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Undersea Warfare in the 21st Century Part One: Anti-Submarine Warfare – Doctrine and Emerging Capabilities

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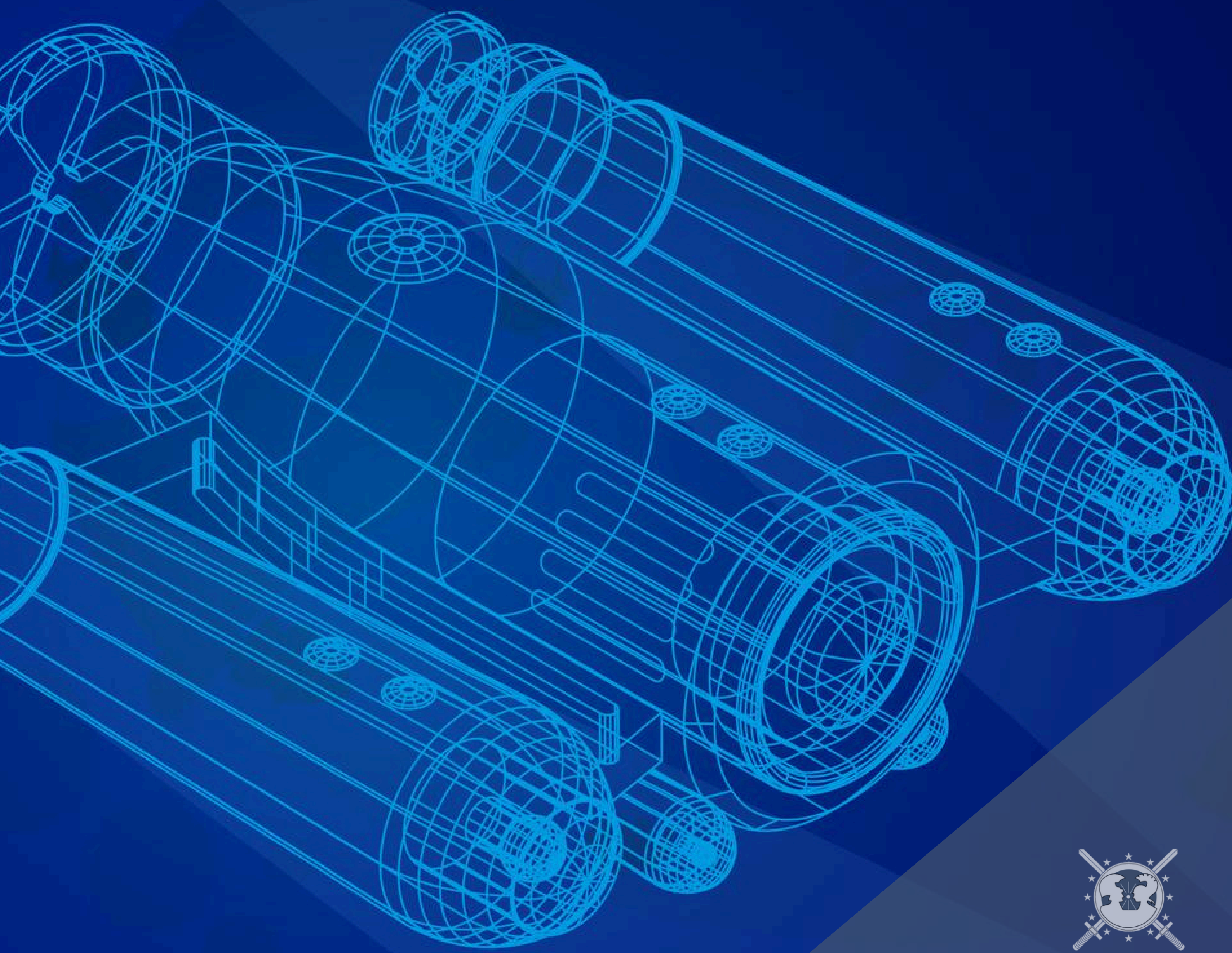

RESEARCH REPORT

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RESEARCH REPORT

Introduction

Since the introduction of combat submarines in the 20th century (Koray, 2024, para. 5), the undersea domain has constituted one of the most decisive yet opaque spheres of strategic competition. This ambiguity defined the Cold War period, brought about by the development of nuclear-powered ballistic submarines (SSBNs), which guaranteed a second-strike capability (Scipanov & Păuna, 2020, p. 310). This dynamic remains one of the cornerstones of global stability, particularly as an increasing number of states develop submarines capable of deploying nuclear warheads as the number of actors operating advanced submarines has increased to the present day (Friedman, 2020, p. 69; Lisman, 2019, p. 2). As these platforms evolve, so do anti-submarine warfare (ASW) capabilities. Nevertheless, to date, states do not possess the ASW capabilities necessary to counter the threat of submarines effectively, and the SSBNs lurking in the vast oceans continue to operate with near invulnerability (Friedman, 2020, pp. 69, 78).

