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Technology of Radar Detection

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Abstract: Radar detection technology utilizes radio waves for target detection, localization, and identification. It involves emitting electromagnetic waves and receiving the reflected echoes from targets, then analyzing the echo characteristics to obtain target information. This paper focuses on the fundamental principles, advantages, and disadvantages of radar detection technology. It emphasizes synthetic aperture radar (SAR), passive radar detection technology seeker, and millimeter-wave active homing guidance target identification technology, as well as the characteristics and development status of other detection methods such as phased array radar, showcasing the multi-directional development trend of radar detection technology.

Keywords: Radar detection technology; Synthetic aperture radar (SAR); Passive radar detection technology; Millimeter-wave active homing guidance target identification technology; Development status

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1. Introduction

Radar is defined as radio detection and ranging, which measures the position of targets in the air, on the ground, and on the water, and is also called radio positioning. Radar uses a directional antenna to emit radio waves into the air. When the radio waves encounter a target, they are reflected back and received by the radar. The distance data of the target is obtained by measuring the time experienced by the radio waves propagating in the air, and the angle data of the target is determined according to the antenna beam pointing [1]. The prominent advantages of radar are its large coverage, long operating range, and strong ability to penetrate haze. The disadvantages are that active detection easily exposes itself, making it susceptible to detection and interference by the enemy, low resolution, and vulnerability to anti-radiation missile attacks.

2. Development analysis of synthetic aperture radar (SAR)

Synthetic aperture radar (SAR) can realistically display the shape, size, motion state, and attitude of targets, breaking through the limitations of the original radar, which could only obtain four-dimensional information of the target's range, azimuth, pitch, and velocity. Airborne SAR is an interdisciplinary field of SAR and precision-guided research. Theoretically, SAR has the ability to perform high-resolution imaging of any area at any time, and it has a long operating range. Its operation is not limited by climatic conditions and solar illumination, and it can penetrate vegetation and surface layers to detect hidden targets [2]. Therefore, the active radar seeker using SAR technology can effectively improve its all-weather and all-time detection capability and accuracy. The application directions of airborne SAR technology are as follows in **Figure 1**.

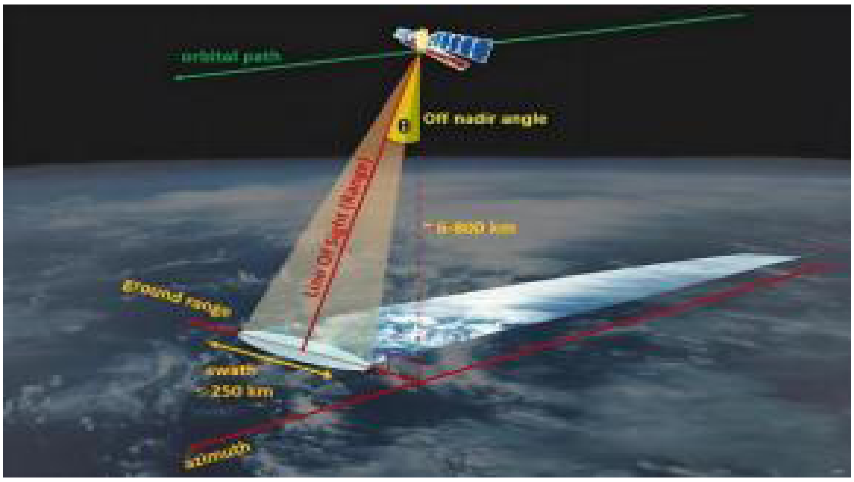

Figure 1. Synthetic aperture radar (SAR).

2.1. Correcting inertial navigation errors

Inertial navigation system (INS) is a self-contained navigation method that has no optical or electrical connection with the outside world. It has good concealment and is not restricted by meteorological conditions. Therefore, it has become a major guidance method widely used in medium- and long-range missiles. Its inherent defects are that the navigation error accumulates with time, and long-term operation will bring large accumulated errors. Using missile-borne SAR for scene matching to correct INS errors is an effective measure to improve guidance accuracy. Real-time images containing typical terrain features are first obtained by the missile-borne SAR and matched with the reference map pre-stored in the electronic map database to obtain the position information of several points in the scene. Then, the missile body position is calculated according to the relative position relationship between the missile and the scene, and the position error of the INS is further corrected. The compensated error can reach the P-code accuracy of GPS. If the data rate is high enough, the velocity error of the INS can also be corrected.

