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A HISTORY OF U.S. NAVY AIRBORNE AND SHIPBOARD PERISCOPE DETECTION RADAR DESIGN AND DEVELOPMENT

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This paper traces the history of the design and development of periscope detection radar (PDR) from the humble origins of radar in World War II to the near present. During the Battle of the Atlantic in WWII, newly developed airborne and shipboard anti-submarine warfare radars, incapable of detecting small targets such as exposed periscopes, were used primarily for detecting surfaced German U-boats. Since then, PDR sensors have evolved substantially, primarily due to notable changes in the threat, missions, requirements, measures, countermeasures, environment, and advances in technology. Owing to a lack of formal requirements, radar detection and classification of exposed periscopes of Soviet nuclear submarines, operating primarily in open-ocean waters, remained a manual, operator-intensive process throughout the Cold War. Today, however, it is necessary to detect relatively frequent, but fleeting, periscope exposures of acoustically quiet diesel-electric submarines against a background of numerous target-like objects in high-clutter littoral environments. Fortunately, state-of-the-art signal processing technology developed under a recent U.S. Office of Naval Research-sponsored program has transformed a labor-intensive, false-alarm-ridden endeavor into a system for automatic radar periscope detection and discrimination, for both airborne and shipboard applications.

I. INTRODUCTION

From the humble beginnings of using radar to detect surfaced German U-boats during the Battle of the Atlantic in World War II to today's state-of-the-art airborne and shipboard anti-submarine warfare (ASW) radar surveillance applications, periscope detection radar (PDR) has played a vital role in achieving and maintaining U.S. Navy ASW superiority through the years. The purpose of this paper is to document and preserve the rich and proud history of the design and development of such PDR sensors.

Radar sensors used for military applications were originally large ground-based units designed, developed, and employed by the British for detecting inbound German aircraft during the Battle of Britain early in WWII. As early as 1940, British radars were also designed compact enough to fit into combat aircraft, as well as mast-mounted on ships, for detecting surfaced German U-boats. However, none of these WWII radars had the appropriate design and performance characteristics to detect small radar cross-section (RCS) targets such as exposed periscopes. It was not until the early 1970s that the first U.S. Navy tactical radar designed specifically for periscope detection, the AN/APS-116 radar on S-3A ASW aircraft, arrived on the scene. Furthermore, it was not until the early 1990s that the U.S. Navy established a formal requirement for automatic periscope detection and classification and subsequently initiated the technology development for detecting and classifying periscope targets automatically. Until recently, all fleet operational PDR sensors still required a skilled and alert human operator to perform their detection function. However, the Office of Naval Research (ONR)-sponsored technology developments, during the 1990s, to automate the target detection and classification process, even for challenging high-clutter littoral operational environments, are anticipated to yield significant improvements in PDR operational capability.

Over the years, the research, development, test, and evaluation (RDT&E) and the operational employment of PDR sensors has involved a rich and proud history of military endeavor. This history is embodied in the knowledge base, technical expertise, innovations, and accomplishments of a cadre of highly talented and dedicated scientists, engineers, managers, program sponsors, and warfighters within the U.S. Navy and industry. Unfortunately, as the years pass and these technical experts continue to retire from the military and civilian workforce, their knowledge base, their memory, and the lessons learned become lost to subsequent generations. Therefore, this paper is intended to capture and preserve the proud history and technical challenges and accomplishments of these dedicated men and women who designed and developed the Navy's state-of-the-art PDR sensors.

Specifically, this paper documents historical highlights and progress in the requirements, design, development, technical issues, and performance implications of PDR sensors from their WWII beginnings, through the Cold War, and into the early years of the 21st century. Specific emphasis is placed on performance enhancement and technical design issues for late-Cold War and post-Cold War PDR sensor developments. The focus is limited to PDR sensors used for U.S. Navy ASW applications (specifically for detecting submarine periscope and mast hard targets) and does not include those related to Submarine Security Program (SSP) investigations into nonacoustic phenomenology and target detectability. However, it should be noted that the SSP investigations have made extensive contributions to the U.S. Navy's understanding of the physics of nonacoustic ASW detection techniques, which in turn provided excellent technical background information to develop design guidelines for such ASW sensors. Both airborne PDR sensors used for ASW surface surveillance and shipboard PDR sensors used for surface ship torpedo defense are addressed. Emphasis is placed on those PDR sensors that have been operationally deployed in the fleet, i.e., that have reached Initial Operational Capability. Also included are promising developmental PDRs that have matured to the Category 6.3 Program Element phase of Advanced Development or beyond and are considered to be promising transition products by ONR.

There exists a rich history of relevant research conducted by U.S. Navy laboratories, e.g., by the Naval Research Laboratory (NRL); by academia, e.g., by the Georgia Tech Research Institute (GTRI); and by industry, e.g., by Raytheon TI Systems that provided the foundation for the subsequent design and development of PDR sensors. Although beyond the scope of this paper, these PDR research efforts, along with the PDR sensor design and development history, are addressed and summarized in a separate ONR-sponsored unclassified document currently in preparation.[1] A separate ONR-sponsored classified document that addresses the operational performance history of airborne PDR sensors has been recently completed.

II. REQUIREMENT AND TECHNOLOGY DRIVERS

This section paints the strategic landscape and identifies those key historical change drivers, including requirement drivers and technology drivers, which have had a notable impact on shaping the design and development of ASW and PDR sensors since their inception in WWII.

Requirement Drivers

As with most military systems, the primary forcing functions that shaped PDR design and technology developments through the years were the operational requirements generated by the fleet, particularly during wartime. That is, the most significant advancements in PDR technologies have been those driven by operational necessity (requirements pull) rather than by technology opportunities (technology push).

Although early radar technology was originally investigated for potential military applications by the British during the mid-1930s, it was the exigencies of war with Germany starting in September 1939 that drove the British to develop radar for various air, sea, and land-based military applications. Without radar, the British would not have prevailed during the Battle of Britain in the fall of 1940, during the Allied strategic bombing campaign of Germany, and during the Battle of the Atlantic against the German diesel-electric U-boat threat.

During the Battle of the Atlantic, the German U-boat, which aggressively attacked the Allied supply convoys from North America, was a major threat to Britain's survival. Until mid-1943, the majority of U-boat attacks against Allied shipping were performed at night, mostly while the submarines were operating on the surface. Thus, until that time, the primary requirement for airborne surveillance radars at sea was to detect German surface ships and surfaced U-boats, not exposed submarine periscopes and masts. It was fortunate that radar technology, which was still in its infancy throughout WWII, was not required for the detection of submarine periscopes and masts until late in the war, when the introduction of the snorkel allowed U-boats to remain submerged for a much greater percentage of the time.

The launch of the first nuclear powered submarine, the *USS Nautilus*, in 1954 was the harbinger of a major paradigm shift in submarine warfare, as well as in ASW. The shift from diesel-electric submarines to nuclear powered submarines eliminated the need to snorkel and, thereby, reduced the ASW opportunities to detect the enemy's submarines.

During the Cold War (circa 1948-1989), the Soviet Union developed a blue water Navy, spearheaded by a vast submarine fleet consisting of more than 300 submarines, including nuclear guided-missile-firing submarines (SSGNs), nuclear attack submarines (SSNs), nuclear ballistic missile submarines (SSBNs), as well as conventional diesel-electric attack submarines (SSKs). The primary mission of the Soviet SSGNs, and to some extent their SSNs, was anti-surface warfare (ASUW) consisting of interdiction of U.S. sea lines of communication and, most importantly, countering the potent American aircraft carrier battle group. Among others, the Soviet Echo II-class SSGNs were first deployed in 1962 and Charlie-class SSGNs in 1969.[2] The U.S. Navy's counter to this formidable SSGN threat was a sea-based air-ASW capability provided by ASW helicopters equipped with dipping sonar to protect the carrier's inner zone, and S-3 fixed-wing aircraft equipped with sonobuoys and modern ASW radar to cover the middle zone.

The early Soviet SSGNs had to be surfaced to fire their anti-ship cruise missiles. Therefore, a good surface surveillance radar was adequate for detecting this attack. However, later in the Cold War, the newer Soviet SSGNs could fire their cruise missiles while submerged, thereby minimizing their vulnerability to airborne surveillance radar since they had to expose their periscopes and masts for only relatively short periods for communications and stand-off targeting. This change in the Soviet submarine's operating profile forced a fundamental change in the operational requirements of U.S. airborne ASW radars. Specifically, in 1974 the U.S. Navy introduced the S-3A carrier-based ASW aircraft with the AN/APS-116 state-of-the-art surface surveillance radar, which was designed particularly for reliable detection of fleeting exposed submarine periscopes and masts.

During the Cold War, ASW consisted primarily of open-ocean operations using mostly passive acoustic sensor systems that were deemed more than adequate. Therefore, radar detection of periscopes was not a priority, and there was minimal PDR system development during much of this period. Furthermore, in open ocean operations there was little concern about clutter from man-made objects. Therefore, interpretation of fairly raw radar data by human operators was deemed adequate.

The Cold War necessitated changes in United States ASW policy and the formulation of requirements documents. A formalized requirements-generation process evolved through which fleet operational requirements were forwarded to the Pentagon and translated into technical procurement requirements.[2] To this day, fleet operators typically provide their inputs on ASW requirements to fleet commanders who, in turn, forward these requirements to the Office of the Chief of Naval Operations (OPNAV). In turn, OPNAV reviews, approves, and formalizes general and specific operational requirements and coordinates their translation into procurement requirements addressed to the acquisition community.[2]

It is of interest to note the relative differences in the research and development (R&D) horizons between the fleet and the R&D community as they pertain to defining operational requirements and the time expectations for achieving the corresponding R&D solutions. In general, the fleet tends to be primarily concerned with maximizing near-term readiness, defining requirements for solving the problems of today. In contrast, the R&D community addresses not only near-term readiness, but also is more concerned with far-term readiness, i.e., addressing the R&D necessary for solving the problems of tomorrow.

During the 1990s, ASW operational emphasis shifted: (1) from Cold War Soviet nuclear submarines operating primarily in blue waters, to enemy non-nuclear diesel-electric attack submarines (SSKs) operating primarily in relatively shallow, acoustically noisy, cluttered, littoral waters, and (2) from countering relatively noisy Soviet submarines with passive acoustic ASW sensors, to countering the acoustically quiet littoral SSK threat with nonacoustic and active acoustic sensors.

