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Igor Garcia-Atutxa

UCAM Catholic University of Murcia
135, Jeronimos Avenue, Murcia, Spain, 30107
E-mail: igarcia839@alu.ucam.edu
<https://orcid.org/0009-0002-1551-2685>

Hodei Calvo-Soraluze

University of the Basque Country
Barrio Sarriena, Basque Country, Spain, 48940
E-mail: hodei.calsor@gmail.com
<https://orcid.org/0000-0003-4966-3078>

Ekaitz Dudagoitia Barrio

University of Murcia
5, Teniente Flomesta Avenue, Murcia, Spain, 30003
E-mail: ekaitz.d.b@um.es
<https://orcid.org/0000-0003-0990-3081>

Francisca Villanueva-Flores*

Centro de Investigación en Ciencia Aplicada y Tecnología Avanzada (CICATA Unidad Morelos), Instituto Politécnico Nacional
1036 Z-1, P 2/2, Technology Boulevard, Atlacholoaya, Morelos, Mexico, 62790
E-mail: fvillanuevaf@ipn.mx
<https://orcid.org/0000-0001-6092-4211>

*(correspondent-author)

The strategic and technological impact of radar in World War II

Abstract. *Radar technology played a pivotal role in shaping the military strategies and operational dynamics of World War II (WWII), revolutionizing both defensive and offensive capabilities. This study provides an in-depth exploration of the evolution of radar, tracing its theoretical underpinnings in electromagnetic science and its subsequent development into critical wartime technology. The paper examines the major advancements that transformed radar from an experimental concept into an*



indispensable military asset, including the British Chain Home system, the German Freya and Würzburg radars, and the American SCR-270 and H2S systems. These innovations redefined air defense, naval warfare, and ground-based operations, granting unprecedented advantages in surveillance, interception, and target acquisition. The study highlights the strategic significance of radar in key WWII battles, such as the Battle of Britain, the Battle of the Atlantic, and the Pacific Theater, where early detection of enemy movements proved decisive. Additionally, the research delves into the technological race between the Axis and Allied powers, emphasizing the role of scientific ingenuity, intelligence-sharing, and industrial production in accelerating radar development. The integration of radar into aircraft, naval fleets, and ground-based anti-aircraft defenses exemplifies how nations leveraged this technology to gain a tactical edge. Beyond WWII, the study explores how radar innovations extended into the post-war era, influencing the development of modern air traffic control, missile defense systems, weather forecasting, and autonomous navigation technologies. The paper underscores the enduring legacy of radar, demonstrating its dual impact as both a wartime breakthrough and a foundation for contemporary applications. By offering a comprehensive historical and technical analysis, this research underscores radar's crucial role in the evolution of military tactics, technological progress, and global security frameworks.

Keywords: *radar development; Second World War; electronic warfare; Chain Home*

Introduction.

Technological advancements have often been accelerated by war, particularly in conflicts such as World War II (WWII), where strategic needs drove progress across various fields, including computing, chemistry, energy, and communications. This paper focuses specifically on radar technology, examining its transformative impact on military strategies and its role in shaping key wartime outcomes. These wartime innovations reflect the urgent need to address immediate military challenges, leading to breakthroughs that would have taken much longer in peacetime. Radar exemplifies how wartime pressures transformed technological potential into strategic advantage, reshaping military tactics and altering the war's course. Its rapid development and deployment reflect the intersection of innovation and necessity in warfare (Brown, 1999; Reed, 2014).

Radar, an acronym for Radio Detection and Ranging, emits electromagnetic pulses reflecting off objects. By measuring the time the reflected signals return, radar systems determine the object's distance and location. Additionally, the Doppler effect detects frequency shifts in the reflected signal, enabling the calculation of an object's velocity. Key factors influencing radar performance include wavelength, signal-to-noise ratio (SNR), antenna design, and polarization. Shorter wavelengths provide higher resolution, while longer wavelengths reduce atmospheric interference. High

SNR ensures accurate detection and advanced antenna designs enhance directionality and beam steering (Jain & Heydari, 2013; Zimmerman, 2013).

