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Target Detection Techniques in Radar Systems: Introduction, Challenges, Opportunities and Applications

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Abstract: Target detection technique is one of the foremost important aspects for surveillance and tracking system in aerospace. This review paper delves in detail with covering the major concerns on the conceptual as well as theoretical concepts required for the suitable space mission requirements. It also highlights the challenges, opportunities and applications for the radar system in aerospace sector. Overall, the detailed review summary has been provided to understand the working aspects of radar tracking systems about its types and other major concepts.

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1. Introduction

The origin of the radar system was initiated in of 1880s, where it was primarily used in sending radio waves to detect and determine the presence of any aircraft and to determine its range and speed of an aircraft. The radar system typically equipped with transmitter, parabolic antenna, duplexer, receiver, signal processor, digital unit and power supply unit the antenna will switched into transmit mode to a receiver mode by a duplexer and it is responsible for emission of electromagnetic radiation/waves to detect any obstacle on its way to be found in natural resources, buildings and other form of engineering aspects [1]. The importance of radar systems in aerospace engineering has played a pivotal role in transferring the older version of technology to a new era, which involves multiple progresses at different segments, such as communication systems, telemetry, and control of frequent changes in amplitude and frequency, satellite signal in space, etc. Shruti et al. describes a short note on ballistic tracking technologies that discusses the challenge of using radar readings to track a re-entry ballistic [51]. The received signal is called "echo," and the reflecting object is called a target. The presence of an echo signal indicates that a target has been detected. The echo is referred to as a "target signal," and the unwanted detections are called "clutter."

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Figure 1. Radar systems [1]

The pulse energy travels at 162,000 nautical miles per second. For convenience, a radar mile, 2000 yards, or 6000 yards is often used. The transmitted signal takes 6.16 microseconds to travel 1 radar mile; therefore, the round-trip for 1 mile is equal to 12.36 microseconds. This equation can calculate the range:

$$\text{RANGE} = \frac{\Delta t}{12.36}$$

Δt = time from transmitter to receiver in microseconds.

For shorter ranges and higher accuracy, the equation is

$$\text{RANGE (YARDS)} = \frac{328\Delta t}{2} = 164\Delta t$$

$$\text{mur} = \frac{PRT}{12.2}$$

After the pulse has been transmitted, a sufficient rest time (receiver time) must be allowed for the echo to return so as not to interfere with the next transmit pulse. This pulse repetition time (PRT), or pulse repetition time, determine determines the maximum distance to the target to be measured. Any signal arriving after the transmission of the second pulse is called a second return echo and would give an ambiguous indication. If a large reflective object is very close, the echo may return before the complete pulse can be transmitted. The fundamentals of the operation of a radar system can be comprehended in such a manner that the echo is completely feedback, which takes place at the end of a pulse to estimate the effective range [2]. The radar transmission must be nature that it correlates with the microwave region and the other bands of nomenclature

Table 1. Band names for different frequency ranges [2]

Band Name	Frequency Range (GHz)	Max Available Peak Power (MW)
UHF	0.3 - 1	5
L	1 - 1.5	30
S	1.5 - 3.9	25
C	3.9 - 8	15
X	8 - 12.5	10
Ku	12.5 - 18	2
K	18 - 26.5	0.6
Ka	26.5 - 40	0.25
V	40 - 80	0.12
N	80 - 170	0.01
A	Above 170	-

