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Undersea nuclear forces: Survivability of Chinese, Russian, and US SSBNS

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ABSTRACT

China, Russia, and the United States base a substantial number of strategic nuclear warheads on submarines. Technologies for sensing, vehicle autonomy, and communication under the oceans are steadily improving. These technologies can be used to protect SSBNs from crewed and uncrewed (autonomous) systems that attempt to detect, localize, track, and threaten SSBNs at sea. These same technologies can be applied to directly threaten SSBNs. Given the geographic and oceanographic constraints on tracking SSBNs at sea, it is more likely that new technologies can be effective in protecting SSBNs than threatening them over an extended time.

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Introduction

The United States, China, and Russia maintain nuclear weapons based in nuclear powered submarines known as ballistic missile submarines (SSBNs). These vessels carry submarine launched ballistic missiles (SLBMs) that can be launched from below the sea surface at targets thousands of miles away. Sea-based strategic forces comprise a significant fraction of the long-range nuclear arsenal of all three nations. The vulnerability of SSBNs and the weapons they carry are therefore an important factor to consider in assessing the capability of each nation to use them at any time during a crisis, a conventional war, or a nuclear war.

All modern navies develop the means to find and destroy submarines as part of the mission of antisubmarine warfare (ASW). Most ASW capabilities are developed to reduce the threat of nuclear-powered attack submarines (SSNs) and conventionally powered attack submarines (SSKs) to surface combatants, merchant ships, and land targets. This tactical ASW mission makes use of undersea sensors and weapons on aircraft, surface combatants, and other attack submarines. Strategic ASW, on the other hand, is the activity of

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applying antisubmarine capabilities to locate, identify, track, and potentially destroy SSBNs at sea.

To function as a nuclear deterrent, a substantial number of SSBNs must continue operating and be able to receive orders from national leaders to launch SLBMs against an adversary at any time during a crisis, a conventional war, or a nuclear war. Nations that rely on SSBNs as part of their deterrent must have confidence in their survivability and must convince their adversary of their survivability. To bolster the credibility of the sea-based deterrent weapons, nations that maintain SSBNs do what they can to introduce costs and uncertainties to an adversary that might try to destroy them.

This paper will argue that new and existing technologies embedded in operations to find and track an adversary's SSBNs can also be used to protect one's own SSBN fleet. The effectiveness of SSBN protection measures is very likely to increase more rapidly than threats to SSBNs. The costs of threatening and attacking SSBNs are likely to be high in the foreseeable future. As a result of this trend, SSBNs are likely to be reliable second-strike nuclear forces over the next 20 years and beyond.

This analysis will begin with the current approaches that the United States, China, and Russia take to the problem of operating SSBNs so that they are most likely to be secure.

Protecting Today's SSBNs

Submarines in their ports, repair facilities, or on the sea surface getting to or from those facilities must be assumed to be detectible from space, given the rapidly growing number of sensing satellites in orbit. There are few details available about all the means that Russia, China, and the US use to protect their SSBNs while they are in these vulnerable states. I will assume that there are procedures for assuring that SSBNs can move from ports and other facilities to larger ocean areas where they can operate submerged and with a greater degree of stealth. Many of the technical concepts are described later, but the specific procedures is largely a matter of speculation.

The United States today operates its SSBNs today in the Atlantic and Pacific Oceans largely independent of any other ships, submarines, or aircraft. US SSBNs are extremely difficult to detect and have direct access to tens of millions of square kilometers of ocean. Strategic ASW against US SSBNs would require enormous military expenditures and yield a highly uncertain outcome in finding let alone reducing the threat of US nuclear retaliation. In other words, US SSBN security relies heavily on making the very first steps of ASW search and detection impractical for any adversary. This means that the US does not need to allocate significant maritime forces to actively prevent an adversary from follow-on steps of trailing or tracking SSBNs.

China and Russia, on the other hand, operate SSBNs in ocean areas relatively close to their home shores because their SSBNs are more detectable by US SSNs and could be detected when they leave port. Russian and Chinese SSBN ports are relatively close to the territories of US allies and partners in the Arctic and the Pacific Oceans. The proximity of US allies and partners to SSBN bases means that Russian and Chinese SSBNs and other maritime forces could be subject to surveillance as they depart their bases or attempt to enter the Arctic, Atlantic, or Pacific Oceans. Chinese and Russian SSBNs cannot rely on forcing the US to undertake long and extensive ocean searches to ensure survivability, so these two countries must compensate by creating risks to any strategic ASW forces themselves in these close-in waters. China's SSBN operating areas are believed to include the South China Sea and the Yellow Sea They may also use parts of the East China Sea and sections of the very shallow Bohai Gulf. Russia's SSBNs probably operate in the Barents and Kara Seas adjacent to the Arctic, and in the Sea of Okhotsk and adjacent regions of the far Western Pacific near the Kamchatka Peninsula, as described in the APPENDIX.