Against this backdrop, this paper is the first in a two-part series discussing anti-submarine warfare. It addresses existing platforms, while contextualising their strategic significance. It then outlines how ASW is conducted and its operational and technological limitations. Finally, in response to such limitations, this paper examines emerging trends and capabilities that may help break the longstanding stalemate between submarines and their hunters, which has characterised operations in the undersea domain. It specifically addresses the role of non-acoustic submarine detection methods, unmanned systems, and advanced computing capabilities in redefining undersea operations over the coming decades. This final section sets the stage for the second paper in the series, which explores how states can apply these emerging ASW technologies to the protection of another central yet distinct element of undersea warfare – subsea cables.

2. Submarines' Strategic Context

SSBNs are the most resilient leg of the nuclear triad (Vedachalam, 2025, p. 4). Thus, one critical pillar of current global strategic stability lies in the near invulnerability of nuclear-power submarines, which grants a credible second-strike capability to the nuclear-armed nations (Friedman, 2020, p. 69). Importantly, the number of actors operating subs has risen. During the Cold War era, there would be little doubt about who launched a nuclear strike. Today, with the United States, Russia, the United Kingdom, France, China, and India operating SSBNs (Lisman, 2019, p. 2), the source of a nuclear warhead launched by a submarine is challenging to determine. Unless a state tracked every SSBN continuously – which remains objectively impossible – the origin of an attack could be traced only to a broad area of the ocean. This dilemma means that potential attacks from SSBNs will be essentially anonymous, particularly when compared to the easily traceable trajectories of land-based missiles (Friedman, 2020, pp. 69, 72). Adding to the threat calculus, more than 40 states now operate diesel-electric attack submarines (SSKs). These submarines are relatively low-cost compared to nuclear-powered vessels and can provide effective local maritime control against a stronger opponent, making them a genuine challenge for ASW (Scipanov & Păuna, 2020, p. 310). As of 2024, around 502 submarines were in service worldwide. The vast majority of these (279) were conventional SSKs, many nearly 80 years old and nearing obsolescence (Fischbach, 2024). Nuclear-powered attack submarines (SSNs), SSBNs, and Nuclear-Powered Guided Missile Submarines (SSGNs) constitute the remaining share of the world's submarine fleets; however, they tend to be more modern, with only two per cent of these 130 nuclear-powered submarines considered outdated, as countries possessing the technological and financial capacity to operate these platforms tend to have larger military budgets to keep them up to date (Fischbach, 2024, paras. 5–6). Indeed, maintaining operational platforms and corresponding undersea countermeasures remains one of the most technically demanding and costly challenges for modern militaries (Peters, 2021, p. 94).

2.1. *ASW Doctrine*

ASW aims to prevent submarines from accomplishing their missions, whether those include attacking surface ships, disrupting supply routes, or firing missiles (AnD Market Reports, 2025). Its doctrine can be divided into detection, tracking, and engagement. Naval strategies typically prioritise the former two, given that a submarine's tactical advantage is tied to stealth; once spotted, the platform will prioritise evasion over combat (Peters, 2021, p. 103).

The detection of submarines relies primarily on sonar technology. Sonar is a technique that utilises acoustic systems to detect propeller noise, engine sounds, and water-flow disturbances amid the background noise of the ocean (Aviation and Defense [AnD] Market Reports, 2025; Scipanov & Păuna, 2020, p. 310). Analysts use the collected data to estimate the location of a submarine through the Cumulative Detection Probability (CDP) model. They run simulations that generate numerous hypothetical paths, named notional tracks, representing possible submarine movements. Each track is assigned a probability weight that is updated as new signals become available, progressively refining the target's location estimate, in a process called Bayesian search (Vedachalam, 2025, p. 11). However, this task is complicated by the fact that passive sonars [1] cannot reliably distinguish between SSBNs and non-nuclear submarines, and active detection methods, which depend on interpreting the echoes of emitted sonar pings, tend to have even greater difficulty in making such distinction (Friedman, 2020, pp. 73). Furthermore, oceans are becoming increasingly noisy and congested due to the growing number of countries operating submarines and the expanding economic use of seabeds (Friedman, 2020, p. 72). Submarines are becoming harder to detect due to noise-reduction designs and the adoption of acoustic jamming technologies (Scipanov & Păuna, 2020, p. 310). At their peak, advanced fixed-array systems, such as the U.S. Sound Surveillance System (SOSUS), were able to estimate a submarine's position with an uncertainty of about a 97-kilometre radius. This lack of precision forces militaries to deploy alternative detection assets, such as maritime patrol aircraft (MPA), following cues from listening networks to further track target submarines (Kaushal, 2025, p. 2).