The primary role of the enemy SSK is to deny freedom of the seas, in particular, to deny access by U.S. forces in selected littoral areas of interest. Their primary mission is ASUW against U.S. forces. However, they have also been known to undertake such missions as inserting special operational forces, smuggling contraband, and supporting state-sponsored terrorism. When operating submerged on their batteries, SSKs are extremely quiet. Because many of these submarines originate in Russia or Western countries, they may have high-end sensor and weapon system capabilities. Some of them also have air-independent propulsion that substantially extends their underwater endurance from a few days to a few weeks.

Nevertheless, the SSK must frequently operate at periscope depth to execute its mission. It must expose a periscope and/or mast to communicate and to recharge its batteries. Also, most of them must expose their periscopes to perform ASUW approach and attack effectively. The modern SSK operating in littoral waters is considered to be an extremely formidable threat, much more difficult to detect acoustically than former Soviet nuclear submarines. However, in the performance of its missions, the SSK frequently operates near the surface and exposes its periscope and masts, which can be detected by airborne and shipboard PDR.

A summary of the historical evolution of the threat submarine, its operating profile while attacking, and the airborne radar deployed to counter the threat is provided in Table 1.

Table 1 – Historical Evolution of ASW Target and Airborne ASW Radar

Era Item	1940 – 43		1944 – 45	1950s & 1960s	1970s & 1980s	1990s →
Predominant ASUW Submarine Threat	German U-boat		German U-boat	Soviet SSGN	Soviet SSGN	Threat SSK
Predominant Operating Posture of ASUW Threat Submarine When Attacking	Attacking and recharging batteries on surface at night 		Attacking at PD with torpedoes and using snorkel to recharge batteries 	On surface to fire ASUW cruise missiles 	At shallow depths to fire sub-surface ASUW cruise missiles 	Attacking at PD with torpedoes 
Predominant Operating Environment	Open ocean		Littoral	Open ocean (with little/no clutter)	Open ocean (with little/no clutter)	Littoral (with high clutter)
Primary USN ASW Radar (Fixed Wing A/C)	1940 – 42 ASV-1, -2 (UK)	1943 ASV-3 (UK) APS-2 (US)	APS-2	APS-20 APS-80 APS-115	APS-116 APS-137	APS-137 ARPDD (under development)
Radar Frequency Band	214 MHz, 176 MHz VHF band	3 GHz S-band (Centimetric)	3 GHz S-band (Centimetric)	Multiple frequencies L-, S-, and X-band	9.5 GHz X-band	9.5 GHz X-band
Periscope Detection Capability	No		No	Minimal	Yes	Yes
Target Detection and Classification Process	Manual		Manual	Manual	Manual	Manual (in Fleet) Automatic (under development)

Through the years, the requirements for shipboard detection of submarine periscopes followed a somewhat different path than that for air ASW. Throughout WWII and during most of the Cold War, shipboard surface surveillance radars were optimized to counter surface and sea-skimming air threats, not submarines. During this era, search and detection of periscopes from a ship were performed primarily by visual lookouts. It was not until the post-Cold War shift to ASW operations in the high-clutter littorals that a formal requirement developed for shipboard detection of submarine periscopes, particularly for surface ship torpedo defense.

Technology Drivers

The principal technology drivers that shaped PDR design and development over the years include the following:

- During WWII: development of S-band (3-GHz) radar, which enabled fitting airborne radar equipment into combat aircraft
- During the Cold War: development of X-band (10-GHz) radar with characteristics suitable for detecting small RCS targets such as periscopes in high sea states
- During the post-Cold War era: development of modern digital signal processors with high computational power and speed, enabling real-time signal processing with sophisticated algorithms capable of automatic target detection and classification, even when operating in a high-clutter littoral environment

Throughout the entire history of PDR developments, the miniaturization of sensor system components and electronics has significantly reduced their size and weight, making them suitable for airborne and mast-mounted shipboard applications.

III. PDR SENSOR FUNDAMENTALS

Radar and the Electromagnetic Spectrum

The frequencies used by radars occupy a portion of the electromagnetic spectrum between the radio frequencies and the infrared region. In the United States, these are grouped into bands of increasing frequency with the following designations: VHF, UHF, L, S, C, X, K_u, K, K_a, and Millimeter. For security reasons, the bands were named cryptically and not in logical alphabetical order. The frequency limits of each band, as applied to radar, are given roughly as: VHF, 50-300 MHz; UHF, 300-1000 MHz; L-band, 1-2 GHz; S-band, 2-4 GHz; C-band, 4-8 GHz; X-band, 8-12 GHz; K_u-band, 12-18 GHz; K-band, 18-27 GHz; K_a-band, 27-40; and GHz, Millimeter, 40-100+ GHz.

Reflection and Attenuation of Microwave Radiation by Seawater

Because microwave radiation from a PDR is incident upon the sea surface typically at a glancing angle, most of its energy is forward scattered and very little penetrates the surface. Depending upon sea conditions, a small, but not inconsequential, amount is back-scattered incoherently by surface waves and ripples as clutter toward its source. This clutter is a significant limiter in system performance, particularly for airborne systems. The small amount that does penetrate is quickly attenuated; for example, at a frequency of 10 GHz, the attenuation is about 3000 dB/m. Accordingly, seawater is essentially opaque to microwave radiation, and subsurface objects are invisible to radar.

Propagation and Attenuation of Radar Energy in the Atmosphere

Microwaves are primarily line-of-sight limited. For wavelengths that are large in comparison to the dimensions of droplets of rain, clouds, and fog, scattering losses are small. For frequencies above about 10 GHz, or a wavelength of 3 cm, molecular absorption by water vapor and oxygen increases significantly.

Operational Characteristics of Effective PDR

Because surface scattering decreases with decreasing grazing angle, the center of a PDR beam is aimed close to the horizon. However, because receiver noise currently limits the detection of small targets such as periscopes to ranges on the order of 20 nautical miles (nmi), and the range to the horizon increases with sensor altitude, it is desirable to operate the PDR at low altitudes to achieve operation that is not noise-limited at low grazing angles. Accordingly, a PDR should be operated at altitudes below approximately 1500 feet, with 500 feet specified as optimum in consideration of other factors such as safety of flight. Ultimately, however, as grazing angles decrease, the clutter becomes spikey and target-like, and shadowing of small targets by waves and swell occurs, especially for high sea states. PDR performance at sea state 5 and above is degraded significantly, owing primarily to increases in sea clutter from breaking waves.

Sensor Characteristics of Effective PDR

The current standard of performance for an airborne PDR is the multi-mode AN/APS-137 radar developed in the early 1980s. In its periscope detection mode, the APS-137 operates in the microwave frequency range of 9.5 to 10 GHz, with a peak power of 500 kW (later versions = 50 kW), a pulse width of 500 ns (later versions = 5 us), horizontal polarization, and a pulse repetition frequency (PRF) of 2000 pulses per second. The transmitted waveform of each outgoing pulse is frequency modulated linearly with time over a 500-MHz bandwidth, i.e., from 9.5 to 10 GHz. The pulse duration of 500 ns corresponds to a linear dimension of 492 feet or a range resolution of 246 feet. However, the returned pulse is compressed in the receiver by a factor of approximately 200, providing a nominal range resolution of 1.25 feet. Pulse compression is achieved by passing the received pulses through a dispersive delay line in which the transit time varies inversely with frequency, allowing the end of the pulse to catch up to the beginning and produce a narrower pulse of increased amplitude. The antenna of the APS-137 is a 42-inch wide by 26-inch high parabolic reflector that is scanned at a rate of 300 rpm and which provides a beam width of 2.4° in azimuth and 4.0° in elevation and a gain of 35 dB. Its output is presented on a multi-purpose display driven by a scan converter.

Natural Background Clutter

Because the sea surface is uneven, a small but still significant fraction of the incident radiation is backscattered to the radar by waves, swell, whitecaps, and natural and man-made debris, creating a background of clutter against which the periscope must be detected. In addition, nearby land masses and birds may contribute to background clutter. For small grazing angles, the sea clutter radar cross section is proportional to the radar altitude, i.e., doubling the radar altitude doubles the radar cross section of clutter and reduces the signal-to-clutter ratio by half. Finding a periscope in the sea clutter background is a difficult task. For moderate to high sea states, the range at which a periscope can be detected by a current airborne PDR is limited to about 20 nmi by both clutter and receiver noise. Sea clutter noise masks the periscope signal at near range and fades as the grazing angle gets smaller. This noise limits the maximum range at which a periscope can be detected. Sea clutter samples tend to de-correlate or become unrelated to each other for sampling periods greater than about one second. However, some sea clutter spikes may persist for several seconds, making simple integration over time inadequate as a means of suppression when considered in the light that the clutter de-correlation time may be of the same order of magnitude as a fleeting periscope exposure. Clutter increases with sea state, with sea state 5 being a practical upper limit for periscope detection. Clutter also varies with wind, sea, and swell direction relative to the sensor. For low and moderate sea states, horizontal polarization yields a smaller amount of clutter than vertical polarization; at higher sea states, they are about equal.[3] However, significant controversy still exists in the scientific community as to the type of polarization that is optimum for PDR operational performance.

Man-made Clutter

Man-made sources of interference include items such as small boats, buoys, and debris. All of these clutter sources, which often exhibit densities numbering in the hundreds in littoral regions, can produce competing signals that have characteristics similar to those of exposed periscopes and masts. Although the principal advantage of a submarine is stealth, it is possible (although unlikely) that, in a difficult tactical situation, radar countermeasures could be employed by a submarine. This might include retransmitting received radar pulses modified to mislead the PDR operator, firing a cloud of metallic chaff into the air, or deploying many floating metal corner reflectors as decoys.

Radar Horizon

As stated previously, microwaves are primarily line-of-sight limited. However, diffraction and refraction may bend and extend the radar horizon beyond the geometrical horizon, although such bending is not, in general, sufficient to overcome the curvature of the earth. Diffraction is the wavelength-dependent bending of radiation around obstacles, such as the horizon. Refraction enters in because there normally exists a vertical gradient of water vapor concentration over the sea. Consequently, the speed of propagation of microwaves increases with increasing altitude, resulting in a downward curving of the beam over the horizon. In addition, if a layer of humid air is capped by a layer of drier air or if a temperature inversion exists, radiation entering the lower layer may be refracted and reflected back and forth between the upper-air layer and the ocean surface and propagate well beyond the normal radar horizon–a phenomenon known as ducting. Ducting can yield increased detection ranges; however, multiple reflections off the sea surface can cause increased clutter.