2.2. Striking time-sensitive targets

Improving the capability to engage time-sensitive targets (TSTs) such as mobile missile launchers and mobile air defense guidance radars is an important development direction for precision-guided missiles. For such targets, the method of determining their location and then attacking cannot be adopted. The area where the target may be located must be searched in the mid-course phase of the autonomous guidance, and after the target is acquired and confirmed, the missile transitions to homing guidance for precision strike. The main problems faced are the influence of strong ground clutter on target detection and the accurate identification of the target. Target strikes in **Figure 2** demonstrate.

Figure 2. Time-sensitive target strike.

The adoption of SAR technology improves the resolution in the azimuth direction. The reduction of azimuth resolution units will greatly improve the signal-to-clutter ratio (SCR), thereby increasing the detection probability and high-resolution imaging of the target can effectively improve the recognition probability. For instance, conduct a large-scope imaging in scanning working patterns such as Doppler Beam Sharpening (DBS), and take advantage of the obtained low-resolution image to detect targets [3]. If a target is detected, perform forward squint high-resolution imaging on the destination area to identify whether it is a target of interests, and after confirming, switch to single pulse tracking for exploitation.

2.3. Attack point selection

When there are multiple targets in the range of the terminal guidance radar, the performance of the target recognition and tracking system will be greatly affected if the target cannot be identified effectively and the real target cannot be selected correctly, as the selection of attack point is a difficult technical problem for the seeker. The missile-borne SAR is used to image the formation target group (**Figure 3**). According to the extracted target characteristics and the law of Tactical Formation mode, the selection ability of guidance radar to valuable targets can be effectively improved. The size, shape and other features are extracted from the high-resolution SAR image of the ship target. Combined with the relative position information of the strong scattering points such as the bridge, the key parts of the ship target can be selected.

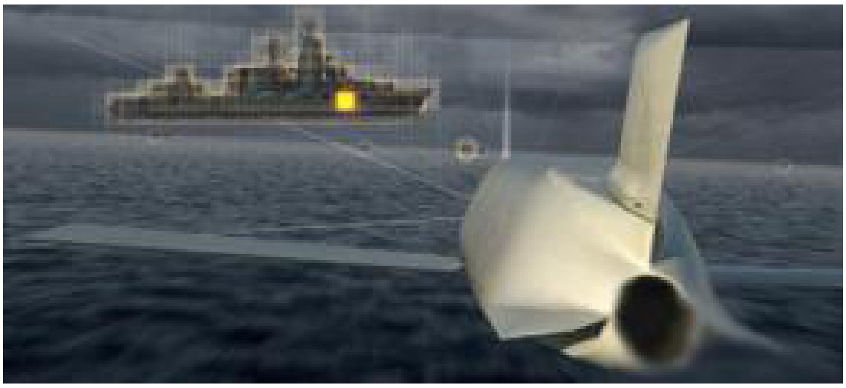

Figure 3. The anti-ship missile chooses the ship's vital position to strike.

2.4. Damage assessment

According to the target image transmitted by the missile through the data link, planners can evaluate the damage of the target, judge the damage effect of the missile on the target, and decide whether to plan the subsequent missile to continue attacking the target, or turn to attack other targets. This instantaneous damage assessment capability reduces the number of missiles needed for a given attack mission. Based on the high-resolution missile-borne SAR image, the geometric shape features and internal structure features of the man-made target are extracted. If the degree of feature change before and after striking reflects the degree of target destruction. The grade evaluation method can be used to evaluate whether the man-made target is destroyed, the degree of destruction and the destroyed part.

3. Development analysis of passive radar detection technology

The passive radar seeker is the key component of the anti-radiation missile (ARM), known as the “Eye” of the ARM, whose main function is to complete the sorting, interception and tracking of the radiation source, its technical performance will directly affect the operational performance of ARM. The passive radar seeker should have a wide frequency band to cover most of the enemy’s radars, and the seeker should have high sensitivity to ensure that the missile can attack the target from both the main lobe and the side lobe of the radar. The seeker must possess high-angle measurement accuracy and angular resolution capability to enable target search, acquisition, tracking, as well as anti-jamming functionalities. The working principle of mono-pulse receiving technology seeker is that the target radiation signal received by the seeker antenna is sent to the signal processing system by the receiver, and the signal is sorted and identified.