Sonobuoys and sensors are the primary submarine tracking devices, including an aircraft's onboard Magnetic Anomaly Detector (MAD), which, while limited to close-range operations, can detect magnetic disturbances from a submarine's metal hull (AnD Market Reports, 2025). If such is the case, an MPA may choose to engage the target directly or request assistance from better-suited trailing [2] platforms, such as destroyers, frigates, or attack submarines (AnD Market Reports, 2025; Kaushal, 2025, p. 2). Ships have proven less effective than submarines in tracking hostile submarines, but even the latter would likely need to be nuclear-powered, as they must shadow their target for lengthy periods (Friedman, 2020, p. 69). Therefore, the successful tracking of hostile submarines is a highly complex process that relies on multiple dispersed sensors

[1] Passive sonars detect sounds emitted by underwater objects, as opposed to active sonars who emit signals of their own and then analyse their reflections.
[2] Trailing means following at close range and is a component in the broader task of tracking an enemy submarine.

and platforms within a large ocean area, making large-scale coordination extremely challenging, even after initial detection. One of the most feasible means of tracking an enemy submarine is detecting and trailing the target after it passes through a chokepoint, but even then, effective tracking remains difficult (Friedman, 2020, p. 74). The ocean area between Greenland, Iceland, and the United Kingdom (GIUK) is one such chokepoint. As Kaushal (2025, pp. 2–3) explains, maintaining continuous coverage of a single submarine passing through the GIUK Gap would require 12 to 14 MPAs at full readiness. Moreover, this estimate assumes an uncontested airspace. Even minor enemy interference could render sustained tracking impossible. Nonetheless, if presented with an opportunity to engage, the 'kill' options would include offensive mines, lightweight torpedoes launched from aircraft or surface ships, heavyweight torpedoes fired from submarines, and, to a lesser extent, depth charges (AnD Market Reports, 2025).

3. Emerging Trends and Capabilities in ASW

Historically, ASW has been time-consuming, resource-intensive, and extremely costly (Peters, 2021, p. 103). As previously discussed, it also faces significant operational limitations. Therefore, there are high expectations within the field that emerging technologies, such as unmanned underwater vehicles (UUVs) and data analytics for detection, could provide a breakthrough in ASW.

3.1. *Unmanned Vehicles*

UUVs can already perform a range of missions, including intelligence, surveillance and reconnaissance, mine countermeasures, communication and navigation support, cargo transport, and strike operations (Zhao et al., 2019, p. 1). Analysts anticipate that such abilities will change the cost and doctrine of undersea operations. Peters (2021, p. 103) envisions how such operations might evolve in the near future, where uncrewed crafts play an increasingly important role in detection, tracking, and even engagement. The author portrays a scenario in which these assets could, in an integrated manner, detect adversaries through fixed and deployable sensors, complemented by UUVs and unmanned surface vehicles (USVs) towing sonar arrays. Once contact is made, unmanned aerial vehicles (UAVs) can be deployed, for example from a coordinating aircraft carrier (Scipanov & Păuna, 2020, p. 312), and conduct further tracking through onboard radars or deployed sonobuoys on the water's surface. Simultaneously, tracking can be enhanced through the use of passive and active sonars on UUVs, operating as a multi-static sensor network.

The next step would be to deploy traditional manned ASW platforms for further tracking or engaging with the hostile submarine. Until now, only these traditional craft are known to possess the capacity to carry torpedoes large enough to ensure the neutralisation of another submarine (Peters, 2021, p. 103). In December 2025, however, the Security Service of Ukraine (SBU) reported using a UUV to strike a Russian SSK at Novorossiysk (Al Jazeera, 2025). While it remains difficult to confirm the submarine's actual incapacitation (Cheetham, 2025), this episode underscores how military operations can surprise and reshape what civilian analysts had considered possible up to that point.