The radius of the earth enters into calculations of the geometrical range to the horizon; calculations of the range to the radar horizon account for normal refraction by assuming that the radius of the earth is 4/3 as great as its actual radius. For sensor altitudes small in comparison with the radius of the earth, the distance to the radar horizon in nautical miles is 1.23 times the square root of the altitude in feet. Thus, for a nominal airborne PDR altitude of 500 feet, the range to the radar horizon is 27.5 nmi, and for a nominal mast-mounted shipboard PDR height of 70 feet, it is about 10 nmi. Note that common surveillance radar heights aboard a U.S. cruiser or destroyer is 100-120 feet, and aboard an aircraft carrier that height increases to 150-180 ft.

IV. EXPLOITABLE TARGET SIGNATURES

Target Characteristics

To enable it to maintain contact with the above-surface world, a modern submarine has a complement of several masts that can be raised through the air-water interface. Included among these masts are optical and electro-optical periscopes and various antennas for communication and electronic support measures (ESM), all of which, when exposed, are potentially detectable by a PDR. Radar detection of an exposed periscope or mast is made difficult because of its brief exposure times, relatively small size, competing sea clutter, and false targets. The fleeting nature of a periscope exposure (sometimes on the order of a few seconds) makes it a particularly difficult and technically challenging target to detect. For example, a modern submarine may be equipped with a photonic mast containing a television camera or a frame-scanning passive infrared imaging sensor connected to a recording device. The photonic mast might be raised, scanned through 360°, and lowered, all within a few seconds, even though its output can be viewed over an extended period of time.

During the Cold War, which was characterized by blue water ASW operations against Soviet nuclear submarines, the opportunities for periscope detection with radar were infrequent. However, in the successful performance of their primary ASUW mission in the littorals, post-Cold War acoustically quiet SSKs operate predominantly at periscope depth, frequently exposing periscopes and masts. For example, the North Atlantic Treaty Organization (NATO) Supreme Allied Commander Atlantic Undersea Research Center database indicates that a mast may be exposed more than half the time a diesel submarine is underway.[4] Therefore, PDR is a primary sensor of choice to exploit this SSK target signature.

Maintaining radar surveillance in the vicinity of threat submarines not only may lead to a significant number of periscope detections, but also may force submariners to minimize their periscope exposures (indiscretion rate), particularly during ASUW submarine approach and attack. This hold-down tactic restricts the submarine's maneuver and mission options, resulting in a soft kill. Depending upon the tactical situation, PDR has been found to be very effective as a hold-down sensor.

Radar Cross Section

The detectability of a target is described in terms of its radar cross section (RCS). For a metallic sphere that is much larger in circumference than the radar wavelength, the RCS is equal to its cross-sectional or projected area. Thus, a 1.13-meter-diameter conducting sphere would have an RCS of one square meter. This is not as large a target for a radar as one might suspect in that most of the radiation impinging on it is reflected in directions other than back toward the radar receiver. Indeed, only the glint, or radiation reflected off the portion of the spherical surface that is nearly normal to the direction of the incoming beam has a chance of being intercepted by the radar antenna. However, radiation reflected off the surface of the water before and after reflection off a periscope can affect its effective RCS. The wake of a periscope and water displaced by it can also contribute to its effective cross section. A favorably oriented flat conducting surface could exhibit a large RCS, which would drop off drastically if its orientation were changed, even slightly. The RCS of a trihedral corner reflector would remain large, relatively independent of its orientation. Periscopes are designed to present a low RCS. They are made as small as possible and may be covered with a radar-absorbing coating. They may also incorporate stealth techniques such as shaping, for example, having flat surfaces that would reflect incoming microwaves away from their incoming path. The maximum radar cross section of a right circular cylinder is given by RCSmax = 2ab2/wavelength. As an example, if the exposed portion a submarine periscope can be approximated as a cylinder of radius a = 0.1 m, exposed length b = 1 m, and the X-band wavelength is 0.03 m, its radar cross section, when viewed normal to its axis, will be 6.7 m2. However, this value decreases dramatically as the angle of incidence departs from the normal. For purposes of calculation, the RCS of a submarine periscope is often taken as a nominal one square meter.

V. HISTORY OF AIRBORNE PDR SENSOR DESIGN AND DEVELOPMENT

This section traces the history of the design and development of airborne radars used for detection of exposed periscopes from their WWII beginnings through the Cold War and into the post-Cold War era.

The Beginnings—WWII Airborne Radars

The use of radio wave technology for target ranging was investigated by researchers in several nations as early as the 1920s. However, it was the British who, in the mid-1930s, first used radio detection and ranging (radar) technology in a practical sense for potential military applications. Radar saw its first military applications during WWII, particularly during the Battle of Britain in the summer and autumn of 1940, during the Allied strategic bombing campaign of Germany starting in 1942, and during the Battle of the Atlantic against German U-boats throughout the war. Initial experimental radars were ground-based for potential use against enemy aircraft. Subsequently, radar was investigated for airborne applications. Because of the interdependence of wavelength, beam width, and antenna size, the wavelength of airborne radar had to be considerably shorter than that of ground-based sets, since the transmitter and antenna had to be small enough to fit into a tactical aircraft.

By late 1939, the British undertook trials with an experimental airborne radar device operating in the VHF band at a frequency of 214 MHz, or a wavelength of 1.40 m, which was designated as Air-to-Surface Vessels radar Mark 1, or ASV-1. By January 1940, the British had outfitted 12 Hudson aircraft with production ASV-1 radar sets for detecting surface ships and surfaced submarines. Although the ASV-1 was only marginally effective in locating surfaced submarines to a maximum range of a few nautical miles at best, it could detect coastlines out to approximately 20 nmi.[5]

By August 1940, the British deployed an updated ASV-1 VHF-band radar operating at a frequency of 176 MHz, or 1.70 m, designated ASV-2. The ASV-2 had a more powerful transmitter and a more sensitive receiver, which enabled improved detection ranges against surfaced U-boats.[6]

By far the most notable and exciting advance in radar technology, which far overshadowed all others during WWII, was the British adaptation and improvement, in late 1940, of a multi-cavity resonant magnetron, one of a long series of inventions by scientists in a number of countries. The first magnetron was invented by an American in 1920. One of many multi-cavity magnetrons was invented in Germany in 1935. The operating frequency (3 GHz) of the British third-generation device corresponded to a much shorter wavelength of approximately 10 cm, and for that reason, it was commonly referred to as centimetric radar. The initial British airborne centimetric radars, designated ASV-3, could detect a surfaced submarine's conning tower at approximately 4 nmi, depending upon weather conditions, but as the power of the magnetron increased, the detection range steadily increased.[7] Although the ASV-3 was invented in 1940, it was not operationally deployed in significant quantities by the British until late 1942.[8]

The ASV-3 gave the British two advantages: (1) it depicted objects such as coastlines and buildings on a radar screen, which the older radars could not do, and (2) the U-boat's radar warning receivers such as the Metox German Search Receivers,[9] which were tuned to the longer wavelength of the older ASV-1 and ASV-2 radars, could not detect it. Accordingly, with the ASV-3, British aircraft could locate surfaced U-boats from a distance without alerting them and thus attack by surprise.[9]

British centimetric radar technology was first introduced to the U.S scientific community in August 1940, after which the Massachusetts Institute of Technology began working with the magnetron in its newly established Radiation Laboratory. The introduction of the S-band magnetron to the U.S. was so significant that one U.S. historian later commented that the magnetron was "…the most valuable cargo ever brought to our shores."[10] By late 1942, the U.S. Navy introduced its first S-band radar, the AN/APS-2.[11]

The Battle of the Atlantic was eventually won by the Allies owing to a variety of operational, tactical, and technological factors (including Operation Ultra deciphering of intercepts of Enigma-machine-encrypted German messages to U-boats, escorted convoys, shipboard direction-finding, surface ship active sonar, long-range patrol aircraft with radar, the U.S. Navy's Tenth Fleet (Phantom Fleet), operational research, and escort aircraft carriers). Of these, one of the most significant was the operational employment of airborne radar, particularly the use of S-band radar that was used with a high degree of success to detect and attack surfaced German U-boats during the summer of 1943.[12]

Throughout WWII, British and U.S. airborne radars were effective only in detecting surface ships and surfaced U-boats, not small-RCS targets such as exposed periscopes. The Allied radar's effectiveness against surfaced U-boats stimulated a cycle of tactical and electronic measures, countermeasures, and counter-countermeasures, which represented the earliest examples of modern electronic warfare. The most significant German countermeasures to Allied radars were: (1) the development of intercept receivers, which today would be called ESM gear, (2) the development of the U-boat Schnorchel to allow battery recharging without requiring the submarine to surface and be exposed to Allied radar, and (3) the development of radar absorbing material to serve as camouflage.[13] Germany developed ESM receivers to counter the ASV-2 radar deployed in 1940 but took until well into 1943 to figure out the Allied switch to 3-GHz radar during late 1942. In fact, it was the Allied Forces' great success with S-band radar in detecting surfaced U-boats during the summer of 1943 that compelled Germany to counter with the development and deployment of the Dutch-invented snorkel.[14]

Allied experience with ASW radar during the Battle of the Atlantic provided a number of general lessons learned that are significant and applicable even to this day. These included:

- Just as with the development of sonar, the military operational requirements during WWII were the primary stimuli for the introduction, rapid technology advances, and combat applications of radar.
- The introduction of new sensors, weapons, and tactics has led to a continued evolutionary interplay of measures, countermeasures, and counter-countermeasures.
- Successful employment of new technology is, to a high degree, a function of tactics and operator training, proficiency, and alertness.

Cold War Airborne PDR Sensors

The earliest U.S. Navy radars for surface surveillance appeared during WWII when radar suites were placed on land-based sites, selected seaplanes, and some carrier-based aircraft to detect low-flying aircraft, surface ships, and surfaced submarines. These radar systems were extremely big, power-hungry, and operator-intensive and were prone to frequent operational failures.[15] Furthermore, they were incapable of detecting relatively small RCS targets such as exposed periscopes and masts.