By operating SSBNs at relatively short distances from shore bases, the navies of China and Russia can use attack submarines, surface ships, and aircraft with medium to long ranges to threaten US SSNs in those waters. Defending the airspace over seas where SSBNs operate is an important part of protecting them. Land-based integrated air defense systems (IADS) and ocean search radars provide warning and targeting against adversary ships and aircraft conducting strategic ASW in these areas. The relatively close-in SSBN operating areas also create options for deploying and maintaining naval mines, autonomous systems, and fixed sensors to protect against strategic ASW forces. These protected areas are known as bastions, a term that originated during the latter part of the Cold War to describe the Soviet Navy's operational approach to protecting their SSBNs. These operating modes are not mutually exclusive, however. SSBNs can operate within protected bastions as well as in open ocean patrols, depending on the evolution of a crisis or war and the perception of risk to the SSBNs among the SSBN commanders and national decision makers.

The United States, Russia, and China must assume that a threat to their SSBNs exists and could be used in a crisis or conventional war, so they develop practical measures to increase their probability of survival over extended durations of a conflict. High-level US national and naval strategy documents do not explicitly call for plans to threaten SSBNs, as they did in the 1980s, but statements to that effect have appeared recently. Regarding strategic ASW directed against Russia, Bradford Dismukes wrote in 2020 that 'the Navy recently let it be known that it contemplates using its submarine force to "deny the bastions": that is, to attack Russian SSBNs'.[1] The Commander US Pacific Command stated in 2018 that 'An armed JIN-class SSBN will give China an important strategic capability that must be countered'.[2] Countering these SLBMs could refer to either use of anti-ballistic missile technology or strategic ASW or both.

Threats to SSBNs can also arise as a consequence of conventional naval operations in or near the bastions. A recent summary of China's views on the role of their SSBNs in national strategy recommends that US decisionmakers take careful measure of the risks of nuclear escalation due to the overlap between operations against Chinese attack submarines and threats to Chinese SSBNs. 'Addressing the risks may require tradeoffs between maximizing conventional advantages and limiting the risks of nuclear use by, for instance, limiting ASW against Chinese SSBNs and supporting capabilities'.[3]

China, Russia, and the US view the survivability of their SSBNs as valuable enough to invest in ways to protect them. The United States, which keeps the highest percentage of warheads on submarines of all three nations prioritizes the construction of its next SSBN class above all other naval programs.[4] By ensuring that these SSBNs are survivable without the need for direct protection from general purpose naval forces, the US Navy investment in SSBNs avoids operational constraints on these expensive conventional naval forces, and therefore avoids the associated opportunity costs. Given the global role of the US Navy these opportunity costs are very large.

As China's ambitions as a maritime trading nation and naval power grow, the Chinese Communist Party leadership is likely to weigh these same opportunity costs in the future. Means for protecting China's SSBNs that depend less on general purpose maritime forces will likely be viewed as good

[1]Bradford Dismukes, 'The Return of Great-Power Competition – Cold War Lessons about Strategic Antisubmarine Warfare and Defense of Sea Lines of Communication', *Naval War College Review* 73/3 (June 2020), 33–63. Dismukes has documented other statements and writings from senior US Navy leaders about strategic ASW in his blog. See Brad Dismukes, 'Strategic ASW in 2022 – A Stunningly Bad Idea', Clio's Musings, 28 June 2022. https://cliosmusings.blog/2022/06/19/strategic-asw-in-2021-a-stunningly-bad-idea/.

[2]Statement of Admiral Harry B. Harris Jr., U.S. Navy Commander, U.S. Pacific Command, Before the House Armed Services Committee on U.S. Pacific Command Posture, 14 Feb. 2018. https://docs.house.gov/meetings/AS/AS00/20180214/106847/HHRG-115-AS00-Wstate-HarrisJrH-20180214.pdf.