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2. Radar Operations Modes

Pulsed System - This section introduces pulsed radar systems, explaining that they can be described using a block diagram of a typical pulsed radar set. After outlining the system's functional blocks, the text discusses antenna scanning, tracing, and display methods. This section explains the major components of a signal flow in a high-powered pulsed radar system. This system begins with a trigger source, which generates timing pulses that activate the modulator. The modulator produces high-voltage rectangular pulses that power the output tube, enabling the transmission of microwaves. If the radar uses low-power transmitters, solid-state microwave sources such as IMPATT Gunn oscillators, or TRAPATT amplifiers may be used. The protects the receiver during transmission and connects the antenna to the receiver during reception. On the receiving side, the signal first goes through the duplexer and then to a mixer, which converts the received RF signal to an intermediate frequency (IF) such as 30-60 MHz. An IF amplifier boosts this signal while minimising noise [2]. A local oscillator provides a reference signal for the mixer. After IF processing, the signal goes to the detector, followed by a video amplifier, which produces the final video signal displayed on the indicator. Additional blocks, such as ATR (anti-transmit-receive) switches and TR switches, protect sensitive receiver components from powerful transmitted pulses. Angle data from the antenna feeds the indicator for target localisation.

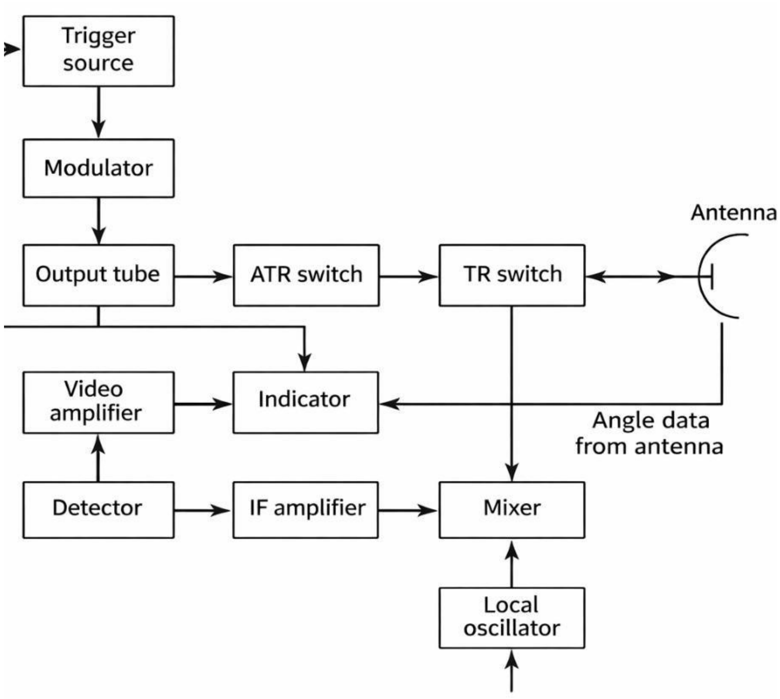

Figure 2. Block diagram of a pulse radar system [2]

This system discusses methods to improve radar receiver performance by reducing noise and stabilising frequency. One issue in radar receivers is noise bandwidth, especially when using diode mixers. To minimise this, some systems use a balanced mixer to reduce noise and improve signal quality. Another important technique is automatic frequency control (AFC). AFC stabilises the local oscillator frequency, so it does not drift. It typically works by comparing the IF signal with a phase discriminator; any frequency error produces a correcting voltage that adjusts the oscillator. The IF amplifiers used in radar receivers are often synchronously tuned -meaning all the amplifier stages are tuned to the same centre frequency and bandwidth. This creates a desired bandpass response that avoids overlaps and maintains signal integrity. The detector output usually passes through a video amplifier with a bandwidth matched to the IF system, producing a clean video signal for the display [2]. In some systems, the local Oscillator is a varactor-tuned device or a cavity oscillator, and AFC can stabilise it further. This ensures the radar operates with minimum frequency drift and maximum reliability.

Search radar system (SRS) - reveals the basic features of the radar including the representation of antenna scanning methods and display system such that the radar system acquires a target in the large volume of space such that the information could be passed on to a tracking radar which quickly acquires and follow the target the most common type a region is the (ATC radar) which is used as both military and civilians airports [2].