AN/APS-20 Airborne Radar (on P-2)

One of the earliest U.S. Navy airborne radar suites with relatively good surface surveillance capability was the AN/APS-20, which was initially developed during WWII but did not enter operational service until 1946. The APS-20 became operationally deployed on Lockheed's maritime patrol aircraft, the P-2 Neptune, in 1953. The APS-20 operated at L-band, S-band, and X-band had selectable PRFs in each band and had a wide selection of pulse widths in each band. It also provided a host of other features and operator tools such as automatic target indicator, plan position indicator, three choices of heading reference and stabilization, selectable azimuth and elevation beam widths, selectable output radiated gain, selectable receiver radiated gain, selectable antenna gain, automatic gain control low and high settings, plus a wide assortment of display and strobe light control selections for the highly-trained operator. It was a powerful radar that could radiate up to 1 megawatt in L-band and could detect large surface ships out to over 200 nmi on a good refracting day. A highly-trained operator could distinguish approximate target size, heading, and speed within three or four antenna sweeps on a good day. The S-band was significantly better at discrimination and resolution of targets at a range of 100 to 150 nmi.

The X-band was even better at detection ranges of 75 to 100 nmi and was especially effective at detecting low-flying aircraft. But like all of these early radars, the APS-20 was very large, heavy, power-hungry, and operator-intensive and was ineffective at detecting small RCS surface targets such as exposed periscopes and masts.[15]

AN/APS-80 Airborne Radar (on P-3A and P-3B)

Many of the APS-20's features and operator controls were subsequently included in the AN/APS-80 surveillance radar suites which were delivered with Lockheed's follow-on aircraft to the P-2, namely the P-3A and P-3B Orion long-range maritime patrol aircraft, in 1962 and 1965, respectively. The performance capabilities of the APS-80 were similar to those of the APS-20.[15] Among other things, the APS-80 was the first airborne surveillance radar that had dual antennas, forward- and aft-looking, to provide continuous 360° area search coverage.[16]

AN/APS-115 Radar (on older P-3Cs)

The AN/APS-115 radar set, used in the P-3C aircraft beginning in 1969, is an X-band air and surface surveillance radar system. It provides surveillance and detection of surface vessels, aircraft, and submarine snorkels. It consists of two radar receiver-transmitters, two antennas (located in the nose and aft section of the aircraft, providing 360° azimuth coverage), associated radar system controls, and a radar interface unit. The APS-115 is a frequency-agile system, meaning that the transmitter carrier frequency is changed between pulses or groups of pulses to reduce the probability of intercept and alerting of a target submarine using ESM equipment. The APS-115 is still currently deployed on many P-3C aircraft in the U.S. fleet. Although excellent for surface surveillance, the APS-115 has a limited capability for detecting exposed periscopes.

AN/APS-116 Radar (on S-3A)

After the Cuban Missile Crisis in October 1962 and during the mid/late 1960s, U.S. Navy carrier battle groups began facing an increasingly menacing Soviet nuclear submarine cruise-missile-firing SSGN threat. In response, the Navy developed and deployed, in 1974, the Lockheed S-3A Viking high-bypass fan-jet aircraft, a follow-on to the older Grumman S-2 Tracker. This aircraft provided carriers with a highly capable organic ASW capability, out to ranges in excess of 200 nmi. The S-3A aircraft incorporated the new AN/APS-116 radar, which had three modes of operation: (1) periscope and small target detection, (2) long-range search and navigation, and (3) maritime surveillance. It was the first airborne surveillance radar designed specifically for the detection of small RCS targets on the sea surface, such as exposed submarine periscopes and masts, and was the U.S. Navy's first airborne radar with a demonstrated periscope detection capability.[17] The APS-116 periscope detection mode grew out of U.S. Navy research in the 1950s on the use of fine range resolution to enhance target detectability and to minimize sea clutter by reducing the clutter patch area.

The APS-116, similar to the APS-115 but with only one radar antenna, was manufactured by Texas Instruments Inc. (TI). Although the APS-116 had an excellent periscope detection capability, the detection and target declaration process was not automated and thus required a skilled human operator to maximize operational effectiveness.

The 500-MHz bandwidth of this radar was exceptional for the period in which it was developed, and the APS-116 long remained the airborne radar with the highest range resolution in the U.S. inventory. The system spun the antenna at a very high rate to enable scan-to-scan de-correlation of the sea clutter, causing the stable periscope return to stand out from the variable sea clutter. Development of this radar was done in collaboration with the former Naval Air Development Center (NADC), Warminster, Pennsylvania. Much of the early testing by the government was done on the sea cliffs overlooking the Kalaupapa Peninsula on the Hawaiian island of Molokai. This cliff setting allowed radar to be tested at altitudes comparable to S-3 operational altitudes and overlooked an unsheltered, deep, uncontaminated ocean which provided various sea state environments.

AN/APS-137 Radar (on S-3B and selected P-3Cs)

The S-3B aircraft followed the S-3A in the mid-1980s. The S-3B incorporated a new multi-mode radar, derived from the APS-116 radar, and designated the AN/APS-137. The APS-137 radar was developed in the early1980s by TI by modifying and upgrading the APS-116 to add an inverse synthetic aperture radar (ISAR) mode developed by NRL, while retaining the original three modes of the APS-116.17 This fourth operating mode enabled better and longer range target identification (albeit still requiring interpretation by a human operator) of Soviet sea-based threats, particularly the cruise-missile-firing SSGN. ISAR provides relatively crude two-dimensional radar images of moving surface targets that extend over many range cells. It relies on roll, yaw, and pitch motions of the target vessel to produce Doppler shifts in the return signals, which vary as a function of position along the length and height of the ship. In addition to the S-3B, the APS-137 has also been deployed on selected P-3C aircraft, replacing the older APS-115 radar.

The parameters of the periscope detection mode for the APS-137 and APS-116 are essentially the same, as given in Section III. However, the APS-137 does include technology upgrades to improve performance. Their common design philosophy was based on three very challenging operational and environmental characteristics: (1) the target periscope is physically small, with a small RCS, (2) during ASUW attack, periscope exposures are very brief, and (3) the surrounding sea clutter de-correlates in time frames that are comparable to the shortest expected periscope exposure times. These characteristics led to a design that incorporated the following: (1) high range resolution of 1.25 feet to enhance the signal-to-clutter ratio, (2) a 5- to 15-second scan-to-scan signal processing integration time matched to expected exposure times and relatively long compared to clutter de-correlation times, (3) a rapid 300-rpm antenna scan rate to yield many independent samples during the nominal sea clutter de-correlation time, and (4) automatic-gain-control loops to maintain a constant false alarm rate.[17]

Operationally, periscope detection is best at low altitudes of about 500 feet and small grazing angles of about 1 degree because sea backscatter is lower at the lower altitudes and smaller grazing angles.[17]

The nominal performance of the APS-137 in the periscope detection mode, operating at an altitude of 500 feet, is described as detection of a small RCS (nominally 1 m2) attack periscope at a range of 19 nmi in sea state 3, with a probability of detection (Pd) of 0.5, and a probability of false alarm (Pfa) of 10-6, corresponding to approximately 1 false alarm per hour. Actual real-world detection is variable, depending on particular operational and environmental conditions, including sea state, wind direction, sea and swell direction, height and duration of periscope exposure, platform altitude, system processing settings such as threshold and gain, and, perhaps most importantly, operator training, proficiency, and alertness.[17]

Air ASW Effectiveness Measurement (AIREM) exercises during the early 1990s, in which the APS-116 served as a surrogate PDR for the APS-137, had produced highly variable performance results, particularly in free-play exercises. These variable results suggested problems in the scan converter and in operator training involving the selection of threshold, gain and system default settings, antenna tilt, and in-flight profiles. The best performance is achieved at low altitudes, but this imperative conflicts with the higher altitudes desired for simultaneously monitoring large fields of sonobuoys. In addition, perhaps the most serious shortfalls of the APS-137 included:

- Automation was lacking in detection, and the operator-intensive detection process was highly dependent upon operator training, experience, attentiveness, and alertness.
- An automatic target discrimination or classification process was lacking.
- Coupled with the post-Cold War policy change in ASW during the early 1990s, these concerns persuaded the Navy to issue, in April 1992, a formal requirements document for airborne automatic periscope detection and discrimination and, in response, to initiate a Category 6.3 program starting in 1993 to address these shortfalls.[17]

The APS-137 radar was designed to meet the ASW threat of the 1980s and, in its ISAR mode, to provide a stand-off surface ship classification capability for the S-3B aircraft. Unfortunately, technology limitations during this period limited the full potential of the APS-137. For example, lossy bandwidth reduction processes had to be incorporated into the radar to reduce the high data rates prior to digital processing, thereby reducing the resolution below its inherent capability. However, by the 1990s, advances in radar sensor and signal processing technology enabled TI to recommend changes to the APS-137 that would enhance its ability to detect and classify smaller RCS targets at longer detection ranges in higher sea states. Accordingly, by the early 1990s, TI proposed to improve the periscope detection capability of the APS-137 and provide for auto-classification of exposed periscopes and masts.[18]

AN/APS-124 Radar (on SH-60B)

The AN/APS-124 maritime surveillance radar was developed by TI for use in the SH-60B Seahawk Light Airborne Multi-Purpose System (LAMPS) Mark III helicopter. LAMPS was designed for use on Spruance-class destroyers and serves as a direct extension of its host surface vessel rather than as a stand-alone system. Because the helicopter can operate at altitude, the APS-124 provides a greatly extended range to the radar horizon than that afforded by a ship-mounted radar. The antenna is mounted under the fuselage and provides 360° coverage. A remote radar operator aboard the ship can control the APS-124 and receive its output via a data link. The APS-124 operates in three modes for: (1) long range search, (2) medium range search, and (3) and fast-scan surveillance. The third mode, which is applicable to periscope detection, uses 0.5-μs pulses at a rate of 1880/s and a scan rate of 120 rpm. These features, coupled with high transmit pulse energy and digital scan-to-scan signal integration, enable sea clutter de-correlation and the detection of small surface targets in high sea states. The false alarm rate can be adjusted to suit conditions.[19]

Post-Cold War PDR Sensors

AN/APS-147 Multi-mode Radar (for MH-60R)

During the mid-1990s, the Navy's program manager for maritime helicopters, PEO(A)/PMA-299, motivated by a need for improved periscope detection capability on LAMPS helicopters, chose Telephonics to develop a new lightweight multi-mode radar, the AN/APS-147, for the new multi-mission MH-60R. Primarily because of weight limitations on the helicopter, the proven, but much heavier, fixed-wing APS-137 ASW radar was not selected. At approximately 260 lbs, the APS-147 is about half the weight of the APS-137 radar.[20] Missions of the SH-60R include ASW, ASUW, strike, and search and rescue. The APS-147 provides six modes of operation: (1) long range search, (2) low-probability-of-intercept search, (3) short range search, (4) small-RCS periscope detection, (5) target designation for the Penguin, Harpoon, and Tomahawk missiles, and (6) ISAR.

