaneous tracking of UAS targets spanning different groups. Examples include Groups 1 and 2, Groups 3–5, and Groups 1–5. For applications requiring simultaneous tracking performance for Groups 1 and 2, and Groups 3–5 a single mode can typically detect and track UAS with good performance. Simultaneously detecting and tracking Groups 1–5 is more challenging. The range of RCS sizes, maximum velocities, and maximum altitudes make this a challenge for a single mode. This is because the number of beams required dramatically decreases the scan rate. The mode can be optimized for Groups 1 and 2 or Groups 3–5, but the nonoptimized group will suffer.

EXISTING SOLUTIONS

Overcoming this challenge is accomplished using two different approaches. The first approach is to use two different modes, each optimized for either Groups 1 and 2, or Groups 3–5. For a single radar this approach does not provide simultaneous coverage and is suboptimal. However, in applications where multiple vehicles are used, the radar on each vehicle can use a different mode and collectively provide the required coverage. Figure 14 illustrates the modes for this approach. The second approach is to use a single mode to provide the simultaneous coverage. To overcome the challenges previously discussed, this can be accomplished by interleaving modes with waveforms that are tailored to different targets. For Groups 1 and 2, the waveform used would have a shorter maximum range, requiring a

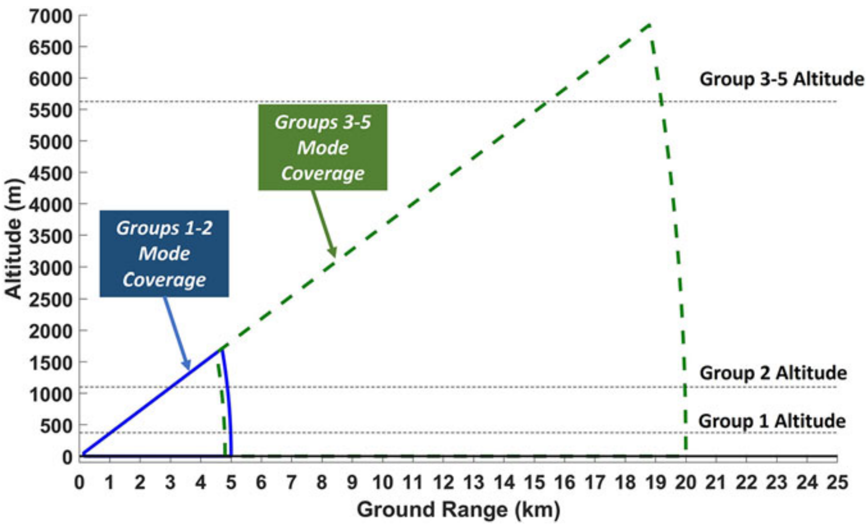

Figure 14.
Two modes when used simultaneously on different vehicles or in a single mode with interleaving provide the desired coverage of Groups 1–5.

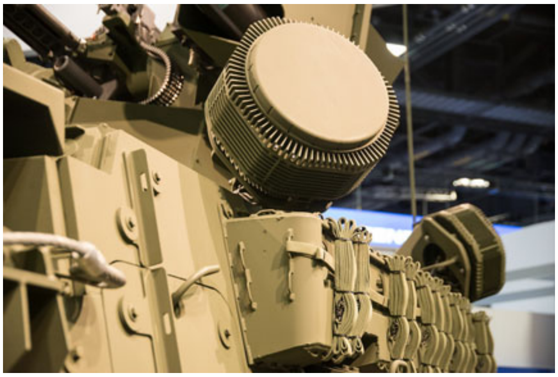

Figure 15.
Radars with AESA technology and software defined architectures, such as the multimission hemispherical radar (MHR), enable challenging simultaneous tracking of Groups 1–5 UAS.

shorter T_{CPI} and less required beams due to the lower maximum altitude. The waveform for Groups 3–5 would have a longer T_{CPI} due to the increased detection range, but an increased minimum detection range and minimum altitude. This allows the waveform to have an increased duty cycle, and less beams to cover the modified FOV. Both waveforms are then optimized together to provide the required scan rate. To accomplish this, a radar like DRS RADA's MHR that uses AESA technology with a software defined architecture is required (see Figure 15). AESA's provide rapid beam scanning and the software-defined capability allows customizable modes for design flexibility.

SWARMS

CHALLENGES

UAS swarms are a low-cost battlefield application that can overwhelm the common operational picture with targets, carry payloads such as explosives, cameras, and jammers, and provide a high-level threat to friendly forces [48]. UAS swarms have no limit on the number of individual UAS that comprise the swarm. This places a demand on the number of simultaneous targets that a radar must be able to detect. Radars that are limited to tracking less than 10–20 targets simultaneously will be vulnerable to larger swarms. Many C-UAS radars use multiple radar panels to provide 360° coverage. For these radars, an additional metric of simultaneous tracks per sector is also important. UAS swarms that are comprised of UAS that ingress at various angles over the radar systems field of regard (FOR) place an additional demand on the radar system to support a large track capacity.