Track radar system (TRS) - Once a target has been acquired, it can be tracked, enabling the ranging information, and the relative target is said to be tracked. The most basic type is that is performs both searching and tracking to be displayed on the plan position indicator (PPI) display. Also, the tracking of extra-terrestrial objects such as satellites/spacecrafts is another specialised form of tracking, mostly in radar systems transmitter and receiver are of nature that they are separated by quite long distances. It is possible to eliminate the variety of clutter from the radar display that corresponds to any station targets which showing only the moving objects. The radars are set to emit the radiation such that the transmitter and receiver actually correlate with the operational devices, that is, a pulsing modulator and switch modulator, respectively [2].

3. Moving-Target Indication (MTI)

It is possible to eliminate the majority of 'clutter' from the radar display that echoes corresponding to stationary targets, showing only the moving targets. This is often required, although of course not in such applications as radar used in mapping and navigational applications. It employs the Doppler effect in its operation. The Doppler effect describes how the observed frequency of sound or electromagnetic waves changes due to relative motion b/w the source and the observer. When they move towards each other, the observed frequency increases; when they move away, it decreases [2]. First proposed by Christian Doppler in 1842 and mathematically refined by Armand Fizeau in 1848, this effect explains phenomena such as redshift in light from stars moving away from Earth and the pitch changes of a passing train's horn. The Doppler effect is also widely utilised in various radar systems. Consider an observer standing on a platform and moving towards a fixed source of radiation with a positive relative Vr. A stationary observer will receive Ft wave crests per sec if the source transmits at frequency Ft. However, because the moving observer is approaching the source, they encounter more than Ft wave crests per second. The observed frequency under these conditions increases due to the Doppler effect. If the relative velocity Vr is less than about 10% of the speed of light Vc, classical Doppler formulas are sufficient. For higher velocities, relativistic Doppler formulas must be used, but the principle remains the same whether the observer or source is moving. A positive Vr gives a positive shift, and a negative Vr gives a negative shift. In radar systems, the Doppler effect occurs twice: once when the transmitted signal hits the moving target, and again when the reflected signal returns to the receiver. Because of this double interaction, the Doppler frequency shift in radar is doubled.

$$2\mathrm{f}'d = \left(2\mathrm{ft}\frac{Vr}{Vc}\right) = \frac{2Vr}{\lambda}$$

where λ is the transmitted wavelength.

The Doppler shift has the same magnitude whether a target moves towards or away from a radar; the frequency increases when approaching and decreases when receding. The Doppler effect occurs only for radial motion, not for motion perpendicular to the radar beam. Therefore, no Doppler shift is seen when a target moves sideways across the radar's field of view. By analysing Doppler frequency shifts, both pulsed and continuous-wave radars can determine targets from stationary ones.

CW Doppler Radar (Continuous-wave)

CW Doppler radar system uses the Doppler effect to analyse motion. The system continuously emits a sinusoidal wave rather than pulses. The circulator is used to isolate the transmitter and receiver in a continuous-transmission system, since a duplexer would be necessary. Typical circular isolation is about 30 dB, so some transmitted signal still leaks into the receiver. The detector extracts the Doppler frequency, which is then amplified, usually with an audio amplifier and sent to a frequency counter. The system is simple and not sensitive because the diode detector performs poorly at low audio frequencies and introduces modulation noise. In the improved CW Doppler radar system, a portion of the transmitter signal is mixed with a local oscillator and combined with the Doppler-shifted return signal. This mixing process produces an intermediate frequency, which is amplified and then demodulated to recover the Doppler frequency. Operating at this higher IF reduces FM noise and increases sensitivity, making the system behave similarly to a superheterodyne receiver [3]. Using separate transmitting and receiving antennas can help increase isolation, since leakage of the transmitter signal into the receiver degrades performance. Isolation limitations also restrict the transmitter's output power; CW radar transmitters typically operate below 100W, often using Gunn or IMPATT diodes or CW magnetrons.

4. Challenges and Opportunities of the Radar System

There are several challenges to be accounted for in the usage of the communication radar system in aerospace, electronics, telecommunication, etc. Some of the major challenges faced with communication-based radar systems are mentioned below.