The primary operational and technical requirements driving the design of the periscope detection mode in the APS-147 were less stringent than those of the new APS-137-oriented Automatic Radar Periscope Detection and Discrimination (ARPDD) program, which was concurrently in development during the 1990s. (The ARPDD program is discussed in detail in Section VII). The general requirements included small target RCS, short exposure time, and automatic detection with low false alarm rate, even in high sea states. To accommodate these ASW requirements, the APS-147 radar's design features include wide bandwidth, high average power, fast scan rate (108/minute), frequency agility, scan-to-scan integration over nine scans, and a track-before-detect capability.[20]

Based on in-house modeling and analyses conducted during the mid-1990s, Telephonics felt that the periscope detection performance of the APS-147 would be comparable to that of the APS-137.[21] Initially, the different signal and clutter processing approaches used by the two radars did not allow the ready incorporation of ARPDD's more stringent signal processing algorithms and software for automatic target discrimination into the APS-147, and it was expected that only lessons learned from ARPDD development would be applicable to a future upgrade of the APS-147.[21] However, by taking advantage of recent technology breakthroughs in processor miniaturization and processing power, Telephonics has been able to upgrade the APS-147 (re-named the APS-153) to include an ARPDD-like capability in its periscope detection mode. This involved replacing the APS-147's signal processor with a much more powerful, high-speed, high-data-rate, automatic-discrimination processor that was designed by the Naval Air Warfare Center Weapons Division, China Lake, California, with the capability of handling the unique ARPDD periscope detection and discrimination algorithms.[22]

Investigating Feasibility of Using UHF Radar (on E-2C) for ASW Applications

The Grumman E-2C Hawkeye is a carrier-based aircraft that employs the AN/APS-145 high-power UHF Doppler surveillance radar for the fleet defense mission. This radar is the latest in a long line of carrier-based airborne early warning (AEW) radar systems (e.g., AN/APS-120, AN/APS-125, and AN/APS-138) from General Electric Aerospace. It uses a rotating antenna, covering 360° within a circular radome mounted on top of the aircraft. Typically flown at an altitude of 15k-25k feet, the radar system can simultaneously and automatically detect and track multiple targets on the sea, in the air, over land, and at the critical land-sea interface.[23]

The APS-145 AEW radar has demonstrated an in-flight capability to detect and track thousands of targets at ranges in excess of 200 nmi over several million cubic miles of volume. Its highly sophisticated signal processing capability, including pulse compression, coherent integration, constant false alarm rate (CFAR) processing, non-coherent integration, and scan-to-scan auto tracking, enables it to discriminate relatively small and large RCS targets under widely varying environmental conditions. The radar continuously monitors and adapts to the environment while its six parallel processors maintain potentially thousands of tracks in its AEW surveillance volume.[23]

Although there were no formal requirements to use this AEW radar for ASW applications, anecdotal information as well as flight- and ground-based test data have indicated that the APS-145 is able to detect and track targets as small as periscopes at extended ranges, much greater than those of X-band radars such as the APS-137. The potential advantages of using UHF for the ASW surveillance mission include:[23]

- There were some indications that radar cross sections of periscopes are larger at the lower frequencies and that radar-absorbing materials surrounding periscopes are less effective at the lower UHF frequencies than at X-band.
- Sea backscatter is smaller at UHF frequencies. Thus, relatively stationary objects such as periscopes, which compete against the sea clutter, appear stronger relative to background clutter.
- Weather-related effects are minimal because this radar operates at wavelengths that are large compared to the size of rain and fog droplets.

However, because the APS-145's scan rate is only 5 to 6 rpm, or one scan every 10 to 12 seconds, it is not well suited for detecting fleeting periscope exposures.

In 1990, NADC, under the sponsorship of ONR, investigated the feasibility of employing high-altitude UHF radar for detecting exposed periscopes at very long ranges, as suggested by previous anecdotal evidence and flight tests. E-2C flight tests with an APS-145 radar, conducted in the Bahamas in June 1990 under highly controlled operational conditions, were successful in validating this assertion. However, at that time, the mechanisms responsible for radar backscatter from the sea surface at low (and mid-) grazing angles were not well understood. Therefore, the E-2C flight tests were followed by further ONR-sponsored investigations to develop a better understanding of the phenomenology of periscope and mast detections from high altitudes and to develop design guidelines for high-altitude PDR sensors.[24] Among other investigations by NADC, a series of low-grazing-angle (LOGAN) radar experiments were made in 1993 from the Chesapeake Light Tower, near Norfolk, Virginia, to measure sea clutter and its Doppler properties and the characteristics of periscopes. These measurements served to expand significantly the knowledge base for low-grazing-angle periscope detection.[25]

However, owing primarily to operational and technical challenges associated with periscope detection from high altitudes, because of new evolving AEW mission requirements on the E-2C operational community to support strike operations, and because of the general post-Cold War decline in ASW emphasis, the potential application of the E-2C's APS-145 UHF radar to long range periscope detection was not pursued further. Likewise, owing to estimated high costs for prospective experimentation, the ONR investigations into using SAR for periscope detection were discontinued.

Airborne ARPDD

By far the most exciting and technically challenging new effort that has substantially advanced the state of the art in PDR technology was the ONR-sponsored ARPDD program initiated in the early 1990s. ARPDD transformed a manual, operator-intensive process into a robust automatic periscope detection and classification capability, even in high-clutter littoral environments. Although the Navy initiated separate Enhanced Advanced Technology Development (EATD) programs in FY93 to address both airborne and shipboard periscope detection applications, these two programs were subsequently merged into a single program, ARPDD, beginning in FY94. This topic is discussed in detail in Section VII.

The major milestones in airborne PDR design and development, from WWII to the early 1990s, are summarized in Table 2.

VI. HISTORY OF SHIPBOARD PDR SENSOR DESIGN AND DEVELOPMENT

Introduction

Like their airborne counterparts, shipboard radars were developed and used during WWII to detect not only aircraft and surface ships but also surfaced submarines. The earliest S-band shipboard radar was the Type 271 fitted on British corvettes in 1942.[26] In order to defend against German U-boats during convoy routing and protection operations, the British had to find them. ASDIC, the newly developed British underwater active acoustic ranging system, could detect submerged, but not surfaced, submarines within a half mile on average, whereas shipboard radar could detect surfaced submarines to several miles, particularly if the weather was calm.[27]

Early Shipboard Periscope Detection Techniques

During WWII, shipboard radar was used primarily to detect aircraft and surface ships, including surfaced submarines. Since, at that time, radar was unable to detect small RCS targets, search and detection of periscopes from a ship were performed primarily by visual lookouts. Although there was some interest in U.S. Navy shipboard PDR developments during the 1950s and 1960s, this interest declined with the switch from diesel-electric to nuclear submarines. The practice of using lookouts continued during the Cold War, when most detections of Soviet nuclear submarines were performed by long range sea-floor-mounted passive acoustic Sound Surveillance System arrays in blue waters, which, in turn, cued tactical maritime patrol aircraft using passive sonobuoys. Accordingly, there was relatively little interest in, or a requirement for, shipboard detection of exposed periscopes, particularly by nonacoustic means.

However, by the mid-1980s, the U.S. Navy and the Defense Advanced Research Projects Agency showed significant interest in exploring industry proposals for developing technology to detect exposed periscopes from ships using various types of nonacoustic sensing techniques. These proposals included:

- *Sea Star*: A concept development, sponsored and pursued by the Navy's Directed Energy Office (PMW-145) between fiscal years 1984 through 1988, that involved active illumination of periscopes using a scanning laser and detecting the retro-reflection from the periscope optics. Unfortunately, this optical augmentation (OA) technique is operationally limited in that it works only when the periscope is looking directly at the ship's sensor.[28]
- *Passive Coherent Location*: A concept for exploiting VHF and UHF signals of opportunity from TV and FM broadcast stations and reflected from targets, such as exposed periscopes, using Doppler processing.[29]

Table 2 – Major Milestones in Airborne PDR Design and Development

IOC Date	Radar Type	Platform	Significance	Ops Requirement	PD Design Features	PD Performance
Early 1940	ASV-1	U.K. aircraft	U.K. introduced first military airborne radar	Surface surveillance to detect German ships and surfaced U-boats	• Pulsed microwave radar • 214 MHz (VHF band) • 1.5-m wavelength • Fits into combat A/C	• Detect surfaced sub at 2-3 nmi (in calm seas) • No PD capability
Late 1940 (U.K.; limited IOC) Late 1942 (U.S.)	Centimetric (S-band) • ASV-3 (U.K.) • APS-2 (USN) • SCR-517 (USA)	U.K. aircraft U.S. aircraft	• U.K. introduced first centimetric radar • Compelled Germans to develop/deploy snorkel	Surface surveillance to detect German ships and surfaced U-boats	• 10-cm cavity resonator magnetron at 3 GHz • High resolution, compact	• Reliably detect surfaced sub at < 4 nmi • No PD capability
1946	APS-20	P-2 (in 1953)	First U.S. AEW and surface surveillance radar	Detect ships and surfaced subs and low-flying A/C	L-, S-, and X-band; 4 PRFs; variable pulse width, etc., but large, heavy, operator-intensive	• Good surface surveillance • No PD capability
Mid-1960s	APS-80	P-3A, P-3B	First radar with dual antennas (fore and aft looking) and digital circuitry	Surface surveillance	X-band	• Similar to APS-20 • No PD capability
Late 1960s	APS-115	Older P-3Cs		Surface surveillance	X-band	• Excellent surface surveillance • Minimal PD capability
1974	APS-116	S-3A	First multi-mode radar designed specifically for low RCS periscope detection	Surface surveillance plus detect fleeting periscope/mast of Soviet ASUW threat	• X-band (9.5 GHz) • High range resolution (1.25 ft) • Rapid scan antenna (300 rpm) • High PRF (2000)	Reliable manual detection of 1-m^2 RCS at 20 nmi in SS3 with $P_d = 0.5$ and PFA = 10^{-6}
Mid-1980s	APS-137	S-3B Selected P-3Cs	Added ISAR capability to APS-116	Same as APS-116; plus surface ship classification for HARPOON targeting		
1980s	APS-124	SH-60B	Helicopter multi-mode surveillance radar without PD capability	Surface surveillance		• Good surface surveillance • Minimal PD capability
Early 1990s (investigations)	UHF radar	E-2C	Potential for using high-altitude AEW radar for ASW	PD capability an opportunity, but not a requirement	High power UHF yields: • Larger target RCS • Smaller sea back scatter • Smaller weather effects	• Significantly longer PD ranges than X-band radar • High altitude ops
Mid-1990s (start development)	APS-147	MH-60R	Helicopter multi-mode surveillance radar with ISAR and PD capability	Littoral ASW, ASUW, and strike missions	Lightweight, compact design = ½ weight of fixed-wing APS-137	
1993 (start development)	Air ARPDD	MH-60R (first candidate)	First airborne PD capability with automatic detection and classification	Air MNS, 21 April 1992	See Table 4 for details	See Table 4 for details

Beyond exploratory investigations, however, most of these nonacoustic sensing techniques were never further developed, owing primarily to significant operational and technical challenges, as well as the lack of a rigorous formal requirement for shipboard periscope detection.