UAS swarms also challenge a radar's resolution capability. Swarms that fly in a tight formation will appear as a single target to a radar that does not have the requisite range and angle resolution to differentiate the individual UAS. This degrades battlefield awareness, as the operator will not be able to assess the composition and potential lethality of the threat swarm. With the increasing advancement of directed energy (DE) weapons, this can be extremely critical. DE HELs are best suited for neutralizing threat UAS one at a time which is not optimal for UAS swarms. DE HPMs are optimal for simultaneous neutralization of multiple drones. It is important for a radar in a C-UAS to be able to discriminate drone swarms to aid in the decision-making process for selecting the right effector.

EXISTING SOLUTIONS

Doppler velocity discrimination is a key tool for drone swarms. Although frequency modulated continuous wave (FMCW) radars can provide target doppler velocity [49], the following discussion will focus on pulse doppler radars. For high performance tracking and long engagement ranges, pulse doppler radars are primarily employed for C-UAS application.

In a typical pulse doppler radar processing chain, the pulse doppler processing is done prior to detection. The processing gain that results from pulse compression and Fast Fourier Transform (FFT) processing is used to increase the SNR of the target return for a detection. The FFT pulse doppler processing measures the doppler velocity of the target from which the absolute velocity can be calculated. After detection, angle of arrival (AoA) processing is performed providing target angle measurement in EL and/or AZ. For swarms, if the velocity difference between drones is greater than the doppler velocity resolution the individual targets will be resolved. This allows the target angles to be measured via AoA processing, even for targets measured in the same radar beam, which is the most stressing swarm condition. This is illustrated in Figure 16. Figure 16 shows that if the drones in the depicted swarm are traveling with velocity differential less than the doppler velocity resolution, they will be detected in the same doppler bin and will not appear as separate targets. If the drones in the swarm are traveling at velocities that differ by an amount greater than the doppler velocity resolution then they will be resolved. For AoA, monopulse processing is typically implemented however high resolution array processing AoA techniques can be used as well [50], [51], [52], [53].

FUTURE ADVANCEMENTS

Current radars in the C-UAS market have significant capabilities for addressing UAS threats. These capabilities were discussed in the previous section and include:

- Simultaneous: Low SWAP and UAS long range detection;
- Multipath Mitigation;
- Micro-Doppler Processing for Classification;
- Track-While-Scan (TWS);

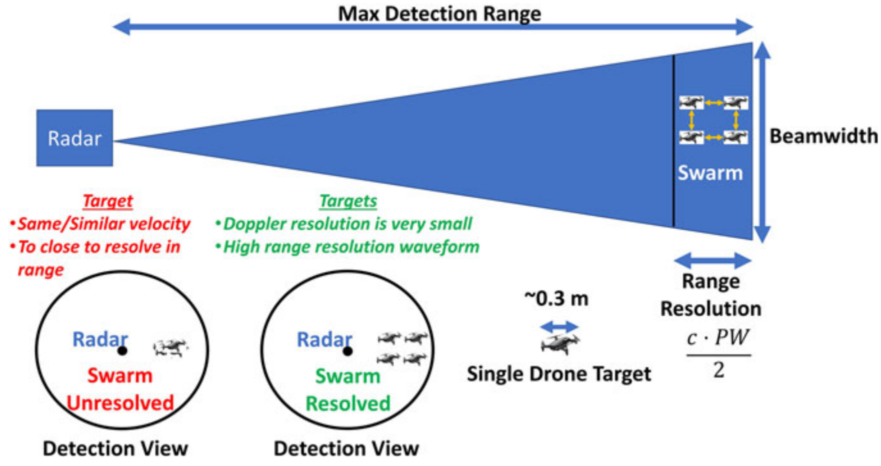

Figure 16.
In the figure the drone swarm targets are in the same range bin. The only way they can be resolved is if they can be separated in doppler and the difference in their range is greater than the range resolution of the waveform. If both of these criteria are met then the targets will be detected individually and AoA processing employed postdetection, i.e., monopulse. This implies waveforms that have a large bandwidth for high range resolution and long CPI dwells for high doppler resolution. Additionally, higher operating frequencies enables better discrimination in doppler as well.

- Waveform interleaving;
- AESA technology;
- Single multimission modes;
- Pulse Doppler processing;
- AoA processing;

Looking toward the future, several technology areas will have an impact on new and emerging C-UAS radars. These forward-looking capabilities are described next.