Uncrewed crafts can serve as an organic combat web, performing tasks ranging from low-visibility reconnaissance and surveillance to deception measures such as torpedo decoys, and full kinetic action when necessary (Zhao et al., 2019, pp. 3-4). Much as submarines progressed over the last century from reconnaissance platforms to blockade enforcers and, eventually, stealth missile carriers, UUVs could follow a comparable evolution (Glassman, 2019, pp. 3, 8).

The potential of UUVs could revolutionise the future of undersea warfare. However, we are still far away from materialising such a change, and there are some caveats to consider. Peters' (2021) conceptualisation of a network of integrated unmanned systems for detection appears to conflict with Friedman's (2020, p. 70) warning that even a notable multiplication these platforms would face challenges in effectively covering the vast waters in which submarines can operate. Moreover, safe communication from underwater to the surface, air, and space has long been a challenge in the undersea domain and will affect the operation of UUVs. Until navigation systems become more advanced, collisions remain an issue to account for, as these platforms will likely face heavy traffic, particularly in coastal zones (Scipanov & Păuna, 2020, p. 312). In addition, militaries must not overlook the threat of cyber-attacks and the corresponding need for cyber resilience, as UUV networks could be increasingly targeted, compromising operational control (Glassman, 2019, p. 11). Lastly, the issue of powering UUVs remains an important hurdle to realising their full potential, as current devices lack endurance. While researchers are studying new batteries, fuel cell technology, and mid-mission homing and docking stations, the future of UUVs appears better suited to detection and tracking rather than to trailing (Scipanov & Păuna, 2020, p. 312; Vedachalam, 2025, p. 30).

3.2. *Non-Acoustic Detection Technology*

As cutting-edge submarines become more silent, passive sonars have seen their range drop from several kilometres to hundreds of meters. Active sonars can still detect targets within a range of a few kilometres, but they alone are unable to classify them, needing to be complemented by human interpreters with specialised training and extensive practice (Peters, 2021, p. 101; Scipanov & Păuna, 2020, p. 311; U.S. Navy, n.d.). Hence, the future of ASW will likely involve non-acoustic detection methods. This outlook is not new, as attempts have been made to develop such technology, but with little effect (Friedman, 2020, p. 77). Nevertheless, the emergence of big data capabilities has renewed hope for the potential of non-acoustic detection methods.

When navigating, a submarine disturbs its surrounding environment in various ways. As it passes, it creates a slight rise in the ocean surface – known as the Bernoulli hump – and a V-shaped wake behind it referred to as Kelvin waves. The magnitude of these signs, however, is infinitesimal, especially when the submarine travels slowly or at great depth (Lisman, 2019, p. 3). Likewise, its hydroplanes create vortices that rise to the surface, though at a speed much lower than that of wind-driven surface currents. The heat generated by submarines can create a surface thermal signature, theoretically detectable by infrared, but too weak to allow for tracking in practice. Its passage disturbs living organisms, whose bioluminescence may be detectable, although a deeply submerged submarine is unlikely to cause sufficient surface light disturbance. Additionally, submarines can leave an electromagnetic signature generated by wake turbulence (Friedman, 2020, p. 78).

Scientists have long understood these effects, yet the vast amounts of data required to detect and analyse such subtle signs have made practical exploitation difficult. Advances in computing power and artificial intelligence could finally enable the applied use of these phenomena (Scipanov & Păuna, 2020, p. 311; Peters, 2021, p. 101; AnD Market Reports, 2025). For instance, sea and airborne LIDAR – which measures changes in emitted light pulses – can now detect wake variations of less than one centimetre, although limited to a depth of 200 metres (Lisman, 2019, pp. 3-5). Conventional sensors have also seen similar developments that could lead to a resurgence in their operational value. Passive listening devices like SOSUS could utilise quantum technology to isolate the subtle sounds of modern submarines from the ocean noise (Peters, 2021, p. 102; Friedman, 2020, p. 77). As enhanced data-processing may enable better signal detection, progress is likely to be complex rather than straightforward.

3.3. *Key Warnings*

While the developments in submarine detection and tracking techniques could change the way states conduct ASW, implementing comprehensive and practical signal-processing capabilities represents a considerable technical and financial endeavour.