However, by the early 1990s, after the end of the Cold War and the subsequent shift in ASW emphasis toward finding quiet SSKs operating in the littorals, the Navy began to take a much more serious interest in periscope detection for surface ship self-defense. At that time, the only Navy technology efforts focused on ASW radar were NRL's testing of the AN/APS-137 airborne radar aboard a ship and the Office of Naval Technology's (ONT) Nonacoustic ASW Block Program (Block OR3A), which focused specifically on airborne radar.

During the summer of 1991, under the ONT's Nonacoustic ASW Block Program manager sponsorship, NADC prepared a task plan for a ship-based periscope and mast (P&M) detection technology development effort to begin in fiscal year 1992. This plan addressed the background, operational requirement, technical status, and issues associated with ship-based P&M detection. The task focused on the respective operational and technical challenges of lidar technology versus radar technology and on investigating which is more suitable for meeting the operational requirements of shipboard P&M detection.[30]

Advanced Technology Development for Surface Ship Periscope Detection

After a Mission Need Statement (MNS) for shipboard periscope detection (along with airborne periscope detection) was issued in April 1992, the U.S. Navy began an EATD program to identify and assess key technologies applicable to shipboard periscope detection in support of surface ship torpedo defense. In December 1992, the Dahlgren Division of the Naval Surface Warfare Center (NSWCDD) issued a Broad Agency Announcement (BAA) for a Surface Ship ASW-Periscope Detection EATD to address the shipboard periscope detection requirements.[31] After an industry brief on this BAA in January 1993, NSWC started a full-scale EATD program whose objective was to explore various sensor concepts such as the use of radar, lidar, and infrared for reliable automatic detection and classification of submarine periscopes/masts.[32]

Throughout the 1990s, NSWCDD, under ONR sponsorship, was actively involved in the design, development, and testing of a prototype periscope detection sensor system which exploited the OA technique using a ship-based laser cued by a ship-based PDR. The objectives of this effort included the development of an improved capability to detect and classify periscopes from a surface ship at tactically useful ranges and to reduce the FAR from a radar-only solution. The ultimate goal was to improve surface ship torpedo defense capabilities through reliable periscope detection. However, owing to certain operational issues, and the absence of a formal requirement to augment a surface ship PDR with a lidar system in order to reduce FAR to acceptable levels, this program was eventually discontinued.

Shipboard ARPDD

As indicated previously, the U.S. Navy originally initiated separate EATD programs in FY93 to address both airborne and shipboard periscope detection applications. Subsequently, these two programs were merged into a single ARPDD program beginning in FY94. Although the ARPDD program chose the airborne APS-137 as its host radar for RDT&E purposes, the ARPDD program addressed shipboard PDR issues on equal footing with the airborne issues. This topic is discussed in more detail in Section VII.

The major milestones in shipboard PDR design and development, from WWII to the early 1990s, are summarized in Table 3.

Table 3 – Major Milestones in Shipboard PDR Design and Development

Era	Radar Type	Platform	Significance	Ops Requirement	PD Design Features	PD Performance
Early in WWII	Surface search radars	Surface combatants and escorts	U.K. introduced first military shipboard radars	Detect low-flying aircraft, ships, and surfaced U-boats	Not designed for periscope detection	No PD capability
Cold War Years	Surface search radars (e.g., SPS-10, SPS-55, SPS-67)	Surface combatants	Designed for detecting surface vessels, not periscopes	Detect ships and sea-skimming aircraft and cruise missiles	Not designed for periscope detection	Very limited PD capability
	Fire control radars (e.g., SPQ-9, Phalanx)	Surface combatants	Designed for AEW fire control support, not for detecting periscopes	Detect / engage sea-skimming aircraft and cruise missiles	Not designed for periscope detection	Very limited PD capability
Late Cold War Years (1980s)	Shipboard applications of airborne APS-137	Surface combatants	Harness best airborne PDR for ships	Reliable detection of threat sub periscope prior to torpedo attack	Same as airborne APS-137, but operated at smaller grazing angles	Reliable manual detection of periscopes similar to APS-137
	Nonacoustic alternative / adjunct concepts to PDR (e.g., optical augmentation)	Surface combatants	Investigate nonacoustic alternatives to shipboard PDR	Reliable detection of threat sub periscope prior to torpedo attack	Potential application to periscope detection	Optical PD capability limited by weather, target / sensor alignment, etc.
1993 (Start development)	Ship ARPDD	HVU surface combatants	First shipboard PD capability with automatic detection andclassification	Ship MNS, 21 April 1992	See Table 4 for details	See Table 4 for details

VII. POST-COLD WAR ARPDD SYSTEM DEVELOPMENT FOR AIR AND SHIP APPLICATIONS

As discussed previously, the APS-116 and the follow-on APS-137 were the first U.S. Navy radars designed specifically for detecting small RCS targets such as periscopes at tactically significant ranges in relatively high sea states. Although effective in detecting periscopes at tactically useful ranges, target classification with these radars was still an operator-intensive process. However, the post-Cold War paradigm shift in the ASW operational environment caused a dramatic change in PDR requirements and in the Navy's technology developments for meeting those requirements. This redirection precipitated the formulation and execution of, what is considered by many to be, the most exciting and technically challenging new effort to substantially advance the state of the art in PDR development—the ONR-sponsored ARPDD program. ARPDD focused on developing an automatic periscope detection and classification capability for both airborne and shipboard applications, particularly in high-clutter littoral ASW environments. This program is discussed herein.

Post-Cold War PDR Sensor Requirements

During the Cold War years, when passive acoustic ASW sensors were the sensors of choice against Soviet nuclear submarines operating primarily in open ocean waters, the opportunities and need for airborne detection of exposed submarine periscopes and masts were limited. Therefore, the fleet's requirements for PDR were not compelling; there were no formalized OPNAV requirement documents for PDR, and with the exception of the new periscope detection mode of the 1970s-developed APS-116, the pace of advancement in PDR sensor technology was mostly incremental during much of this era.

Mission Need Statement (MNS), April 1992

During the post-Cold War 1990s, the U.S. Navy's ASW policy changed significantly in terms of mission priority, threat submarine type, and operating environment. In particular, the Navy shifted its mission priorities toward expeditionary force operations in support of regional conflicts, primarily in the littoral environment. The new ASW threat became the acoustically quiet, elusive SSK whose primary mission was anti-access, area-denial ASUW. Operating in a high-clutter littoral environment, the SSK posed a particularly difficult detection and classification challenge for the manual, operator-intensive PDRs of the day.

As a result, the specific requirements for developing and fielding a robust automatic periscope detection and discrimination capability became very compelling. At that time, the formal Department of Defense (DoD) requirement for developing and fielding such a capability was an official requirements document called a Mission Need Statement. Specifically, to meet the challenges of the proliferating acoustically quiet diesel-electric submarines operating in an area-denial role in the shallow water littorals, the OPNAV Anti-Submarine Warfare Division (OP-71) issued, on April 21, 1992, two separate MNSs for the development of a robust capability to detect and classify exposed periscopes automatically. These two MNSs documented the following requirements, respectively: (1) an airborne periscope detection capability for offensive ASW applications, and (2) a shipboard periscope detection capability for own-ship self-defense against a torpedo-launching submarine. Because of distinct, unique operational natures, separate MNS performance specifications had to be issued for each application.[33]

These MNSs specified only the following generic requirements for periscope detection, as opposed to stipulating a particular ASW sensor solution:

- Day/night, all-weather operation
- High area search rate
- High detection rate, even for short duration exposures
- Low false alarm rate, independent of sea state
- The ability to classify targets while maintaining search volume
- The ability to detect and to classify automatically.

The first two requirements (day/night, all-weather operation and high-area search rate) tended to strongly favor radar over optical devices as the sensor type of choice. By far the biggest technical challenges for any MNS sensor solution were the requirements for responding to very short exposure times and for automatic detection and classification.

National Security Industrial Association Quick Reaction PDR Study, Summer 1992

Immediately after the MNSs for airborne and shipboard periscope detection capability were issued, OP-71 engaged radar experts in industry through the National Security Industrial Association (NSIA) to assess the capabilities of available commercial and military radars to satisfy the requirements specified in the MNSs. An ad hoc study was performed, over approximately 90 days, to address two specific questions: (1) Are there any commercial-off-the-shelf (COTS) products which could help solve the problem? and (2) What processing improvements would enable existing shipboard or airborne radar systems to meet Navy requirements?[33]

Three representative commercial/military shipboard radars and two airborne radars were selected as potential solution candidates: (1) the AN/SPS-70 (shipboard version of the AN/APS-137), (2) the Close-In-Weapons-System Ku-band radar used in the Phalanx ship defense system, (3) a hybrid system combining components of the RASCAR commercial radar system with the AN/BPS-16 submarine radar, (4) the AN/APS-137 X-band radar used on S-3B and some P-3C aircraft, and (5) the AN/APS-145 UHF radar used on E-2C aircraft.[33]

In response to the two key questions, the ad hoc study group reached the following conclusions:

1. There were no airborne or shipboard COTS products that could, without substantial and costly modifications, solve the MNS requirement. Moreover, none of the military radars could fully meet all MNS requirements. The best military candidates were the APS-137 PDR and its shipboard counterpart, the SPS-70. However, neither could meet the challenging MNS requirement of automatic detection and classification. The main operational and technical challenges were: (a) very short target exposure times, (b) high potential rates of false alarms from sea clutter, and (c) difficulty in discriminating real from false targets.[33]
2. There was sufficient evidence that existing radars could be modified to meet the MNS requirements through processing improvements, although with great difficulty. It also concluded that employing more than one radar type and employing and fusing data from other sensor types (e.g., lidar, passive optical sensor) may be useful, especially for a shipboard system.[33]

Based on these study results, the NSIA committee recommended that the Navy initiate advanced development programs as soon as possible to develop and field a radar with a periscope detection and discrimination capability for both airborne and shipboard applications.