Once it is determined as the target signal, the target is intercepted immediately, the angle error signal is extracted, and the error signal is sent to the Torquer of the gimbal after processing, so that the antenna can always point to the target and realize angle tracking. After the angle tracking of the Seeker, the command device in the signal processing system is connected to the autopilot, and the flight control system continuously corrects the route to the target according to the predetermined guidance law.

The early 1960s was the initial stage of the development of passive radar seeker. Due to technological constraints, first-generation ARM seekers featured narrow frequency bands, could only track the main lobe of target radars, and exhibited poor anti-jamming performance. Second-generation ARM seekers employed broader frequency bands with improved receiver sensitivity, enabling engagement of multiple target types. However, their high cost resulted in suboptimal cost-effectiveness ratios, incompatibility with small aircraft, and relatively low launch rates, rendering them inadequate for increasingly complex battlefield electromagnetic environments. Building upon previous generations, third-generation ARM seekers incorporate advanced microwave and signal processing technologies to expand frequency coverage, enhance receiver sensitivity, and strengthen signal processing capabilities [4]. Through composite guidance, they achieve improved autonomous homing and anti-jamming performance, supporting multiple operational modes including self-defense, random, pre-programmed, and known/unknown range engagements.

The representative models of the third generation of direct attack on ARM are the AGM-88(HARM) of the United States (**Figure 4**), the X-31 of Russia, the ARF of France, the ALARM of Britain, the ARMIGER of Germany, etc., another type of patrol ARM is represented by Israel’s “Star-1”, South Africa’s “Lark”, the United States AGM- 136, Germany’s Dar and so on.

Figure 4. Agm-88 anti-radiation missile.

4. Research and analysis on millimeter wave active homing guidance target identification technology

ATR technology is an important indicator of the intelligentization level of precision-guided weapons. Millimeter wave technology is a supporting technology for the development of radar weapon systems towards intelligentization. In the millimeter wave band, the improvement of detection accuracy and the miniaturization of missiles enable millimeter wave precision-guided weapons to strike critical parts of targets. From the perspective of information processing, the difference between millimeter wave radar and microwave radar lies in the different amount of target information provided by the two. In the millimeter wave band, due to the improvement of resolution, the amount of information provided increases by orders of magnitude, making intelligent information processing functions such as target discrimination, target identification, interference discrimination, and target vulnerable area identification more realistic radar functions.

Considerable achievements have been made internationally in the research of millimeter-wave active homing guidance target identification technology and its related fields. However, there are still many challenging problems that need to be solved urgently in its development. These problems can be summarized as follows.

4.1. The identification algorithm is required to have the adaptability to arbitrary attitude angles of the target

Taking missile ground attack as an example, due to the complexity of terrain, the pose of ground vehicle targets relative to the radar seeker is random and cannot be predetermined through prior tracking. Therefore, it is necessary to design algorithms capable of omnidirectional matching and recognition [5]. Currently, the widely adopted approach primarily relies on template matching. While this method can address target feature matching under different pose angles, it requires a substantial number of templates. Reducing feature dimensionality and compressing the template library serve as effective strategies. Furthermore, variations in target features also lead to recognition difficulties, which impose additional modeling burdens for template-based recognition methods and consequently result in decreased recognition rates.

4.2. The recognition algorithm is required to have the adaptability to the clutter background

Given the complex ground background conditions characterized by high false alarm rates and numerous false targets, it is essential to develop flexible and practical algorithms to separate targets from the background and discriminate against background-induced false targets [6]. As noted by Indian scholar Mhamodi *et al.* in their study on millimeter-wave seeker signal processing, when integration time is constrained by real-time requirements, the approach for enhancing weak signal detection in strong ground clutter environments should adopt relaxed false alarm criteria. The high false alarms generated during detection can subsequently be eliminated through target recognition algorithms, which simultaneously increases the difficulty of target identification and underscores its critical importance.

4.3. The target recognition algorithm is required to be realizable

Owing to the fact that the recognition algorithm is loaded on the seeker information processor, the processor is required to have fast processing speed, small data storage space and small hardware structure, therefore, modern advanced digital signal processing technology and parallel processing technology must be adopted.

4.4. The collection, analysis, modeling and simulation of target and background data require a large amount of work and a long development cycle

Due to the diversity of the background environment and the variability of the target attitude, a large target and background echo database is needed to train, test and improve various algorithms of target recognition and evaluate and select the best, many experiments are needed to finalize the algorithm and processor structure.