Spectrum sharing and interference management- Spectrum sharing uses frequency bands as of same to radio spectrum, which makes it more viable and efficient for users. It also allows for different sharing models such as exclusive, primary (which is also known as hierarchical) and open, respectively. The spectrum sharing also plays

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a critical role in detecting incumbents reliably and avoiding harmful interference [4, 5]. Interference management relies on techniques such as power control, spectrum access policies, and scheduling to limit interference, distributed power control. Advanced physical-layer methods, e.g., interference alignment increase network degrees-of-freedom by aligning multiple interferers into subspaces, letting desired signals pass unharmed. Machine learning and database-driven approaches (centralised or distributed) are increasingly used to predict spectrum availability, optimise sharing policies and detect/mitigate interference in real time. Good interference management balances these to meet QoS and protect incumbents [6, 7, 8].

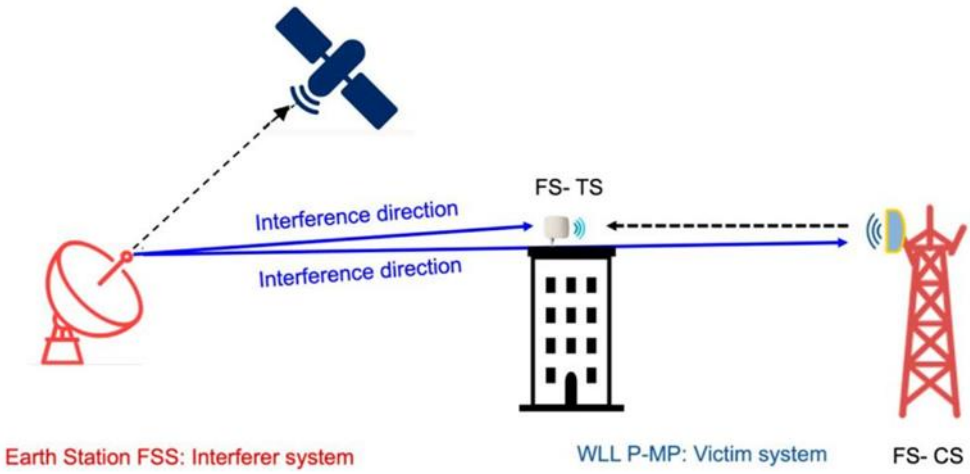

Figure 3. Coexistence scenario: FSS E-S interfering FS WLL P-MP [32]

Power and Hardware Limitations- Power and hardware constraints are critical in modern wireless and IoT systems because devices often must operate on limited energy budgets (e.g., batteries or harvested power) and with modest, low-cost hardware. The hardware limitations include low power amplifiers (PAs) with non-ideal efficiency and linearity, analogue front-end impairments (e.g., I/Q imbalance, phase noise, nonlinear distortion), and circuit-level power consumption in sensors, memory, communication interfaces and microcontrollers [9, 10]. The power consumed by radio transmission, sensing, processing, and memory access competes with the limited supply, forcing trade-offs between range, data rate, latency, and lifetime [11]. Hardware impairments degrade system performance (e.g., reduced capacity, higher error rates) and increase power demands or reduce achievable efficiency to illustrate, in large-scale antenna arrays, non-ideal hardware imposes ceilings on capacity and energy efficiency [12].