[3]David C. Logan, 'China's Sea-Based Nuclear Deterrent: Implications for the PLAN, Chinese Nuclear Strategy, and U.S.-China Strategic Stability', in Andrew Erickson and Ryan Martinson (eds.), *Chinese Undersea Warfare* (Newport, RI: Naval War College Press forthcoming). In addition, Tong Zhou, 'Tides of Change: China's Nuclear Ballistic Missile Submarines and Strategic Stability', Carnegie Endowment for International Peace, 2018. https://carnegieendowment.org/files/Zhao_SSBN_final.pdf is an excellent starting point for gaining an understanding of Chinese views of their SSBNs and nuclear strategies based on Chinese sources. The most comprehensive analysis of the Chinese Navy is produced by Andrew Eriksen, Lyle Goldstein, and others at the China Maritime Studies Institute of the US Naval War College. The Chinese technical references that I rely on in this paper are useful for their technical content, but should not be viewed as statements of Chinese naval development priorities or policies.

[4]The new SSBN has been the top priority since 2013. Ronald O'Rourke, 'Navy Columbia (SSBN-826) Class Ballistic Missile Submarine Program: Background and Issues for Congress', *Congressional Research Service Reports*, 31 Mar. 2023. p. 1. https://crsreports.congress.gov/product/pdf/R/R41129.

investments by the PLA Navy. While the situation for the Russian Navy is different, Russia's hopes for dominating the Arctic in the face of competition from many world powers – including China – rest heavily on its ability to maintain a Northern Fleet that is present and capable from the Norwegian Sea to the Bering Strait. The Russian Navy also must trade off valuable flexibility in how they use their general-purpose naval forces to support their top mission of protecting their SSBN bastions. Thus, all three nations view SSBN survivability as highly desirable and will likely pursue cost-effective means for securing them.

This paper provides arguments why SSBN survivability will be technically feasible and cost-effective through the adaptation of current and future technology and operations over the next 20 years.

Two reasons why SSBNs will be able to retaliate

There are two broad reasons that the United States, China, and Russia will be capable of preserving some level of survivable second-strike forces at sea over the coming two decades.

Search, detection, and tracking is difficult and can be disrupted

The first reason is that new physical sensors and data fusion algorithms will always be constrained by the problems associated with searching for, identifying, and tracking multiple SSBNs in the presence of background noise, deliberate jamming, sensors, and deceptive decoy signals produced by adversaries. There are fundamental limits on the ability of computer algorithms to extract useful information about submarines from noisy, cluttered, and deceptive data. There are many ways to inject uncertainty into each of the many stages of strategic ASW search, detection, identification, and continuous tracking over the course of a long crisis or conventional war.

Technology for undersea warfare is increasingly available for SSBN protection

The second reason that entire SSBN fleets will be difficult to destroy with high confidence stems from the fact that improvements in sensor hardware and sensor data processing applicable to tracking submarines at sea are likely to proceed in parallel between the US and its allies on the one hand, and China and Russia on the other. Advances in searching for, detecting and tracking undersea threats including submarines and other vehicles are easier to install, maintain, and use in oceans close to home territory than they are as part of a distant oceanic sensing architecture. Over the course of a long conflict, combinations of existing and new sensors, ocean vehicles, and signal processing methods are likely to be successfully used for defending one's own SSBNs near home territories before they are widely and effectively deployed for the much more challenging and costly tasks of detecting, tracking, and destroying the SSBNs of a distant adversary. For the United States, this will provide the intelligence community with opportunities to collect data about the state of Russian and Chinese ASW technology.

Continued role for conventional maritime forces

For the next 20 years, some portion of general-purpose maritime forces of China and Russia will likely be tied to the role of protecting SSBNs in bastions near their national territories. Land-based integrated air defense systems, oceanic radars, and space sensors are needed to provide some measure of control over the air and sea surface to protect homeland territory and military infrastructure, so the role of air defense in protecting SSBNs is not an additional burden in bastion areas. However, allocating ships, aircraft, and attack submarines specifically to protect SSBNs in these bastions restricts their use in other conventional roles. Chinese and Russian military leaders will recognize this constraint and likely value technology developments that can improve the survivability of SSBNs at lower cost and with reduced reliance on general purpose naval forces. Applications of mines, new undersea sensors, communications methods, and autonomous platforms in these local areas are likely to be applied to disrupting threats to the SSBNs. Chinese and Russian sources openly describe technology and operational concepts for protecting nearby ocean areas from undersea threats, as I will discuss later.

The most potent threat to Russian and Chinese SSBNs has long been US nuclear-powered attack submarines. These SSNs have many possible roles in naval competition and are viewed by the US Navy as critical for deterring conventional war. Should a war begin, US SSNs would be important throughout the Atlantic and Pacific Oceans for many missions that are essential to winning a prolonged conventional war including striking ships and land targets, protecting essential logistics, and intelligence gathering.