5. Development of other radar detection methods

5.1. Laser synthetic aperture radar (SAL)

Laser synthetic aperture radar (SAL) combines optical coherence detection technology and synthetic aperture imaging technology, and its weak signal detection ability can reach the order of photons, and the imaging resolution can break through the diffraction aperture limit of the telescope, high-resolution images can be obtained regardless of the detection range. At present, airborne SAL detection imaging experiments have been completed at home and abroad.

5.2. Phased array radar

In phased array radar seekers, the active phased array antenna replaces the traditional radar seeker's antenna, mechanical seeker platform, and transmitter. Fundamental changes have occurred in aspects such as antenna configuration, scanning method, platform stability, and structural dimensions, providing the means for the seeker to achieve new performance capabilities. The phased array radar seeker boasts multiple technical advantages, including high power density, rapid electrical scanning for tracking, multi-target information extraction, space-time adaptive processing (STAP), adaptive anti-jamming capabilities, compact size, and high reliability [7]. It represents the development direction for precision-guided radar seekers and has become a subject of common interest worldwide.

The phased array radar seeker is basically in the active test and development stage, and only a few countries are successful in the research, such as the United States, Russia, Britain, Germany, Japan, etc., in this regard, the United States has been at the forefront of the world.

5.3. Terahertz radar

Ultra-narrow antenna beam can be easily realized in terahertz band. Under the same antenna size, the beam of terahertz wave is much narrower than that of millimeter wave and microwave, which can obtain higher antenna gain and angle tracking accuracy. Compared with microwave radar and infrared detector, the application of terahertz technology to radar will bring many advantages, such as high range resolution, strong penetration, low interception rate and strong anti-jamming ability, it is one of the main application directions of terahertz technology. Throughout the development process and current progress level of terahertz radar system, it is still in the stage of demonstration and demonstration of experimental system.

5.4. Quantum radar

In missile weapon operation, quantum radar can effectively counter active deception jamming and achieve high-resolution anti-stealth detection, which will have a subversive impact on anti-stealth air defense operation. In 2012, the University of Rochester successfully demonstrated the application of quantum information technology to enable radar to effectively detect stealthy targets with deception capabilities [8]. In 2015, the University of York in the United Kingdom developed a dual-cavity converter using a nano-oscillator to realize microwave and optical wave coupling, which can be used as a core device for future quantum radaQuantum Radar (**Figure 5**). In 2017, the 14th Institute of China Electric Power Science and Technology released public information that its quantum radar prototype could already detect targets hundreds of kilometers away. If finalized, it will represent China's leading position in the world in this technology. In the future, quantum radar technology will be applied to various platforms such as missile-borne and airborne.

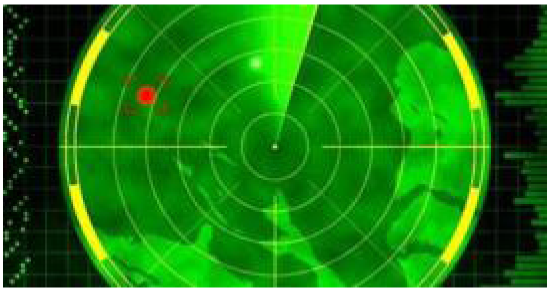

Figure 5. Quantum radar.

6. Conclusion

Radar detection technology has become a pivotal detection means in military, civilian, and scientific research fields, evolving from traditional radio positioning into a multidimensional, high-precision integrated system. Among these advancements, SAR significantly enhances target recognition and guidance accuracy through high-resolution imaging, strengthening all-weather operational capabilities. Passive radar, centered on ARM, utilizes wide-frequency band and high-sensitivity seekers to effectively counter complex electromagnetic environments. Millimeter-wave active homing guidance technology addresses challenges such as target posture adaptability and background interference via high resolution and intelligent algorithms, driving the development of precision guidance toward greater intelligence. Emerging technologies like phased array radar, terahertz radar, and quantum radar further expand capabilities in anti-stealth, anti-jamming, and extreme environment detection. Currently, radar technology still faces challenges in real-time processing, miniaturized integration, and environmental adaptability. Looking ahead, the integration of artificial intelligence and quantum sensing technologies will steer radar systems toward higher precision, stronger anti-jamming capabilities, and multifunctional integration, providing more robust support for both defense and civilian applications.

Disclosure statement

The author declares no conflict of interest.

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