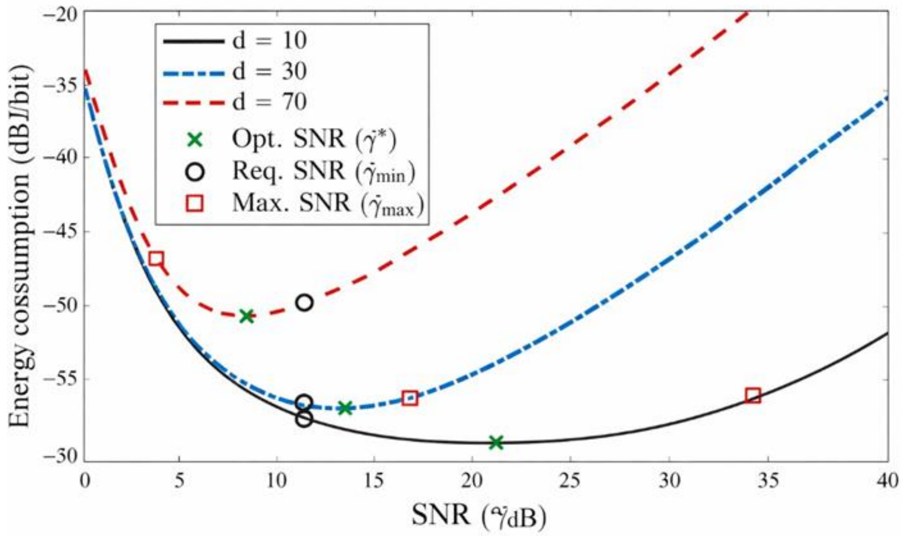

Figure 4. Comparison of optimal, required and maximum achievable SNRs at different distances (d) for 4-QAM under reliability constraints of P = 0.001, τmax r = 3, np = 976 bits, and maximum transmit power P0 = 10 MW [9]

Signal Synchronisation- It refers to a set of step processes where signals are received and aligned with time, frequency with the transmitter, so later on can be used for demodulation, decoding and amplification. Signal synchronization generally refers to three type-firstly the timing synchronization- which states the identification of samples with over the range of time, secondly carrier synchronization which is more concerned with the oscillation values to match out with the transmitted frequency and phase and finally the frame/packet synchronization which converts the large set of data information to be delivered in short divisions to avoid any sort of fluctuations and loss of signals [13, 14]. Synchronisation also provides a deep understanding of network systems, which involves another type of synchronisation, i.e., clock synchronisation, which describes the certainty of nodes to occur in phenomena such as beamforming, cooperative communication, etc., to maintain the frequency frame [15]. One of the major challenges to be faced while performing synchronisation is the poor signal module that could lead to increased bit error rate, reduce throughput, cause loss of orthogonality (for OFDM), and may necessitate heavier buffering or guard-intervals [16]. In order to overcome these problems, modern systems integrate sophisticated synchronisation algorithms (coarse then fine estimation/tracking), compensation for residual offsets, hardware impairments (phase noise, I/Q imbalance) and sometimes machine learning techniques to handle time-varying conditions [17].

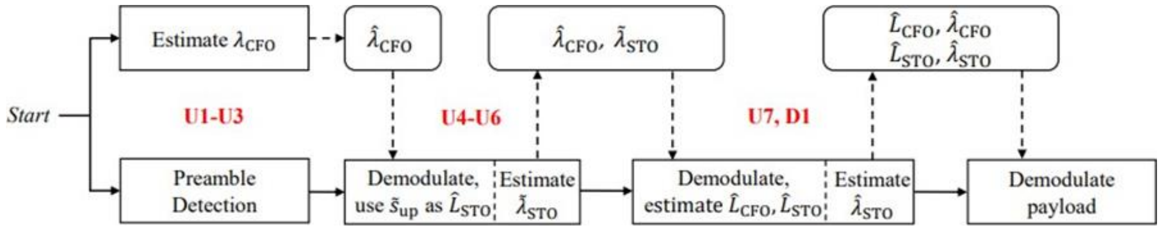

Figure 5. Flowgraph of the synchronisation algorithm [16]

Security, jamming, and spoofing issues- In modern radar and joint communication-sensing systems, security vulnerabilities arise because the radar waveform and communication links share open radio access and lack built-in authentication, making them susceptible to jamming, spoofing and other malicious attacks. In a jamming attack, an adversary transmits high-power noise or signals in the radar/communication band to raise the noise floor or saturate the receiver front-end, thereby denying detection or reliable communication [18, 19]. In a spoofing or deceptive attack, the adversary injects false returns or false communication/echo signals that mimic legitimate radar echoes or communication messages, thereby causing the system to detect phantom targets, mis-estimate velocity/range, or decode wrong messages, which is especially dangerous in safety-critical systems [20, 21].