Towards the end of the Cold War, the United States clearly stated in the Maritime Strategy of 1986 that US SSNs would operate in Soviet SSBN bastion areas to threaten and attack SSBNs throughout all phases of a war.[5] In that era, there were many more US SSNs than there are now. In 1985 the US had 57 SSNs in the Atlantic and 39 SSNs in the in the Pacific, whereas as the end of FY2022 there were 50 SSNs in service in the US Navy, divided about evenly between the Atlantic and Pacific. During the Cold War, US attack submarines were vastly superior to Soviet SSBNs, and China was not considered a likely adversary in a major war.

[5]Bradford Dismukes, 'The Return of Great-Power Competition'. The original publication of the Maritime Strategy is Admiral James D. Watkins, 'The Maritime Strategy', *US Naval Institute Proceedings* 112/1 (Jan. 1986).

Today, the United States has not emphasized threats to Russian or Chinese SSBNs as part of its public declaratory naval strategy.[6] Over the course of a long war, however, thinking on this matter could evolve. The United States will need to continuously evaluate the tactical and strategic impacts of the use of limited and valuable SSNs at various stages of a future conflict. The risks to SSNs from emerging technologies applied to defending Russian and Chinese SSBNs will be an increasingly important part of that evaluation over the coming decades.

SSBN designs and survivability

Ballistic missile submarines are used as platforms for strategic nuclear weapons because they are difficult to find, identify, and track when out of ports at sea submerged at substantial depths. The requirements that follow from this are that SSBNs must operate for long durations at sea and at depths that make detection difficult. The first issue to address is what technologies that are part of the SSBNs themselves will impact their survivability over the next 20 years.

SSBN stealth improves when it is more difficult to sense them at a distance. Since sound is constantly produced by submarines and is transmitted efficiently in water over substantial distances, technologies to reduce emitted sound are used to make stealthy submarines.[7] Passive sonar that can detect underwater sound but which is not detectable itself is the most immediate threat to SSBNs from other SSNs, since passive sonar can – if operated from a very quiet submarine – determine the direction to a noisier SSBN and, with some maneuvering, its location. Sources of sound in a nuclear-powered submarine include internal machinery that converts reactor heat into mechanical energy for propulsion as well as propellers and other devices for propulsion itself. Techniques for reducing radiated sound include acoustically isolating internal machinery from the outer hull, reducing sound from propellers, and other methods, all of which require skilled technicians to maintain.

[6]Chief of Naval Operations Navigation Plan (July 2022). https://www.navy.mil/Press-Office/Press-Releases/display-pressreleases/Article/3105576/cno-releases-navigation-plan-2022/. The Navy, Marine Corps, and Coast Guard released the Tri Service Maritime Strategy in 2020. 'Advantage at Sea', 17 Dec. 2020. https://www.navy.mil/Press-Office/Press-Releases/display-pressreleases/Article/2449829/navy-marine-corps-coast-guard-release-maritime-strategy/. A more complete discussion of US naval strategy as of 2019 can be found in Sam J Tangredi, 'Running Silent and Algorithmic: The U.S. Navy Strategic Vision in 2019', *Naval War College Review*: 72/2 (Apr. 2019). https://digital-commons.usnwc.edu/nwc-review/vol72/iss2/20.

[7]Sound produced underwater by submarines does not effectively move to the atmosphere except for sources very near the surface and at very low frequencies of order 1 cycle per second. See Godin, Oleg A., (2008) 'Sound Transmission through Water-Air Interfaces: New Insights into an Old Problem', *Contemporary Physics* 49/2 (2008), 105 – 123). http://dx.doi.org/10.1080/00107510802090415.

In addition to quieting, the ability for SSBNs to evade quiet SSNs or other undersea mobile threats depends on the effectiveness of external acoustic sensor arrays and the signal processing algorithms that provide useful information to the SSBN commander about other vehicles in the vicinity. There are fundamental limits to signal processing, however, and it cannot in general be improved sufficiently to fully compensate for quieting of an adversary submarine and increases in ambient noise due to the unavoidable tradeoffs between detection probability and false alarms, as well as limits imposed by the fluctuating noise and transmission of sound in the ocean.[8] Despite improvements in sonar and signal processing, passive detection ranges appear to be diminishing for all submarines. In fact, nuclear-powered submarines have for many years been so difficult to detect from other submarines that they occasionally collide underwater.[9]

As submarines have become quieter, active sonar has become an increasingly important means of finding them. This trend has been well-understood since the end of the Cold War.[10] Active sonar emits momentary but powerful pulses of sound from a transmitter into the water. The pulse of sound scatters off objects in the ocean and can be detected at a receiver. Methods for reducing the backscatter of active sonar sound from submarines include surface coatings that absorb incoming sound energy as well as methods to sense the incoming sound, calculate waveforms that can cancel part of this incoming sound, and then radiate those cancellation waveforms back toward the active sonar. However, active sonar sources are generally detectable at much greater ranges than the active sonar users can detect objects in the water. This powerful transmission gives away the presence and direction of the active sonar and creates opportunities for an SSBN to avoid it.