This study highlights radar's direct influence on pivotal WWII engagements, such as the Battle of Britain and the Battle of the Atlantic, where early detection systems and naval radars decisively shaped military tactics. By bridging technological advancement with strategic execution, radar not only provided tactical advantages but also influenced the broader trajectory of the war. Early radar systems faced significant challenges, particularly noise interference that limited their precision, necessitating intense research to improve their performance. By the onset of the war, these efforts had revolutionized radar, making it a vital military tool for detecting and tracking enemy aircraft and ships. The British Chain Home (CH) radar network exemplified radar's critical impact on military strategy, providing early warnings of Luftwaffe attacks and enabling precise defensive coordination. Similarly, radar systems used in naval engagements and anti-submarine warfare transformed tactical planning by providing real-time information critical for decision-making (Blanchard & van Genderen, 2014). Post-war innovations, such as those introduced by Woodward in the 1950s (Woodward, 1953), further optimized radar by reducing noise and improving cost-effectiveness, paving the way for broader applications in meteorology, air traffic control, and space exploration. However, its military applications, particularly in defense, remain predominant (Butt & Jalil, 2013).

From Karl Popper's falsificationism perspective, radar's evolution reflects a process of trial and error. Initial limitations were tested and overcome through practical applications, resulting in increasingly effective solutions (Popper, 2002). Today, continued advancements, including the integration of artificial intelligence, further enhance radar's capabilities in defense, aviation, and weather forecasting (Chernyak & Immoreev, 2009).

By focusing on the scientific origins, wartime applications, and lasting influence of radar technology, this article emphasizes its unique contribution to the evolution of modern warfare and technology. It situates radar within a historical, scientific, and strategic analysis framework, distinguishing itself from existing studies by its comprehensive treatment of radar's dual role as both a technological innovation and a strategic tool. The article is structured to provide a comprehensive exploration of the topic: it begins with the historical and scientific contexts that set the stage for radar development, followed by an analysis of early advancements in Germany, the United States, and the United Kingdom. The paper's core focuses on radar's pivotal role during WWII, illustrating its influence on critical battles and strategies. Finally, the discussion extends to modern radar applications, reflecting on how wartime innovation shapes military and civilian technologies. This structure aims to offer a cohesive narrative of radar's evolution and its enduring significance.

Methodology for Historical Literature Review.

Literature Search: A systematic exploration was undertaken on Google Scholar, employing Boolean operators to refine the search query: ("Second World War" OR "World War II") AND ("radar" OR "electronic warfare").

Inclusion and Exclusion Criteria: The search combines primary sources, academic articles, and historical documents on the evolution of radar during WWII and its impact today. Non-academic sources, duplicate publications, and studies that diverged from the research focus were excluded. Studies in English and Spanish were included to capture the historical significance of radar.

Quality Assessment: The credibility and reliability of selected sources were rigorously evaluated, considering the reputation of journals, authors, and the coherence of presented arguments. A critical examination of the literature identified gaps, contradictions, and controversies in the historical narrative of radar's development.

Ethical Considerations: Stringent adherence to copyright laws and meticulous citation practices were employed to ensure ethical handling of the literature, respect for intellectual property rights, and acknowledgment of the origin of all extracted information.

From Electromagnetic Theory to Military Innovation: The Birth of Radar.

Radar's development stems from decades of groundbreaking scientific discoveries and technological innovations. It blends theoretical physics with practical engineering to create a transformative tool of modern warfare.

In 1865, James Clerk Maxwell formulated the foundational electromagnetic theory through eight differential equations, later streamlined to four by Oliver Heaviside in 1884. These equations describe the behavior of electric and magnetic fields and predict the existence of electromagnetic waves, forming the theoretical basis of radar (Maxwell, 1865). Maxwell's work bridged the gap between theoretical physics and practical applications, showing that electromagnetic waves could propagate through space.

In 1887, Heinrich Hertz experimentally confirmed Maxwell's theories by generating and detecting electromagnetic waves. Hertz demonstrated that these waves could reflect off metallic surfaces, a phenomenon that became critical for radar technology (Blumtritt, Petzold, & Aspray, 1994). His work established that electromagnetic waves could be manipulated and harnessed for practical purposes.

Building on Maxwell and Hertz's discoveries, Guglielmo Marconi significantly advanced wireless communication through experiments combining transmitters and receivers in the 1890s. Incorporating an LC resonant circuit for frequency selection in his wireless telegraph marked a crucial technological breakthrough. Around the same time, Alexander Popov also contributed to detecting electromagnetic waves by designing a radio wave receiver in 1895, though his work primarily focused on weather telegraphy rather than long-distance communication (Marconi, 1909). These

innovations demonstrated electromagnetic waves' potential for communication and object detection.