On a technical level, Coy (2025, p. 39) notes that even if advances in signal processing enable magnetometers such as MADs to overcome environmental noise, their detection range would remain small relative to the size of the oceans, with a predicted maximum of around 10 kilometres in the near future. Such a figure implies that one million floating MADs would be required to achieve full ocean-wide detection. Beyond feasibility questions and the challenges of maintaining such a large infrastructure, exposed to natural and human interference, navies would need to be cautious not to alert adversaries to the existence of the expanded surveillance network. Nonetheless, detection is not the primary challenge for modern MAD systems. Instead, the difficulty lies in classifying anomalies at sub-nanotesla levels, particularly as modern platforms increasingly incorporate non-ferrous metals, and in distinguishing submarines from other sources of noise (Coy, 2025, p. 40; Lisman, 2019, p. 5). Regarding the remaining alternative sources of information for detection and tracking, similar reservations about viability arise, particularly in the case of SSBNs, which can operate at speeds of up to 20 knots. Consequently, sustained tracking, regardless of the method employed, would require a fleet of high-speed unmanned or crewed vehicles dedicated to trailing all foreign submarines of interest. Paradoxically, this strategy would complicate a navy's ability to surprise an adversary and achieve a disarming first strike (Coy, 2025, p. 40).

On a financial level, ASW is highly expensive, both in capital expenditures (CAPEX) and operational expenditures (OPEX) (Wehner et al., 2023, p. 5). A priority-focus on ASW would shift funding away from other naval operations that, outside the context of war, may carry greater strategic significance (Friedman, 2020, p. 77). Thus, the expectation is that as unmanned aerial vehicles (UAVs) emerge as a cost-effective combat platform in modern conflicts, like in Ukraine (Jensen & Atalan, 2025, p. 2), UUVs could similarly become a cost-effective tool for ASW. As in Kaushal's (2025) GIUK Gap example, Wehner et al. (2023, p. 5) project that in a corresponding alternative that employs uncrewed MPA, there could be an estimated 82 per cent saving in combined CAPEX and OPEX. The prediction is that the MPA approach would amount to approximately EUR 58 million per month, whereas the uncrewed concept would cost around EUR 10 million per month. Notably, while MPA operations are OPEX-intensive, the uncrewed model inverts this proportion, with higher CAPEX but significantly lower OPEX. Consequently, the long-term financial sustainability of UUV-based ASW may prove superior to the operational costs of maintaining advanced submarines, potentially weakening their longstanding stealth edge. Yet, current submarine fleets represent a sunk cost, and affordably achieving UUV primacy may require a significant upfront CAPEX investment.

Overall, the implications of emerging trends for ASW do not appear as groundbreaking as anticipated. Even with today's progress, the capacity to effectively detect, track, and engage an entire enemy SSBN fleet within a short timeframe would require a gigantic leap in ASW capabilities (Lisman, 2019, p. 8). The logistical scale of the envisaged networks centred on quantum and big data-enabled sensing, combined with the likely adaptive responses of submarine operators, ensures that submarines will retain their stealth for the foreseeable future (Coy, 2025, p. 43; Peters, 2021, p. 100). The substantial investments by navies in SSBN programmes support this view, underlining the expectation that the oceans will remain opaque despite the prospect of technological advances (Childs, 2021). While this reality may frustrate military officials and scientists responsible for developing and deploying ASW capabilities, conventional global stability relies on the strategic value of submarines for nuclear deterrence (Lisman, 2019, p. 1). Disrupting that delicate equilibrium is neither trivial nor necessarily desirable.

4. Conclusion

Anti-submarine warfare remains trapped in a stalemate. Insufficient detection and tracking capabilities fail to reduce the opacity of the undersea domain, thereby preserving the central role of submarines in global deterrence. Emerging technologies, ranging from unmanned systems to quantum computing and big-data analytics, are increasingly expected to disrupt this balance. Nevertheless, their implementation faces operational, technical, and financial hurdles that limit their immediate potential. As such, while these innovations may bear fruit, they are unlikely to eliminate the opacity that defines the undersea battlespace. Furthermore, improvements in ASW capabilities must compete with advances in submarine technologies, such as non-ferrous hulls and greater operating depths. SSBNs will likely retain their stealth and strategic value for the foreseeable future. This high-stakes predator-prey dynamic requires navies to maintain secrecy to protect their competitive edge. Therefore, this paper may not capture the full scope of current capabilities, as it relies on open-source information and literature.

The study of emerging ASW tools prompts a broader reflection on their applicability beyond the conventional military scope. Many of the surveillance capabilities being developed to detect submarines could, in principle, be adapted to protect other critical undersea assets. The second part of this series builds on this idea, examining how new ASW technologies could contribute to the much-needed securitisation of subsea cables, which are an increasingly attractive target in hybrid warfare.

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