In addition to passive and active acoustic sensors, there are a number of nonacoustic physical effects produced by submerged submarines of all types that can in principle be detected. Slow speeds and deeper operations sharply reduce some observable signatures such as surface effects, but other disturbances in the ocean cannot easily be reduced. Ballistic missile submarines are massive steel vessels close to 170 meters long and about 13 meters in diameter so that even at speeds of a few knots with careful maneuvers they inevitably create some physical disturbances in the ocean. These effects are

[8] Robert J. Urick, *Principles of Underwater Sound,* Third Edition (Westport, CT: Peninsula Publishing 1983), Ch. 12.

[9] The UK submarine HMS Vanguard and the French submarine Le Triomphant collided in the Atlantic in 2009. *BBC News*, 'Nuclear Subs Collide in Atlantic', 16 Feb. 2009. http://news.bbc.co.uk/2/hi/uk_news/7892294.stm. In 1992, a Russian Sierra-Class attack submarine hit the USS Baton Rouge, a Los Angeles-class attack submarine in international waters just off Murmansk as described in Eugene Miasnikov, 'Submarine Collision off Murmansk', *The Submarine Review* 6 (Apr. 1993), 6–14. https://archive.navalsubleague.org/1993/submarine-collision-off-murmansk-a-look-from-afar.

[10] Gordon D. Tyler, Jr., 'The Emergence of Low-Frequency Active Acoustics as a Critical Antisubmarine Warfare Technology', *Johns Hopkins APL Technical Digest* 13/1 (1992). https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V13-N01/13-01-Tyler.pdf.

only marginally influenced by changes in the hull design, and include the turbulent wake created behind any large self-propelled body, the follow-on influences of these wakes on the temperature profile of the ocean, and related hydrodynamic effects. Other physical effects that are independent of depth and speed include distortions of the earth's natural magnetic field as well as electric fields produced by dissimilar materials on the submarine hull. These effects can be reduced through improved materials and design, but generally these are fields that are small and can only be detected locally. There is evidence that submarine-generated hydrodynamic effects create observable changes at the sea surface that can, in certain conditions, be detected from remote sensors such as synthetic aperture radars at longer ranges through the atmosphere. However, there is no available evidence that such sensors can be reliably used for open-ocean search and tracking of SSBNs operating at great depths and slow speeds. These topics are addressed in more detail later in this paper.

The SSBN signature that is likely to continue to be the most important aspect of SSBN stealth is the radiation of sound. Consequently, the main thrust for SSBN development over the next 20 years will continue to be acoustic quieting and improved sensing. As submarines become quieter and the oceans become noisier, there is a point where additional efforts to reduce radiated sound do not yield tactically useful reductions in detectability. SSBN design changes over the next 20 years will probably yield small reductions in detection ranges by acoustic or non-acoustic sensors. SSBN maintenance and testing will continue to be a very important part of minimizing these signatures.

Russia, China, and the United States continue to invest in improved SSBNs. Russia is in the process of completing the replacement of its Cold War era SSBNs. There are five of the older Delfin (Delta IV) class SSBNs in the Northern Fleet, four Borei class SSBNs, and two newer Borei-A class SSBNs.[11] In addition to these SLBM-firing submarines, there is a new large Belgorod submarine designed to launch the nuclear-armed long-range torpedo known as Poseidon. Russia's shipbuilding plans call for ten Borei-class SSBNs, with five to be deployed in the Northern Fleet operating in the Barents Sea and other parts of the Arctic, and five in the Pacific, based on the Kamchatka Peninsula.[12] The Office of Naval Intelligence has assessed that the Borei class SSBNs radiate marginally more noise than the Severodvinsk SSN.[13] A recent statement from the US Northern Command indicated that the

[11] Hans M. Kristensen, Matt Korda, and Eliana Reynolds, 'Russian Nuclear Weapons, 2023', *Nuclear Notebook: Bulletin of the Atomic Scientists* 79/3 (May 2023), 174–99.

[12] Mary Beth D. Nikitin, 'Russia's Nuclear Weapons: Doctrine, Forces, and Modernization', *Congressional Research Service Reports*, 21 Apr. 2022. https://crsreports.congress.gov/product/details?prodcode=R45861.