In 1897, Ferdinand Braun's invention of the cathode ray tube revolutionized data visualization, enabling the graphical representation of signals, a key component in radar systems. Meanwhile, in 1904, Christian Hülsmeyer patented the first operational radar system capable of detecting ships up to 3 km away. Contrary to earlier narratives, Hülsmeyer ceased work on his device in the 1910s due to a lack of demand rather than commercialization issues. Telefunken experts at the time dismissed his radio wave detector as impractical, further stalling his progress. The 1920s witnessed incremental progress in radio technologies, including the development of echo systems, radio altimetry, and vacuum tubes. These innovations improved signal generation and detection capabilities, though radar's potential remained limited by frequency constraints and insufficient power. A significant breakthrough came with Albert Hull's 1920 invention of the magnetron, which provided a more robust and stable source of radio waves. Hull's split-anode magnetron generated low-power L-band waves, but its limited stability restricted its practical use. Notably, during the late 1930s, advancements in magnetron technology included the development of the L-band magnetron by Slutskin in Ukraine (then part of the USSR). By 1940, Slutskin's magnetron achieved an output power of 14 kW and served as the power source for the USSR's gun-aiming radar system, Zenit (Kostenko, Nosich, & Tishchenko, 2001). This progress laid the groundwork for the resonant cavity magnetron (RCM), developed by Boot and Randall in the 1940s, which enabled high-frequency, high-power microwave transmissions essential for modern radar (Boot & Randall, 1946; Hull, 1923).

Significant experiments during the 1930s paved the way for radar systems. For instance, Marconi's 1932 microwave transmission between the Vatican and Castel Gandolfo demonstrated the practical use of high-frequency waves for precise communication. In 1937, Hans Erich Hollmann and Rudolf Kühnhold in Germany and Robert Watson-Watt in the United Kingdom (UK) conducted pioneering experiments in radar using advanced magnetron technology (Martin, 1988).

In parallel, the United States, Germany, and the UK accelerated their research into microwave technology, focusing on detecting aircraft and ships. The establishment of the UK's Chain Home system in 1938 marked the first large-scale application of radar technology, setting the stage for its transformative role in WWII.

The foundational discoveries in electromagnetic theory and the subsequent technological advancements of the late 19th and early 20th centuries provided the scientific basis for radar. However, these theoretical principles translated into practical systems during the heightened innovation spurred by military challenges in World War I (WWI) and the interwar period. The following section explores how these early developments were refined and expanded upon, laying the groundwork for radar's pivotal role in shaping the strategies and outcomes of WWII.

Laying the Groundwork: Technological Advancements Leading to Radar in WWII.

During WWI, the introduction of new technologies like poison gas, tanks, and aviation revolutionized military tactics. Initially used for reconnaissance, aircraft evolved into tools for aerial combat and bombing, introducing a new dimension to warfare. Efforts to counter this aerial threat led to the development of acoustic listening devices and primitive detection systems that laid the foundation for more advanced technologies like radar (Brown, 1999).

The interwar period saw rising political tensions and accelerated technological innovation, particularly in military research. The Treaty of Versailles (1919), which imposed severe restrictions on Germany's military capabilities, indirectly influenced the development of radar by encouraging covert technological research, including advancements in electromagnetic waves for object detection. Lessons from WWI highlighted the importance of early detection, prompting nations like Britain, Germany, and the United States to explore electromagnetic waves for detecting distant objects. By the late 1930s, the UK established the Chain Home system, the world's first operational radar network to detect and intercept incoming aircraft. Contrary to earlier descriptions, the Chain Home network operated at a wavelength of 26 meters when it first became operational in 1938, later shifting to 10 meters. The Chain Home Low system used a wavelength of 1.5 meters. Both systems could detect groups of a dozen or more aircraft, providing azimuth and range data, but could not determine elevation (Beavor, 2012; Buderer, 1996).

By the 1930s, radar research had intensified globally, leading to advancements in directionality with parabolic antennas, interference reduction through polarization and frequency filters, and enhanced detection capabilities (Shiers, 1974). These innovations laid the groundwork for radar's pivotal role in WWII, where it became a cornerstone of military strategy. Radar allowed for precise tracking of enemy aircraft, contributing decisively to battles such as the Battle of Britain, where the Chain Home system played a central role. However, the limitations of early radar systems, such as poor resolution in azimuth and the inability to detect elevation, spurred efforts to develop shorter-wavelength technologies, ultimately improving detection precision and reliability (Goss, Hooker, & Ekers, 2023).