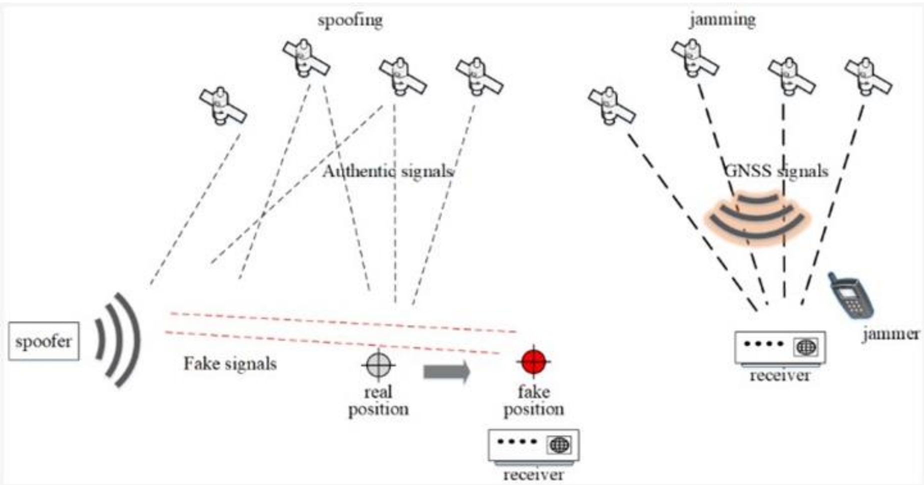

Figure 6. Main principle of spoofing and jamming attack [20]

Reliability in extreme aerospace conditions- In aerospace systems, communication and radar hardware must survive harsh environments characterized by high radiation levels (cosmic rays, solar energetic particles, trapped belt protons), extreme temperatures (very low in shadow, very high in sun, large thermal gradients) and severe mechanical loads (launch vibration, shock, and long-term thermal cycling). Radiation can cause single event effects (SEEs), total ionising dose (TID) degradation and displacement damage in electronics, degrading radar or communication system performance or causing failure [22, 23, 24]. Temperature extremes produce thermal fatigue, solder joint cracking, package delamination, shifts in component characteristics (amplifiers, oscillators) and

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can degrade signal stability and reliability [25]. Vibration and shock during launch impose fatigue on solder joints, PCBs and mechanical mounting structures, potentially misaligning antennas or degrading radar front-end calibration [26].

5. Opportunities in Radar System

There are several opportunities that are currently in the investigation phase for the usage of the communication radar system in aerospace, electronics, telecommunication, etc. Some of the major opportunities in communication-based radar systems are mentioned below.

6G-enabled aerospace ISAC (Integrated Sensing & Communication)- 6G will treat ISAC as a first-class network capability: communication infrastructure (terrestrial, aerial and space nodes) will also provide radar-like sensing functionality to enable high-resolution situational awareness, tight localisation, and synergistic use of spectrum and hardware [27]. Aerospace ISAC faces unique challenges: long propagation delays, large Doppler from high relative velocities, stringent pointing/beamforming and strict hardware/SWAP constraints on airborne/spaceborne platforms that complicate joint waveform design and real-time beam management [28]. Aerial and space segments introduce heterogeneous link budgets and dynamics: cooperative ISAC across satellites, HAPS and UAVs (a SAGIN approach) can fuse multi-view sensing to overcome individual platform limits but requires tight synchronisation and distributed resource allocation [29, 30]. Security and robustness are critical ISAC signals can be spoofed or jammed; aerospace ISAC needs secure waveform authentication, resilient beam control and cross-modal sensor fusion (radar + EO/IR + communications) to validate sensed events [31].