Automatic Radar Periscope Detection and Discrimination (ARPDD) Program

Introduction

Based on the formal requirements for reliable periscope detection, as documented in the Airborne and Shipboard MNSs of April 1992, and the recommendations and impetus provided by the NSIA quick-reaction study in July 1992, the Navy initiated, in October 1992, two separate periscope detection EATD programs, one for airborne applications to be executed by NAVAIR and one for shipboard use to be executed by NAVSEA.

The initial NAVAIR approach was to develop test plans and to use the APS-137 radar to perform tests and collect data, early in 1993, against submarine periscopes and other small targets in a variety of sea states. The basic question to be answered was: Are the fundamental characteristics and range resolution of the APS-137 sufficient for discrimination of periscopes from small confusion targets? Following the establishment of the feasibility of an APS-137-based approach, system architecture plans and data analyses were begun to develop a prototype ARPDD system.

The initial NAVSEA approach was to develop, during the first year, an extensive plan for collecting data relevant to radar, passive mid-/long-wave infrared, and near-infrared lidar sensors, followed by the actual data collection and analysis and system architecture definition and design in the second year.

At the request of the Office of the Assistant Secretary of the Navy for Research, Development & Acquisition (ASN RDA), the Naval Studies Board of the National Academy of Sciences reviewed the EATD programs during the summer of 1993. Following this review, ASN RDA directed, in September 1993, that the Airborne and Shipboard Periscope Detection EATDs be combined into a single new program, primarily to reduce costs by leveraging PDR technology developments common to both applications. Sponsorship of the combined program, now called ARPDD, was assigned to ONR, and management responsibility was assigned to NAVAIR. Subsequently, an APS-137-based common system architecture (with variations) was defined for both the airborne and shipboard applications, to be implemented by NAVAIR and NAVSEA, respectively.

ARPDD Requirements and Technical Challenges

The primary requirement for the ARPDD program was to develop a radar that fully satisfied the Navy's Airborne and Shipboard Periscope Detection MNSs of April 1992. In particular, the radar should:[34]

- Detect periscopes with short duration exposures, at operationally significant ranges, reliably and automatically
- Discriminate periscopes from false targets, with low FAR, reliably and automatically
- Develop these capabilities suitable for both aircraft and ships operating in littoral areas.

Detection of such fleeting targets requires, among other things, a radar system with a sensitive detection threshold, a high PRF, and high range resolution. Modern airborne ASW radars such as the APS-137 are designed to provide such a capability on open ocean waters where there are few false targets. In such relatively benign waters, an alert operator viewing a radar display can readily detect and classify a pop-up periscope. However, in littoral environments with large numbers of false targets, the operator of such a system may be overwhelmed by returns from "confusion" targets such as debris, buoys, and small boats. This false alarm problem directed the ARPDD program's primary goal of automating target detection and classification.

During its first year, the ARPDD program's technical team, consisting of NAVAIR, Naval Air Warfare Center Weapons Division/China Lake, Naval Air Warfare Center Aircraft Division/Patuxent River, John Hopkins University Applied Physics Laboratory (JHU/APL), NRL, and Raytheon TI Systems formulated a comprehensive RDT&E program to address and resolve these technical issues. The ARPDD program was divided into three major development phases:

1. Develop and gather data with a breadboard ARPDD system
2. Develop and test a land-based brassboard ARPDD system
3. Develop and test shipboard and airborne ARPDD Fleet Demonstration Units (FDUs).

The unique algorithms and signal processing software developed under the ARPDD program were intended to be forward-fit and back-fit into: (1) surface search radar replacements on surface combatants and (2) upgrades to air ASW radar systems such as the APS-137 (on selected P-3Cs) and the APS-147 (on MH-60R).

Breadboard ARPDD System

The first phase of the ARPDD program, which began in 1994, focused on building a breadboard test radar system to investigate and evaluate detector-processing schemes, to validate the motion compensation algorithm, to validate target discrimination feasibility, to develop target discrimination algorithms, and to enhance the detector design. The breadboard system consisted of an APS-137 host radar from NRL, a limited coverage automatic detector prototype, and data recorders. To achieve automatic detection and discrimination, the high-resolution APS-137 radar was coupled to a two-stage periscope declaration processor with the following functions: (1) conventional target detection with a moderate FAR, followed by (2) signature discrimination to reduce false alarms. The ARPDD program's approach to discriminate real periscopes from false targets and ocean clutter spikes was to identify and then eliminate the false targets by their spatial and temporal characteristics, enabled by a temporal processing scheme called retrospective processing.

Among other things, the breadboard development phase successfully demonstrated the application of retrospective processing to the periscope detection problem.[35]

Brassboard ARPDD System

The second phase of the ARPDD program began in 1995 and involved development of a brassboard radar system. This prototype engineering system extended the limited-coverage breadboard retrospective processor to full area coverage. It incorporated additional capabilities including automatic detection, direct discrimination, tracking, and indirect discrimination. It also incorporated extensive data recording capabilities which were used for land-based field testing in Hawaii in 1997. The brassboard system was used successfully to determine the performance of individual system components, the sensitivity of performance to various system parameters, and total system performance.[35]

Ship Tests of ARPDD Brassboard System (1998)

The third phase of the ARPDD program was to involve testing both the shipboard and airborne developmental FDUs by fleet personnel to demonstrate its operational capabilities and utility. However, because of funding limitations, the FDUs were not built, and instead, follow-on testing was done with modified versions of the brassboard system.

In the summer and fall of 1998, a series of field trials was conducted on the *USS Stump* (DD-978) with the ARPDD brassboard system replacing the ship's SPS-55 surface search radar. During work-up exercises and subsequent deployment with a carrier battle group and during Ship Anti-submarine Readiness and Evaluation Measurement (SHAREM) exercises in the Mediterranean, the shipboard brassboard system underwent extensive testing with numerous submarine interactions. Among other things, ARPDD's sea clutter rejection algorithms were validated under way, with performance found to be equal to that experienced during the land-based tests with the brassboard system the previous year. In terms of operational capability against submarine periscopes, the ARPDD system on the *USS Stump* demonstrated such a high probability of detection and low probability of false alarms, that fleet operators developed a high degree of confidence in its ability to detect and declare targets automatically.[36]

The highly successful performance of the ARPDD system during its Mediterranean deployment prompted several laudatory messages and comments from fleet commanders. For example, in post-test discussions between the commanding officer of the *USS Stump* and the ONR program sponsor, the sponsor commented: "The CO personally told me that ARPDD accounted for the majority of detections during the SHAREM. He said that he soon came to depend on ARPDD more than [on] acoustics and began to plan his [ASW] tactics around the ARPDD range of the day."[37] Furthermore, the relatively low FAR levels achieved during the *USS Stump* tests negated the potential need for using a supplemental lidar system (e.g., using the OA technique), cued by an ARPDD radar, to achieve the low FARs necessary for reliable target classification.

Airborne Tests of ARPDD Brassboard System (1999 and 2001)

After completion of the ARPDD tests on the *USS Stump* in late 1998, the brassboard system was modified and re-installed in an NRL P-3 aircraft in March 1999 to collect target discrimination data and to perform flight evaluations of the system. During the summer of 1999, a series of P-3 flight tests of the ARPDD brassboard was conducted in various littoral areas to develop and evaluate target discrimination algorithms and to obtain system optimization data under various environmental and operational conditions. In addition, the P-3 ARPDD system participated in operational exercises in the Western Pacific during the fall of 1999 to quantify the density of detected objects in high-clutter littoral regions of interest and to assess target discrimination performance.[38]

The SHAREM flight tests revealed some unanticipated technical issues. Specifically, under certain sea state conditions, the false alarms (periscope declarations with no target present) were significantly higher than expected.[39] Sea clutter detections were found to be a much greater problem for ARPDD than man-made clutter. To gain a thorough understanding of the relationship between the observed ARPDD false alarm rate and the littoral environmental conditions during these SHAREM tests, it was necessary to obtain a much larger statistical sample of false alarms under a variety of environmental and operational conditions. Therefore, a second series of P-3 flight tests was conducted with the ARPDD brassboard system in the summer of 2001 to obtain the necessary data. These flight tests were successful in resolving the technical issues uncovered during the 1999 SHAREM flight tests.[40]

Upon completion of the second series of P-3 flight tests in the summer of 2001 and upon the successful accomplishment of all of the ARPDD program's major technical objectives, ARPDD formally ended as an ATD program on 30 September 2001. Subsequently, ARPDD undertook a series of follow-on engineering development activities in preparation for the acquisition of airborne and shipboard PDR systems.

Assessment Activities and Endorsements for ARPDD

In 2001, the ASW Requirements Division (OPNAV N74) conducted several major ASW technology assessments to develop an investment strategy applicable to ASW operations in contested littorals. OPNAV engaged several blue-ribbon panels, including the *Littoral ASW Future Naval Capability Integrated Product Team* (IPT), *the Sensor Systems IPT*, and the *Nonacoustic Sensors Sub-Committee* of the Chief of Naval Operations' *Planning and Steering Advisory Committee* to assess promising ASW Science and Technology (S&T) efforts and to help define, select, and recommend the best ASW sensor system candidates for near-term development and transition into operational capability. In general, these assessment activities concluded that both airborne and shipboard ARPDD had a high warfighting priority and a potential capability that should be transitioned into the fleet as soon as practical.[41] Other less formal, but no less compelling, endorsements from the fleet and from high-level Navy leadership echoed the same recommendations.