As the war progressed, radar countermeasures emerged as a critical area of innovation. Techniques such as "Chaff" (called "Window" in the UK and "Düppel" in Germany) were developed to disrupt enemy radar systems while jamming technology was used to block radar signals (Blake, Philpott, & Guthrie, 1943; Putley, 1986). These countermeasures underscored the dynamic interplay between radar advancement and the ongoing need to neutralize enemy systems, illustrating the constant evolution of electronic warfare strategies (Pun, 2021).

Early Radar Development in Germany, the UK, and the USA.

Germany's Strategic Shift Toward Radar.

Following WWI, Germany prioritized offensive military strategies centered on aircraft, submarines, and tanks, enhancing radio communications to enable rapid, coordinated maneuvers. Initially, radar was viewed solely as a defensive measure to protect coastal regions like the North Sea, and its development was deprioritized (Brown, 1999). However, this perspective shifted in 1933 with the establishment of the Experimental Station for Communication by Telefunken. By 1934, Hans Kühnhold founded GEMA (Gesellschaft für Elektroakustische und Mechanische Apparate) in collaboration with Telefunken and Siemens, marking the beginning of concerted radar research efforts (Buderi, 1996).

In the mid-1930s, GEMA initiated experiments in the microwave spectrum, culminating in the development of the Freya radar in 1937. Initially designed for maritime detection, Freya was adapted for air defense and was first operationally deployed during the Sudeten Crisis in 1938. By 1939, Freya entered mass production, with 2,000 units serving as early warning systems. Germany's strategic advantage in radar stemmed from its early adoption of shorter wavelengths, such as the 2.4 m used by Freya, 0.8 m in Seetakt, and 50 cm in Würzburg systems. These innovations provided higher resolution and detection precision than the longer wavelengths used by other nations (Brown, 1999).

Germany further expanded its radar capabilities with systems like Wassermann and Mammut, which extended detection ranges, and Würzburg and Lichtenstein, designed for anti-aircraft artillery and night combat (Watson, 2009). Integrating Freya and Würzburg radars became the foundation of the Kammhuber Line, an innovative air defense system stretching across Europe. Initially, the line relied on Freya radars for long-range early warning and manually controlled searchlights for bomber illumination. Over time, Würzburg radars were incorporated to provide precise tracking and guidance for night fighters. This layered approach represented a tactical shift in German air defense, with the Kammhuber Line evolving into a coordinated network capable of targeting Allied bombers effectively.

Introducing radar systems on night fighters, such as the Lichtenstein radar, further revolutionized German tactics. These radars enabled pilots to independently detect and engage Allied bombers without relying on ground control or searchlights. This autonomy marked a significant shift in air defense strategy. The Naxos radar warning receiver also allowed German fighters to home in on H2S emissions from Allied bombers. However, its effectiveness diminished as the Allies introduced X-band radars capable of greater precision and stealth (Pun, 2021).

Despite these advancements, the Allies' deployment of shorter-wavelength S-band and X-band radars in 1943 diminished the effectiveness of German systems, marking a turning point in radar warfare. Additionally, introducing Naxos, a radar warning receiver, allowed German night fighters to home in on Allied H2S radar emissions. However, the Allies' shift to X-band radars, capable of detecting periscopes

at distances up to 5 miles, rendered Naxos largely ineffective, further undermining Germany's radar capabilities (Pun, 2021).

However, despite these early advancements, Germany fell behind in developing shorter-wavelength technologies, such as the S-band (10 cm) and X-band (3 cm) radars enabled by the British cavity magnetron breakthrough in 1940. By 1943, these shorter-wavelength radars were deployed extensively across Allied forces, providing a decisive technological edge, particularly in anti-submarine warfare and aerial detection (Pun, 2021). Table 1 highlights the technical specifications and applications of these and other radar systems, showcasing their pivotal role in Germany's military strategy during WWII.

The UK's Defensive Focus and Radar Innovations.