Integration with LEO/MEO satellite constellations for global aerospace communication- The integration of LEO/MEO satellite constellations plays a pivot role in understanding the global connectivity that extends coverage, reduces end-to-end latency (vs GEO), and enables continuous service where terrestrial infrastructure is absent [33]. The integration with on-board switching/RAN functions, and hybrid distributed edge/cloud process across space–air–ground nodes; each has different trade-offs for latency, complexity and scalability [34]. Payload constraints (power, antenna aperture, payload processing) and ground segment costs push for software-defined payloads, flexible beamforming, and on-board AI for resource allocation, compression and traffic shaping [35].

Quantum radar and quantum communication possibilities- Quantum radar uses pairs of entangled photons (signal and idler) to detect targets in noisy environments with improved sensitivity and lower error probability compared to classical radar [36]. Even if entanglement is partially lost after reflection, quantum correlations allow detection beyond the classical limit. Quantum illumination-based radars can outperform traditional radars in low-SNR or jamming environments by exploiting quantum correlations rather than amplitude alone, making them attractive for stealth and counter-stealth operations. These systems can enable low-power detection, enhanced range resolution, and resilience to electronic countermeasures key benefits for aerospace surveillance and defence [37, 38]. Quantum communication, meanwhile, uses entangled photon pairs or single-photon states to transmit information securely most notably through Quantum Key Distribution (QKD), which guarantees unbreakable encryption through the laws of quantum mechanics [39].

Swarm Intelligence and Distributed Sensing for UAVs- Swarm intelligence (SI) in UAV systems draws inspiration from collective behaviours found in nature such as flocks of birds or colonies of ants to enable decentralised decision-making and cooperative mission execution [40]. Distributed sensing enhances swarm capabilities by enabling UAVs to collaboratively gather, process, and fuse environmental data, thus forming a robust sensor network in the sky. The strength of swarm-based UAV networks lies in scalability, fault tolerance, and adaptability if one UAV fails, others can dynamically reconfigure and continue the mission [41, 42]. Swarm-enabled distributed sensing supports real-time environmental monitoring, precision agriculture, and disaster management by offering coverage of large and dynamic areas with minimal human supervision [43]. Machine learning and reinforcement learning techniques are increasingly being integrated to improve autonomy and cooperative decision-making. Challenges remain in reliable inter-UAV communication, collision avoidance, energy management, and secure coordination, especially in contested or GPS- denied environments [44, 45].

6. Applications for Radar Systems

1) Air Traffic Control (ATC)- The purpose of the ATC system is to enable ground controllers to maintain safe separation of aircraft, both on the ground and in the air. In addition to this, the controllers are managing the flow of traffic in a given airspace. The system is based on secondary surveillance radar (SSR) located at strategic sites near airfields. To identify individual aircraft on their screens, controllers use the SSR system [46]. The ATC system operates on two frequencies within the L-band of radar, having interrogation codes on a 1030MHz carrier wave and reply codes on a 1090MHz carrier wave, respectively. The different types of operational modes in an ATC are mentioned below.

2) Communication and Telemetry- Integrated radar-communication systems (IRCS) and radar telemetry protocols integrate sensing and data transmission using shared waveforms, like chaotic signals or optimised transport layers to handle both target detection and real-time data exchange [47, 48].

2.1) Key Waveform Designs- Chaotic signals from solvable systems serve as baseband waveforms in IRCS, offering thumbtack-shaped ambiguity functions for superior range- doppler resolutions compared to LFM, m-code, or Frank code, while enabling low BER communication via matched FIR filters [47]. These signals support frame structures with pilot and information symbols for synchronisation, channel estimation, and dual radar/comms processing, achieving BPSK-like performance under AWGN channels.

2.2) Telemetry Protocols- For radar data streaming, TRABOL (TCP-friendly Rate Adaptation Based on Loss) over UDP outperforms TCP and plain UDP by adapting rates (e.g.- 120-220 Mbps) with sample selection schemes like uniform or contiguous pattern, minimising standard deviation in moment parameters (reflectivity, velocity) under congestion [48]. sample groups (single samples for reflectivity, pairs for velocity) ensures Qos, with TRABOL maintaining fairness to TCP cross-traffic while maintaining fairness to TCP cross-traffic while meeting real- time minimum rates.