[13] Office of Naval Intelligence, 'Submarine Quieting Trends', in *The People's Liberation Army Navy: A Modern Navy with Chinese Characteristics* (2009), p. 22. https://apps.dtic.mil/sti/citations/ADA510041.

Severodvinsk is 'very quiet, nearly on a par with ours'.[14] This suggests that the Borei class may be approaching a quieting level close to those of US submarines. As these newer SSBNs are built and deployed over the next 20 years, it is likely that they will become incrementally quieter and therefore more difficult to trail with passive sonar.

The relative level of quieting of Chinese SSBNs can only be roughly inferred from various sources. The Office of Naval Intelligence published information in 2009 that indicates that China's JIN class SSBN is more detectable than the Russian Akula submarines.[15] Russian Akula submarines were shown to be about as detectable as US SSN 688 classes.[16] This suggests that the SSN 688 class submarines would also be quieter than the 2009-era JIN-class SSBN. However, analysis of Chinese open-source material discovered statements from Chinese sources indicating that noise levels of the earlier JIN-class SSBNs were 'on a par with' the US SSN 688 class.[17] A recent analysis of comments from authoritative Chinese sources indicated that they believe their latest versions of the Type 094A SSBNs were becoming quieter through the adoption of more advanced internal designs.[18] Analysis of Chinese submarine technology by US experts conclude that China is 'on the verge of producing world-class nuclear-powered submarines'.[19] Finally, a retired senior US Navy intelligence officer testified in 2018 that US detection capabilities against Chinese SSBNs, or boomers, have practical limits: 'Chinese boomers are not so loud that when a crisis begins we will with high certainty be able to find these boomers'.[20]

It is difficult to predict how quickly China will be able to make their SSBNs quieter but given the strategic importance of survivable nuclear weapons on SSBNs, there is a strong incentive to do so. China has a recent history of

[14]Trevithick, J., 'Russia's Newest Submarines are "On Par with Ours" According to Senior American General', *The Drive*, 16 June 2021. https://www.thedrive.com/the-war-zone/41105/russias-new-cruise-missile-submarines-are-on-par-with-ours-says-senior-u-s-general. The original context was in a hearing where cruise missile submarines were being discussed. General VanHerck. 'Russia has Developed Capabilities from undersea with their Advanced, Very Quiet, Nearly on Par with Our Submarines to Field that [Cruise Missile Attack] Capability,' *Hearing on National Defense Authorization Act for Fiscal Year 2022*, 15 June 2021, p. 21. https://www.hsdl.org/c/view?docid=873328.

[15]Office of Naval Intelligence, 'Submarine Quieting Trends', 2009. p. 22.

[16]There were variants of both the Akula and the SSN-688, and their broadband noise levels largely overlapped. Norman Polmar and K.J. Moore, *Cold War Submarines* (Lincoln, Nebraska: Potomac Books 2004), 319.

[17]This Chinese source from the early 2000's 'states that the 094's acoustic signature has been reduced to 120 decibels. According to this report, this is definitely not equal to that of the Ohio class, but is on a par with the Los Angeles'. Andrew S. Erickson and Lyle J. Goldstein, 'China's Future Nuclear Submarine Force', *Naval War College Review* 60/1 (Dec. 2007), 67.

[18]Logan, David, 'China's Sea-Based Nuclear Deterrent'.

[19]Christopher P. Carlson and Howard Wang, 'A Brief Technical History of PLAN Nuclear Submarines", China Maritime Report No. 30, China Maritime Studies Institute, U.S. Naval War College (Newport, RI: Aug. 2023), 1.

[20]Captain James E. Fanell, U.S. Navy (Retired), 'China's Global Naval Strategy and Expanding Force Structure: Pathway to Hegemony', House Permanent Select Committee on Intelligence, Hearing on 'China's Military Expansion,' 17 May 2018. https://docs.house.gov/meetings/IG/IG00/20180517/108298/HHRG-115-IG00-Wstate-FanellJ-20180517.pdf.

struggling with the development of complex military subsystems for years and then applying concentrated resources and organizational changes to overcome the engineering obstacles. The development of advanced jet engines is a case that has some analogies to submarine quieting. Both require a broad range of expertise in physics, computational science, and various engineering disciplines including materials science and mechanical engineering. Equally important is the need for skilled technicians who can fabricate machine components to precise tolerances and then assemble, install, and maintain these complex machines. China has built the organizations and workforce needed to accomplish these tasks for their most demanding jet engines, despite many challenges.[21] Given the importance of submarine naval architecture for acoustic stealth as well as acoustic sensing, it is reasonable to assume that China could assemble the necessary skills to improve the quieting in newer SSBNs.