In contrast to Germany's offensive strategies, the United Kingdom (UK) pursued a defensive approach, relying on its intelligence services and naval dominance to counter emerging threats. The rise of Hitler and the growing threat of aerial bombardment underscored the need for technological advancements, particularly radar, to safeguard the British Isles (Watson-Watt, 1957).

Despite initial skepticism from the Royal Air Force (RAF), radar emerged as the cornerstone of Britain's defense strategy. Early experiments in the 1920s, such as attempts to develop a "death ray," were abandoned due to limited efficacy. By 1935, Robert Watson-Watt had pioneered the Chain Home (CH) system, the world's first operational radar network. CH stations along Britain's east coast became operational in 1938, capable of detecting aircraft at altitudes of 150 meters and distances of up to 40 km. This system provided early warnings of incoming Luftwaffe attacks, and challenges like multiple detections were resolved with Filter Rooms, enabling efficient differentiation between friendly and enemy aircraft (Buderi, 1996). By 1940, complementary systems like Chain Home Low (CHL) enhanced low-altitude detection capabilities, proving vital during the Battle of Britain (Blanchard & van Genderen, 2014). Radar's role in the sinking of the Bismarck underscores these technological advances. While radar was not the primary means of locating the German battleship, British ship-based radar contributed to tracking its movements. The critical discovery of Bismarck's location resulted primarily from Enigma codebreaking and reconnaissance efforts, including visual spotting by a Catalina aircraft (Watson, 2009).

The UK's collaboration with the United States and Canada through the Tizard Mission in 1940 accelerated radar advancements. The mission introduced critical technologies, including the RCM, which improved radar accuracy and power. Innovations such as the air-to-surface-vessel (ASV) radar further extended radar's applications, particularly in anti-submarine warfare (Berkner, 1946).

The United States Accelerated Radar Development.

Before entering WWII, the United States lagged behind Germany and the UK in radar development due to its lack of immediate offensive or defensive pressures.

However, institutions like the Massachusetts Institute of Technology (MIT) and the Naval Research Laboratory (NRL) laid the groundwork for radar innovation in the 1920s and 1930s. Early systems, including the SCR-268 and SCR-270, demonstrated the potential of radar for early warning and target tracking (Colton, 1945). The attack on Pearl Harbor in December 1941 catalyzed rapid advancements in U.S. radar technology. In 1941, the Airborne radar was still nascent, and the Royal Air Force's first operational airborne radars, like the AI Mark II, lacked microwave capabilities. Subsequent advances, such as the SCR-584 for anti-aircraft targeting and the 10-cm wavelength H2S radar introduced later in the war, demonstrated radar's transformative potential in strategic and tactical operations (Watson, 2009). The SCR-270, which detected the incoming attack but failed due to a lack of response protocols, underscored the need to integrate radar into military strategy effectively.

Radar's influence extended beyond defense, significantly shaping offensive strategies. For example, the RAF's adoption of H2S ground-scanning radars on bombers like the Stirlings and Lancasters enabled precise night raids on German cities, complementing the USAF's daylight bombings. American aircraft, such as the Liberators and Flying Fortresses, initially relied on superior optical aiming systems but later incorporated radar technologies to enhance accuracy. This strategic division of labor, with the RAF targeting at night and the USAF focusing on daytime operations, showcased radar's critical role in coordinating Allied bombing campaigns and maximizing their impact on German targets (Gregory, 2011).

A critical innovation during this period was the introduction of proximity fuses in anti-aircraft artillery. Developed using Doppler radar principles in the UK and refined in the United States after 1940, these fuses automatically detonated shells within a certain distance of their targets. Combined with systems like the SCR-584, they drastically improved the efficiency of anti-aircraft defense, enabling effective countermeasures against fast-moving targets such as V-1 cruise missiles, especially in the defense of London and Antwerp (Goss, Hooker, & Ekers, 2023).

Subsequent developments, such as the CXAM radar for fleet defense and the SCR-584 for anti-aircraft targeting, showcased the United States' ability to leverage its industrial and scientific capacity. The invention of the klystron in 1937 enabled compact radar systems for airborne applications, further advancing U.S. capabilities. As detailed in Table 1, these systems positioned the United States as a radar technology leader by the war's end.

The Strategic Impact of Radar in Key WWII Battles.

Radar's transformative impact on WWII cannot be overstated. Its applications spanned early detection, air interception, ground control, and naval operations, fundamentally reshaping military strategies.