2.3) Performance Insights- Radar range errors for chaotic signals drop below 0% at SNR>-4 dB, outperforming traditional waveforms at low SNR due to strong autocorrelation; velocity estimation via MUSIC on phase vectors achieves 0.1 m/s error at SNR=5-9, depending on vector dimension. (1) Communication BER nears theoretical BPSK limits (e.g., suboptimal threshold yields,0.2 dB gap) with chaotic signals showing the highest spectral sufficiency versus spread-spectrum alternatives [47, 48].

3) Attitude Control System- Attitude control system related to radar-equipped platforms focuses on determining and controlling the orientation (attitude) of vehicles such as UAVs and satellites using radar data combined with sensors and control algorithms. Accurate attitude estimation is critical for stable flight, precise remote sensing, satellite pointing, and communication [49, 50].

3.1) Radar-based attitude estimation for UAVs- research demonstrates that radar sensors, such as the ARS-548 automotive radar repurposed for UAVs scan estimate roll and pitch angles by analysing 3D radar point clouds reflected from the ground. The approach involves filtering radar data to isolate the ground plane, the fitting a plane to these points by least squares. The plane orientation gives pitch and rolls angles with root mean square errors of about 1.5 degrees for roll and 1.4 degrees for pitch in favourable conditions. The radar-based estimation aligns well with IMU data and provides a backup or complement in case of IMU drift or failure. The yaw angle remains a challenge to determine radar alone [50].

3.2) Radar And Sensing Fusion Approaches- Radar provides valuable attitude-related data for UAV navigation, especially when fused with IMU, GNSS, or barometric measurements using Kalman filters to enhance accuracy and robustness. In remote sensing applications, the fused data supports stable flight and precise sensor pointing, improving data quality. These advances show radar play a significant role in attitude control systems for various platforms by augmenting and enabling accurate orientation estimation and control required for mission success [49].

3.3) Surveillance and Operations- Primary radar high energy via antenna to illuminate a 'target' which could be a ground, aircraft or water droplets in a cloud. In the case of ATC primary radar, the echo is reflected from the aircraft's body to provide range and azimuth measurements. The target should be displayed in PLAN POSITION INDICATOR (PPI). One of the major disadvantages of primary surveillance radar is transmitting a very large amount of energy compared to the amount of energy received back from the target. Small targets with poor surfaces could further reduce the energy reflected from the aircraft. There are some other obstacles that are naturally made, and some other engineering constructions and wind farms shield the radar signals.

4) Automatic dependent surveillance-broadcast (ADSB)- The emerging technology for air traffic management is designed to replace conventional Secondary Surveillance Radar (SSR) and ground-based Air Traffic Control (ATC) systems. It also provides surveillance capabilities in remote areas where traditional ground coverage was previously impossible. This Advanced Data Broadcast System (ADBS) is part of the next-generation air transport system and is set to revolutionise the cockpit by supplying pilots with traffic density information. As a result, pilots will take on direct responsibility for their own aircraft separation and collision avoidance. This new automated system does not require interrogation to initiate a transponder broadcast from the aircraft, eliminating unsolicited broadcasts such as squitter [46].

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7. Conclusion

Radar systems remain sophisticated technology for detection, tracking and some physical parameters of an aircraft, and they are developed for both civilian and military applications. Radar systems are not only used for detection purposes but also for surveillance technologies. Pulse radar enables accurate range measurement, while MTI is busy helping to eliminate all the clutter in those premises. Doppler and CW radar will give accurate velocity measurements and real-time monitoring and also bring some ambiguity and interference. The different challenges and opportunities for radar detection based on communication systems will enable the solution for all sort of integrated problems that are to be majorly affected for a launch-based mission. Overall, modern radar systems focus on improving resolution, reducing noise, and integrating with advanced signal processing and adaptive algorithms, to achieve reliable, precise and efficient radar performance in future.

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