ELEMENTAL AND QUASI-ELEMENTAL DIGITAL BEAMFORMING

Digital beamforming (DBF) is currently being implemented in C-UAS radars. An example of this is DRS RADA's nMHR that is a multichannel DBF radar (see Figure 17).

Figure 17.
DRS RADA's nMHR is an X-band multimission DBF radar that supports C-UAS missions.

DBF provides the ability to do rapid FOV scanning with simultaneous narrow beam accuracy. Additionally, advanced algorithms can be implemented for performance enhancing capabilities such as adaptive array nulling, high resolution AoA algorithms, space time adaptive processing (STAP), etc. DBF is currently primarily implemented at the subarray (SA) level in practice. With the continued advance of high-speed wideband digital receivers and existing wideband front-end electronics, elemental DBF (EDBF) is becoming more feasible. For short range C-UAS applications ($<$ 3 km), the number of elements required is approximately less than a hundred depending on the operational frequency. This is an optimal range for EDBF implementation since the number of channels equals the number of array elements. For larger arrays $>$100 elements, SA DBF is typically implemented because the number of channels is more than can be practically implemented [54]. EDBF provides the ultimate capability because it offers the highest number of degrees of freedom (DOF) to process target returns. This provides improved performance for advanced algorithms and multiple simultaneous beams [54]. Impediments to EDBF implementation are usually cost and power dissipation. For small radars with a low number of elements/channels, the cost is becoming practical. Typical C-UAS waveforms have bandwidths on the order of several megahertz, which reduces the data rate for EDBF processing. These factors make EDBF very attractive for short range C-UAS.

For longer C-UAS detection ranges ($>$ 3 km), EDBF is not practical. This would require greater than a hundred channels (equals the number of elements for EDBF) of streaming detections. A quasi-EDBF approach is to design repeatable and manufacturable SA building blocks with a

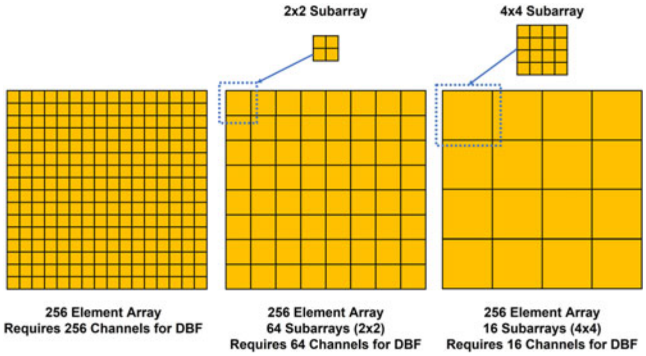

Figure 18.
Subarrays enable quasi EDBF performance. The subarray is comprised of a subset of array elements for a repeatable building block. In this example, subarray building blocks of 2 × 2 elements and 4 × 4 elements are shown.

small number of elements. The SAs would be tiled together to form the complete array. The small number of elements has similar behavior to a single element enabling quasi-EDBF performance. Using the same repeatable building block lowers cost and enables scalability. As an example, consider a radar that requires 256 elements. By building a 2 × 2 SA building block (four elements), the number of channels to process is reduced from 256 to 64. Similarly, a 4 × 4 building block (16 elements) would reduce the number of channels from 256 to 16 as shown in Figure 18. For both examples, a family of radars with different sizes could be produced with the same repeatable building block as shown in Figure 19.

AI/ML

As discussed previously, the primary methods of mitigating false bird tracks for classification is to pair a radar with an EO/IR sensor and/or microdoppler processing. Using an accompanying EO/IR sensor in a C-UAS suite adds more hardware, and more user responsibility to monitor both the radar tracks and the camera verification tracks. Microdoppler although effective requires a large SNR and is limited in maximum detection range implementation. Using AI/ML to process radar detections for classification [55] without requiring a companion EO/IR sensor provides the ultimate flexibility. This can be done at the IQ level, detection level, track level, or a combination of the three. This paired with microdoppler could enable false positive performance to less than 10%. Also, an EO/IR sensor with AI/ML image classification could still be used in parallel for an even more robust total solution. In addition to bird-drone classification, UAS threat intent is also an application of radar only AI/ML classification. Training on UAS flight profile behaviors for surveillance, loitering munition, etc., would provide valuable situational awareness for the operator. This will require significant amounts of training data to train AI/ML algorithms but could provide valuable capability.