Table 1. Characteristics of the primary radars of WWII.

Radar's name	Country	Year	λ	Power	Range	Type	Use
<i>Freya</i>	Germany	1937	2.4 m	8 kW	130 km	Ground	Early warning of air attacks
<i>Wassermann</i>	Germany	1940	2.4 m	100 kW	300 km	Ground	Early warning of air attacks
<i>Mammut</i>	Germany	1942	2.4 m	200 kW	300 km	Ground	Early warning of air attacks
<i>Seetakt</i>	Germany	1938	0.82 m	8 kW	20 km	Maritime	Detection of ships and aircraft
<i>Würzburg C</i>	Germany	1940	0.53 m	8 kW	25 km	Ground	Anti-aircraft artillery fire control
<i>Lichtenstein C</i>	Germany	1942	0.61 m	1,5 kW	5 km	Air	Detection of ships and aircraft
<i>SCR-268</i>	USA	1940	1.5 m	75 kW	45 km	Ground	Early warning of air attacks
<i>SCR-270</i>	USA	1940	3 m	100 kW	160 km	Ground	Early warning of air attacks
<i>CXAM</i>	USA	1937	1.5 m	5 kW	80 km	Maritime	Detection of ships and aircraft
<i>SCR-584</i>	USA	1943	0.1 m	250 kW	45 km	Ground	Anti-aircraft artillery fire control
<i>Chain Home</i>	UK	1938	10 m	350 kW	300 km	Ground	Early warning of air attacks
<i>Chain Home Low</i>	UK	1939	1.5 m	150 kW	40 km	Ground	Early warning of air attacks
<i>ASV-Mark II</i>	UK	1940	1.7 m	7 kW	58 km	Air	Detection of ships and aircraft
<i>AI Mark IV</i>	UK	1940	1.5 m	10 kW	6,1 km	Air	Detection of ships and aircraft

The Battle of Britain: Radar as the Cornerstone of Air Defense.

The Chain Home (CH) system played a pivotal role during the Battle of Britain, marking the first large-scale integration of radar into air defense. This network of early warning radar stations provided continuous tracking of incoming Luftwaffe aircraft,

enabling the Royal Air Force (RAF) to allocate limited fighter resources efficiently. CH radar primarily offered early warnings of large formations of German bombers, allowing Fighter Command to concentrate scarce fighter squadrons on the most threatened directions while leaving less threatened areas uncovered. Though initially straightforward, this revolutionary tactical approach depended on effectively integrating radar data into centralized decision-making. CH radar data allowed the RAF to intercept German bombers before they reached critical targets, preventing widespread destruction. Despite German reconnaissance detecting CH signals in May 1940, the Luftwaffe underestimated its importance, leading to critical miscalculations. Rather than systematically targeting radar stations, German forces focused on bombing urban areas, missing an opportunity to disable the system early in the campaign. This oversight kept the CH network operational, providing the RAF with crucial situational awareness throughout the battle. Complementary systems like the AI Mark IV radar proved decisive in night combat, enabling effective interception of bombers during low-visibility conditions. Combined with CH system intelligence, these technologies allowed Britain to resist the Luftwaffe's offensive, marking a turning point in the war and demonstrating the strategic interplay between radar technology and military operations (Brown, 1999; Watson-Watt, 1957).

Naval Warfare: The Battle of the Atlantic and the Mediterranean.

In the Battle of the Atlantic, radar systems like the ASV Mark II initially struggled against German U-boats operating at periscope depth. However, introducing shorter-wavelength radars in 1943, such as the British RCM, significantly enhanced submarine detection capabilities, transforming the strategic landscape. Aircraft with improved ASV radars effectively neutralized U-boat threats, demonstrating radar's pivotal role in Allied naval operations. While radar contributed to tracking the German battleship Bismarck, its discovery in 1941 was primarily due to intercepted and decoded Enigma communications. Ship-based radar played a secondary role in maintaining situational awareness during the hunt, but a Catalina aircraft achieved the final sighting through visual reconnaissance (Buderer, 1996; Watson, 2009). In 1941, Sunderland flying boats equipped with longer-wavelength radars (1.7 m and 1.5 m) combined with powerful searchlights effectively disrupted U-boat traffic in the Bay of Biscay, a critical route for German submarines. In response, the Germans introduced the Metox radar warning receiver. However, the advent of S-band (10 cm) radars in 1943 rendered this technology obsolete, tipping the balance in the Allies' favor (Goss, Hooker, & Ekers, 2023). British radar systems, including Type 279 and ASV radars, were instrumental in protecting supply routes and supporting naval operations in the Mediterranean. Meanwhile, German deployments of Freya and Würzburg radars in North Africa strengthened anti-aircraft defenses, although Allied advancements eventually surpassed these systems. During the Battle of Cape Matapan in March 1941, radar's primary role was in assisting accurate gun aiming during the British night attack on Italian cruisers. Intelligence from decrypted Italian naval codes by Bletchley Park