Over the next 20 years, the United States will invest in replacing the Ohio-class SSBNs, which are already probably the quietest nuclear submarines in the world, with improved Columbia-class SSBNs.[22] This investment in an SSBN design that is even less detectable than its predecessor is expected to enable the US Navy to operate SSBNs largely independently of general-purpose naval forces well beyond the next two decades, although this cannot be taken for granted.

As a result of these trends in submarine quieting over the next 20 years, the survivability of SSBNs will depend more on adequate maintenance and evolutionary updates in submarine machinery than in major design changes. New technologies and operations for finding and tracking submarines will emerge in parallel with new methods for disrupting ASW search and tracking. These new technologies will involve sensors, communications, and platforms of all kinds. Weapons are crucial to ASW, of course, but as this paper addresses the survivability of SSBNs, I will focus on the processes of gaining targeting information, since targeting and tracking is necessary before the use of weapons.

Preview

The first section below addresses the many sources of uncertainty in ASW beginning with probabilistic search and proceeding to the tracking problem of estimating how many entities are present, what they are, and where they are moving. Tracking depends on sensors for data, so the second section

[21] Andrea Gilli and Mauro Gilli, 'Why China Has Not Caught Up Yet: Military-Technological Superiority, Systems Integration, and the Challenges of Imitation, Reverse Engineering, and Cyber-Espionage', *International Security*, 43/3 (Winter 2018/19), 141–89. See also Reuben Johnson, 'China's J-20 Fighter seems to have a New Homegrown Engine, after Years of Struggle', *Breaking Defense*, July 18 2023, https://breakingdefense.com/2023/07/china-j20-fighter-engine-ws15/.

[22] O'Rourke, 'Navy Columbia (SSBN-826) Class Ballistic Missile Submarine Program'.

addresses how existing and new sensor concepts can be used to protect SSBNs as well as attempt to find and track them. The third section considers the uses of uncrewed systems and naval mines to protect SSBNs as well as threaten them. The final two sections address operational factors and the potential of deep neural network-based artificial intelligence algorithms applied to ASW.

Search and tracking

To understand how SSBN fleets might survive over an unpredictable and possibly a prolonged period of crisis or conventional war, it is useful to consider the processes of strategic antisubmarine warfare in terms of search and detection, localization, identification, and tracking SSBNs. The uncertainties that govern each of these stages of targeting SSBNs introduce possibilities for countermeasures against strategic ASW. Actions taken to protect SSBNs will be referred to as pro-SSBN activities taken by the pro-SSBN side, and the anti-SSBN side will engage in strategic ASW activities. I will address these targeting processes in the context of search, detection, and tracking of SSBNs by the anti-SSBN side using passive sonar. Passive sonar mounted on very quiet SSNs or UUVs is perhaps the most important near-term sensor threat to SSBNs operating in protected bastions. However, the concept of introducing a beacon or tag on each SSBN to reveal its location is an idea that in theory could eliminate the need for ASW. This will be addressed first.

Tagging

A device that could be physically attached to an SSBN to reveal its location is a tag. A tag might work by continuously sending a signal to the attacking side about the location of the tagged SSBN, either continuously or intermittently, or in response to an interrogation signal. A tag could communicate the location of the SSBN by sending an acoustic or laser signal, although this would need to be so powerful in order to be detectable by the anti-SSBN forces that they could also be detected – and neutralized – by pro-SSBN forces.

The simplest countermeasure to tagging is to prevent anti-SSBN efforts to attach a tag in the first place. This would require surveillance of the SSBNs from when they are in port through their movement to the open ocean. All of the technical and logistical advantages lie with the pro-SSBN side, and so it is reasonable to assume that tagging in port or as SSBNs go on patrol is very unlikely.[23] UUVs and underwater robots have been developed for inspection

[23]Chinese researchers watch US developments in SSBN port security and have a good understanding of the kinds of technologies required to protect SSBNs in ports, including US systems. See Lan Tong-yu, Liu Ben-qi, and Liu Liang, 'Review on Anti-UUV Detection Sonar System', *Journal of Unmanned Undersea Systems*, 30/6 (2022), 704–13. doi: 10.11993/j.issn.2096-3920.2022-0033.

of ship hulls for a number of years. These could be adapted to inspect the hull for tagging devices, and China already has expertise in developing methods for attaching undersea robots to ship hulls.[24] In the US, there are substantial investments to protect SSBNs from threats while they are in port through egress to secure dive sites in the open ocean.[25] Similarly, it is assumed that both China and Russia provide protection for SSBNs leaving ports to go on patrol.