LOW PROBABILITY OF INTERFERENCE (LPI)/LOW PROBABILITY OF DETECTION(LPD) WAVEFORMS

For force expedition applications, using a radar limits the ability to remain undetectable. The radar is scanning the FOV with high gain array beams for maximum detection

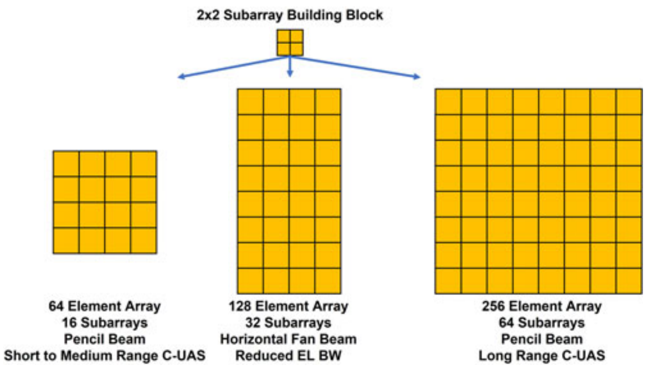

Figure 19.
Using a single SA building block different radars can be manufactured leveraging the subarray scalability. The difference in radar topologies would differ only in number of channels and subarrays.

range. To counter this, using LPI/LPD waveforms would reduce the radar signature and minimize the radar's probability of being intercepted or detected [56], [57], [58], and [59]. One way of accomplishing this is using wide bandwidth waveforms that have a very low probability of detection. Another approach is to use the commonly known practice of frequency hopping. This would require the radar to operate over a wideband, but would reduce its probability of being intercepted. Techniques similar to these described will ultimately require AESA radars with wide operational bandwidths greater than 1 GHz to be effective. Wide operational bandwidths will be discussed next.

WIDE OPERATIONAL BANDWIDTHS

Wideband operation is becoming more important for intentional and unintentional RF interference. This is especially true for operational frequencies at X-band or higher. C-UAS are being deployed in locations, where there is a large amount of interference from other RF systems. This creates an interference rich environment that the radar must operate in with acceptable performance. Radars with wide operational bandwidths will be able to find available spectrum regions to operate. From an Electronic Counter-Countermeasures (ECCM) perspective, wideband operation enables the radar to dynamically switch to different frequencies when being jammed. Current work is being developed for radars to autonomously switch frequencies and bandwidths when operating in RF signal rich environments [60]. This could be of added benefit for C-UAS radars. However, for optimum effectiveness, wideband operation is required.

NETWORKED INTEGRATION FOR CO AND CROSS MISSION APPLICATION

As the types of UAS threats increases with increasing capability using a single radar system may in some cases not be beneficial. The ability for radars to communicate with each other in the battlefield is becoming an emerging capability. The radars can be performing the same or different mission(s) with the ability to communicate and share information [61], [62], and [63]. This ability can reduce the burden on the C2 system by providing it with an integrated common operating picture without having to manage the multiple radars on its own. Below are some examples of the utility of radars communicating with each other in a networked configuration.

- Multistatic Operation—One radar is transmitting while the other radars are passively receiving.
- Layered Defense—Multiple radars optimized for short, medium, and long range UAS detection spread out diversely to protect critical infrastructure.
- Multimission—Multiple radars optimized for different mission such as C-UAS and Counter Rockets, Artillery, and Mortars (C-RAM).
- AI/ML Battle Space Awareness—C2 can use the networked track data to identify patterns and use for engagement response

CONCLUSION

This article illustrates the importance of radars for the C-UAS mission. Radars are predominantly the primary sensor for C-UAS. They provide target range, angle, and velocity measurements to detect, track, and classify UAS threats. Radars provide persistent surveillance with 24/7 operational capability in all-weather environments at beyond LOS ranges.

With the increase of threat UAS such as loitering munitions, C-UAS have become an increasingly vital asset for the warfighter on the battlefield. This has placed a premium on high performance radars that can be the backbone for C-UAS defense. Understanding the challenges radars are presented with for C-UAS and the current solutions is of value for forecasting future advanced radar capability. The challenges and current solutions were discussed for

- SWaP;
- Multipath at low elevation angles;
- Biological versus man-made target classification;
- Maximizing detection range;
- FOV coverage;
- Simultaneous tracking of multiple UAS groups;
- Swarms.

Forward looking capabilities were described based on their relevance and impact to the C-UAS mission. These capabilities are based on existing and emerging trends in C-UAS defense. The future advancements described were

- Elemental and quasi-elemental digital beamforming;
- AI/ML for radar only UAS classification in the presence of birds;
- LPI/LPD waveforms;
- Wide operational bandwidths;
- Networked integration for co- and cross-mission application.

Many of these capabilities are starting to be incorporated in new radars coming to market. As the C-UAS mission continues to advance, these capabilities will mature and advance as well.

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