cryptanalysts, including Mavis Lilian Batey, determined the timing and course of the Italian fleet, enabling the ambush. Radar-blind Italian warships were unprepared for the radar-guided attack by British forces, which inflicted significant losses on the Regia Marina (Blumtritt, Petzold, & Aspray, 1994).

The Eastern and Pacific Fronts: Diverging Strategies.

On the Eastern Front, Germany's use of radar evolved as the Soviets gained strength. Freya and Würzburg radars were instrumental in providing early warnings and coordinating anti-aircraft artillery during nocturnal Soviet bombing raids, enabling effective defense of critical areas such as Ploesti's oil fields. These systems were vital in limiting Soviet air superiority, particularly during critical engagements where German radar-guided defenses inflicted heavy bomber losses (Blumtritt, Petzold, & Aspray, 1994). In contrast, the Soviets, facing technological gaps, depended heavily on imported Allied radars like the SCR-584 and GL Mark III, which bolstered their ability to detect and respond to German air strikes, especially in defending Moscow and Leningrad. These Allied systems provided much-needed situational awareness and improved the Soviet military's coordination during critical offensives.

In the Pacific, radar underscored stark contrasts between U.S. and Japanese capabilities. By 1939, U.S. CXAM radars, deployed on aircraft carriers, provided fleet protection and critical early warning against air and naval threats. The CXAM radar's effectiveness was exemplified during the defense of U.S. fleets in the Solomon Islands campaign, where early detection allowed timely countermeasures against Japanese assaults. Japan, by contrast, initially lacked operational radar, relying on inadequate magnetron systems with limited range and power. Although radar was not decisive in battles like Midway, the SCR-270 radar played a crucial role in detecting incoming Japanese aircraft during the Pearl Harbor attack, highlighting the strategic potential of radar technology even under limited protocols. As the war progressed, U.S. radar systems, including the air-to-surface-vessel (ASV) radar, proved critical in isolating Japan by enabling effective submarine attacks on Japanese merchant and military fleets, ultimately contributing to the Allied blockade strategy (Wilkinson, 1946).

Current Radar Applications.

After WWII, radar began to be used in civilian applications. This usage has continuously evolved to the present day. Below are the most important current applications of radar.

Ground-based interferometric radar is widely used for monitoring civil infrastructure, such as bridges, dams, and buildings. This type of radar can detect deformations and structural movements with precision over time, providing critical data for preventive maintenance and safety. The radar's ability to offer continuous, non-contact measurements allows for early identification of structural failures, preventing them from becoming severe hazards. Recent advancements in machine learning algorithms have improved the efficiency and accuracy of data analysis, making

monitoring more effective and proactive (Elshaboury, Mohammed Abdelkader, Al-Sakkaf, & Zayed, 2023).

In medicine, radar technology is increasingly used to monitor vital signs and detect diseases. This method enables continuous, contactless heart sound monitoring, facilitating early detection of cardiovascular diseases and reducing patient discomfort. Studies have shown high accuracy in classifying heart sounds using radar, indicating significant clinical potential. Additionally, radar measures vital signs such as respiratory and heart rates in hospitals and homes, providing a non-invasive and comfortable solution for continuous monitoring (Schellenberger et al., 2020).

Radar is essential in detection and ranging systems for autonomous vehicles. It is used to detect objects and measure distances with high precision, which is critical for safe navigation and collision prevention. Unlike other sensors, such as cameras, radar is less affected by adverse weather conditions, making it indispensable in all environments. Studies highlight the combination of radar with other sensors, such as LIDAR and cameras, to enhance the accuracy and reliability of perception systems in autonomous vehicles. This multimodal integration enables a more robust and precise understanding of the surroundings, improving the vehicles' ability to navigate safely and efficiently in complex environments (Liu, Cai, Wang, & Chen, 2021).