The combination of a highly successful ATD program coupled with strong fleet and Navy leadership endorsements has made the ARPDD program one of ONR's most successful transition candidates for further development, acquisition, and fielding in the fleet. Having been fully responsive in meeting OPNAV and fleet requirements, ARPDD is expected to significantly enhance fleet ASW operational capabilities.

Air ARPDD Status and Plans

In May 2002, the Chief of Naval Operations directed OPNAV N78 to fund an Air ARPDD acquisition program. As a result, Air ARPDD was funded in Program Objective Memorandum 2004 (POM-04), with funding starting in fiscal year 2005.[42] The airborne version of ARPDD was originally targeted for deployment on P-3C aircraft. However, upon the decision to twilight the decades-old P-3C's in favor of the new P-8A, ARPDD was redirected to the MH-60R.[43]

Ship ARPDD Status and Plans

Similar to Air ARPDD, U.S. Navy leadership has provided strong endorsements for the development, acquisition, and fielding of a shipboard ARPDD capability. Along with the further brassboard demonstration of an upgraded shipboard ARPDD system in selected fleet exercises during 2003 and 2004, these endorsements have led to CNO direction and subsequent Navy plans to develop and incorporate ARPDD technology into a suitable mast-mounted radar system, with an APS-137-like capability, on selected high-value surface ships and surface combatants.[44]

The major milestones in ARPDD system concept formulation, design, and development are summarized in Table 4.

Table 4 – Major Milestones in ARPDD System Concept Formulation, Design, and Development

Date	Major Milestone	Significance	Program Sponsor and Manager	Technical Team	Comments
21 Apr 1992	MNS issued for: • Airborne PD • Shipboard PD	First formal OPNAV requirement for automatic airborne and shipboard PD in high-clutter littorals	OP-71	Navy and industry	Specified: • Day / night all-weather ops • High detection rate against short exposures • Automatic detect and classify with low FAR
Summer 1992	National Security Industrial Association Quick-reaction PDR study	Industry investigation into existing air and ship radar systems that could, if modified, meet MNS	National Security Industrial Association	National Security Industrial Association	Concluded that: • No existing COTS or military radars could fully meet MNS requirements without major modifications • APS-137 is best candidate
Oct 1992	Start EATDs for: • Air PD capability • Ship PD capability	First Navy program to develop air and ship PD capability; responsive to MNS	Air: PMA-264 Ship: PEO-USW/ASTO	Air: NAWC AD, NAWC WD, APL, NRL, and TI Ship: NSWC/Dahlgren	
01 Oct 1993 (start ARPDD program)	Merge both EATDs into single ARPDD program	Programmatic decision to focus common PDR technology developments and reduce costs	ONR sponsor and PMA-264 manager	N/A	Most stressing technical challenges for ARPDD: • Detect short transient low-RCS target • Automatically discriminate target in high-clutter with low FAR
1994 – 1995	Develop breadboard ARPDD system	Successfully demonstrated automatic retrospective processing	ONR sponsor and PMA-264 manager	NAWC WD, JHU/APL, NRL, TI	• Leverage high-resolution APS-137 as ARPDD baseline • Collect data to develop two-stage target discriminator
1996 – 1997	Develop brassboard ARPDD system	• Engineering asset which incorporates all elements of ARPDD design • Additional capabilities plus extensive data recording	ONR sponsor and PMA-264 manager	NAWC WD, JHU/APL, NRL, TI	Data collection and testing at low- and high-elevation shore sites in Hawaii
1998	Fleet demo – ship (ship tests on *USS Stump*)	First shipboard test of brassboard system by fleet operators	ONR sponsor and PMA-264 manager	NAWC WD, JHU/APL, NRL, TI	SHAREM 125 and other tests in Mediterranean
1999	Fleet demo – air (first air test on NRL P-3C)	• First airborne test of brassboard system by fleet operators • Identified littoral FAR issues	ONR sponsor and PMA-264 manager	NAWC WD, JHU/APL, NRL, TI	SHAREM 138 tests in WESTPAC
2001	Fleet demo – air (second air test on NRL P-3C)	• Second airborne test of brassboard system by fleet operators • Resolved littoral FAR issues	ONR sponsor and PMA-264 manager	NAWC WD, JHU/APL, NRL, TI	
30 Sep 2001 (complete ARPDD program)	Complete ARPDD ATD program	Successful completion of ATD prior to follow-on activities in support of transition to air and ship programs	N/A	N/A	Assessments and strong Navy endorsements recommended full-scale air and ship PDR programs

VIII. LESSONS LEARNED

While there is no guarantee that successful PDR measures of the past are accurate predictors for success in the future, there are some fundamental lessons learned from the historical evolution of the design, development, and employment of PDR sensors. In addition to those lessons learned from the days of WWII (see Section V), a number of other enduring lessons can be gleaned from the historical development of airborne and shipboard PDR sensors.

Lessons Learned in PDR Technology Improvement

- Significant historical advancements in PDR technology have been driven primarily by operational necessity (requirements pull), particularly during wartime, rather than via technological opportunities (technology push).
- During peacetime, affordability and vetted requirements issued formally by Navy leadership are the principal drivers for PDR RDT&E programming and funding.
- The size and weight restrictions for airborne radars, particularly for highly weight-sensitive helicopter and unmanned air vehicle systems, are among the biggest drivers in the choice of the PDR's wavelength, power, PRF, and scan rate.
- The paradigm shift from Cold War ASW in blue waters to post-Cold War ASW in the cluttered littorals has resulted in a corresponding shift in emphasis from PDR target detection to the much more difficult problem of automatic target classification (discrimination). Accurate target classification has been, and continues to be, the most difficult operational and technical challenge for PDR.
- When fully fielded, the technology development pursued under the ONR-sponsored ARPDD program during the 1990s will transform a manual, operator-intensive PDR process into a robust automatic target detection and classification capability, for both airborne and shipboard ASW applications.

Lessons Learned in PDR Operations

- Historically, and until very recently, PDR operations in the fleet have been manual, operator-intensive processes.
- Air superiority is effective in suppressing SSK ASUW operational effectiveness since the SSK's need for periscope exposures during final ASUW targeting (except for the most proficient, advanced SSK crews) is readily exploitable by an effective airborne PDR.
- Maintaining radar surveillance in the vicinity of threat submarines not only may lead to a significant number of periscope detections, but also may force submariners to minimize their periscope exposures (indiscretion rate) particularly during ASUW submarine approach and attack. This hold-down tactic restricts the submarine's maneuver and mission options, often resulting in a soft kill.
- PDR utility is, and will continue to be, relatively high against most SSK submarines, even those with the longer submerged endurance capability provided by air-independent propulsion, since (with the exception of high-end-crewed SSKs) they typically require one or more periscope looks to satisfy torpedo attack criteria against a surface ship.

IX. SUMMARY

The intent of this paper is to trace and summarize the historical development and technical design issues of airborne and shipboard radar used for the detection of exposed submarine periscopes. Over the years, periscope detection radar sensors have evolved with a concurrent interplay of changes in the threat, missions, requirements, measures, countermeasures, environment, and advances in technology.

Early during World War II, the first airborne radars operated at wavelengths of 1 to 2 m in the VHF band and required large arrays of dipoles as antennas. During the Battle of the Atlantic, they were effective in detecting only surfaced

German U-boats, not their periscopes. Later in the war, S-band (10-cm wavelength) technology advancements, such as the development of the cavity magnetron, yielded higher resolution with smaller antennas more suitable for fitting into aircraft.

During the Cold War, the switch to X-band (3-cm wavelength) in the U.S. Navy's APS-116 and APS-137 airborne ASW radars enabled resolution sufficient for detecting periscopes of low radar cross-section in high sea states at tactically significant ranges. However, because of a lack of formal operational requirements, radar detection and classification of rarely exposed periscopes of Soviet nuclear submarines, which operated primarily in relatively benign open-ocean waters, remained a manual, operator-intensive process.

In contrast, during the post-Cold War era, it became necessary to detect relatively frequent, but fleeting, exposures of periscopes of acoustically quiet diesel-electric submarines against a background of numerous target-like objects in acoustically challenging littoral environments. This provided the impetus for automating the periscope detection and discrimination process for airborne PDR and for adapting PDR to Navy ships, thereby endowing shipboard surface surveillance radars with a periscope detecting capability in support of self-defense against torpedo-firing submarines.

The recent development of modern digital signal processors, with their high computational power and speed, enabled significant improvements in both airborne and shipboard radars. These advances made possible real-time signal processing with sophisticated algorithms capable of automatic detection and classification of targets in high-clutter littoral environments. This technology development, pursued under the ONR-sponsored Automatic Radar Periscope Detection and Discrimination program during the 1990s, has transformed a manual, operator-intensive PDR process into a robust automatic target detection and classification capability for both airborne and shipboard ASW applications.

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14. ABSTRACT

This paper traces the history of periscope detection radar (PDR) from the origin of radar in World War II to the near present. During this period, PDR sensors have evolved substantially, primarily due to notable changes in the threat, missions, requirements, measures, countermeasures, environment, and advances in technology. Today, it is necessary to detect relatively frequent, but fleeting, periscope exposures of acoustically quiet diesel-electric submarines against a background of numerous target-like objects in high-clutter littoral environments. State-of-the-art signal processing has transformed a labor-intensive, false-alarm-ridden endeavor into an automatic radar periscope detection and discrimination system.

15. SUBJECT TERMS

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DEPARTMENT OF DEFENSE
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12 February 2016

Mr. Robert B. Stokes, CIV DTIC EM (US)
Defense Technical Information Center
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Dear Mr. Stokes:

I am the sponsor of work performed by John G. Shannon and Paul M. Moser of Rite-Solutions, Inc. in preparing two documents: (1) a technical paper by John G. Shannon entitled "A History of U.S. Navy Airborne and Shipboard Periscope Detection Radar Design and Development" that was published in the U.S. Navy Journal of Underwater Acoustics Volume 62, Issue 2, in January 2014, and (2) a still-unpublished expansion of this paper in the form of a monograph by John G. Shannon and Paul M. Moser entitled "A History of U.S. Navy Periscope Detection Radar, Sensor Design and Development." The first of these is already in the possession of DTIC under the accession number ADA618106.

Both of these documents are UNCLASSIFIED and are approved for public release, distribution unlimited.

Respectfully yours,

David H. Johnson

David H. Johnson, PhD
Team Leader, LASW

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