Earth observation through radar satellites is essential for environmental monitoring. This technology is used for land-use mapping, detecting environmental changes, and monitoring natural disasters. Radar data is crucial for natural resource management and emergency response, particularly where atmospheric conditions hinder optical observation. The fusion of optical and radar data improves the accuracy and usefulness of information for environmental applications, facilitating better disaster management and ecosystem conservation (Brisco, Mahdianpari, & Mohammadimanesh, 2020).

Conclusions.

The conclusions of this research demonstrate that the development and implementation of radar during WWII played a crucial role in shaping military strategies and outcomes, providing the Allied forces with a decisive technological advantage. Radar's impact extended across multiple theaters, from early detection systems in the Battle of Britain to its transformative role in strategic operations, such as tracking enemy fleets and enabling precise coordination during night battles. This research confirms that radar not only enhanced defensive capabilities but also influenced the offensive strategies of the Allies, shifting the balance of power through technological superiority.

The study's objectives were achieved through a comprehensive analysis of radar's evolution, highlighting its role in accelerating technological advancements in electronics and communication. Key breakthroughs, such as introducing shorter-wavelength S-band and X-band radars, proved instrumental in anti-submarine warfare and aerial detection, ultimately tipping the balance in favor of the Allied forces.

Moreover, the research underscores the lasting significance of radar, not only in WWII but also in its continued influence on modern military and civilian applications, such as weather forecasting, air traffic control, and autonomous vehicle technologies.

The findings confirm that radar development during the war marked a turning point in military history and technological progress. They illustrate the profound interplay between innovation and strategy in shaping the outcomes of WWII. This research further emphasizes the importance of multidisciplinary advancements and international collaboration in driving technological innovation during times of crisis.

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Conflict of interest.

The authors declare no conflict of interest.

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Ігор Гарсія-Атуча

Католицький університет Мурсії, Королівство Іспанія

Ходей Кальво-Соралузе

Університет Країни Басків, Королівство Іспанія

Екайтц Дудагойтія Барріо

Університет Мурсії, Королівство Іспанія

Франсіска Вільянуева-Флорес*

Центр досліджень у галузі прикладної науки та передових технологій, Національний політехнічний інститут, Мексика

Стратегічний та технологічний вплив радару під час Другої світової війни

***Анотація.** Радарна технологія відіграла вирішальну роль у формуванні військових стратегій та операційної динаміки під час Другої світової війни, революціонізуючи як оборонні, так і наступальні можливості. Ця стаття надає глибоке дослідження еволюції радару, прослідковуючи його теоретичні основи в електромагнітній науці та його подальший розвиток у критичну технологію для військових потреб. У статті розглядаються основні досягнення, що*

трансформували радар з експериментальної концепції в незамінний військовий ресурс, зокрема британська система Chain Home, німецькі радари Freya та Würzburg, а також американські системи SCR-270 та H2S. Ці інновації переосмислили повітряну оборону, морську війну та наземні операції, надавши безпрецедентні переваги в спостереженні, перехопленні та захопленні цілей. Дослідження підкреслює стратегічне значення радару в ключових битвах Другої світової війни, таких як Битва за Британію, Битва в Атлантиці та Тихоокеанський театр, де своєчасне виявлення рухів ворога виявилось вирішальним. Крім того, дослідження занурюється в технологічну гонку між воюючими сторонами, підкреслюючи роль наукової винахідливості, обміну розвідданими та промислового виробництва у прискоренні розвитку радарів. Інтеграція радару в авіацію, військово-морські флотилії та наземну протиповітряну оборону є прикладом того, як нації використовували цю технологію для здобуття тактичної переваги. Поза Другою світовою війною дослідження також розглядає, як інновації в радарних технологіях перейшли в післявоєнну еру, впливаючи на розвиток сучасних систем управління повітряним рухом, протиракетних систем, прогнозування погоди та автономних навігаційних технологій. У статті підкреслюється незмінна спадщина радару, демонструючи його подвійний вплив як прориву воєнного часу та основи для сучасних застосувань. Завдяки комплексному історичному та технічному аналізу це дослідження підкреслює важливу роль радару в еволюції військової тактики, технологічного прогресу та глобальних систем безпеки.

Ключові слова: розвиток радару; Друга світова війна; електронна боротьба; Chain Home

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