Detection and false alarms

Searching an ocean area with one or more passive sensors for an unknown number of moving targets is a fundamental process in undersea warfare. Search is the systematic application of a sensor with a limited range, or field of view, throughout a large region. When there is no prior information about the location of the target of the search, the search process involves two random elements. The first random element is the chance encounter of the limited sensor field of view with the target. Given that the search sensor encounters a possible target, the second random element involves making the correct inference as to whether a target signal is present or not present in background noise based on the data that is collected during that chance encounter. Consider just the detection problem first, and the two kinds of errors inherent in the detection of signals in noise.

Sensors feed data to computer algorithms that test the data to determine whether it is most likely to represent the presence or absence of a target signal in the background noise. With each test there are always two possible errors. One error is deciding that only noise is present when in fact a real target signal is present: a missed detection. The other error is deciding that a target is present when in fact only random noise or clutter alone is present: a false alarm. Searching over a large, noisy ocean area with a sensor of limited range involves making many thousands or millions of such statistical decisions every hour. Since targets are rare and noise is everywhere, there is a potential to produce false alarms at a very high rate, which quickly renders the sensor ineffective. Therefore, the sensitivity of the detection algorithm must be reduced to keep the false alarm rate low.

[24]For examples of existing robots and ideas from Chinese experts on the future of automating these robots, see Changhui Song and Weicheng Cui, 'Review of Underwater Ship Hull Cleaning Technologies', *Journal of Marine Science and Application* 19 (Oct. 2020), 415–29. https://doi.org/10.1007/s11804-020-00157-z.

[25]The SSBN 'Transit Protection System … is a group of vessels, personnel, and weapons systems intended to protect SSBNs transiting between a homeport and a safe surface/dive location'. United States Government Accountability Office Report to Congressional Requesters, 'Greater Focus on Analysis of Alternatives and Threats Needed to Improve DOD's Strategic Nuclear Weapons Security', GAO-09-828, Sep. (Washington, DC: GAO 2009). https://www.gao.gov/assets/gao-09-828.pdf,

This requirement to control false alarms leads to an unavoidable tradeoff: if the sensor processing algorithm is not sensitive enough, a weak target signal may be missed, whereas if it is too sensitive, ever-present background noise will overwhelm the users with false alarms. While some false alarms are tolerable, an excessive rate of false alarms can completely undermine the ability to track submarines over an extended time, as will be discussed below. Methods for controlling the false alarm rate in undersea acoustic environments that are continually changing with time and location can be applied to many kinds of underwater sensing problems.[26]

Methods to reduce the detrimental effects of background noise in detection algorithms include reducing the size of the region that is sampled on each glimpse of a sensor and increasing the time over which data is collected and integrated. While these methods do improve the ability to detect targets in noise at a fixed false alarm rate, they require larger physical arrays of sensors or longer times devoted to sensing, and there are limits to both. Longer arrays require longer vehicles to mount them on, or more careful maneuvering if the arrays are towed behind. Longer time spent accumulating data can be impractical in a rapidly changing situation. In addition, the random processes of sound transmission in the ocean tend to reduce the coherence of the data over time and space which in turn limits the gains of these approaches. Research into new signal processing techniques that use information about the ocean medium are ongoing, but typically make improvements that are unlikely to compensate for the trend decrease in submarine radiated noise.[27] That is to say, submarines will continue to be difficult to detect at significant ranges using passive sonar as was the case during the Cold War.

Search and trailing SSBNs

In addition to the statistical detection problem described above, the random element of search is a separate source of uncertainty. It is easier to understand random search if the detection process is simplified to its essential geometry. Assume that the searcher uses a sensor that detects the target with a probability of 100% if it passes within a fixed distance of the target and misses it otherwise. To simplify further, assume for the moment that the sensor does not produce false alarms and that the target is stationary. When searching for a stationary target that is equally likely to be anywhere in a search area, an exhaustive search of an area can be accomplished in a

[26]Lu Shuping, Ding Feng, and Li Ranwei, 'Robust Centralized CFAR Detection for Multistatic Sonar Systems', *Chinese Journal of Electronics* 30/2 (Feb. 2021) 322–30. doi: 10.1049/cje.2021.02.003. https://cje.ejournal.org.cn/article/doi/10.1049/cje.2021.02.003.

[27]Lei Xie, et. al., 'Matched-Phase Weighting Beamformer to Improve the Gain of a Long Linear Array in the Range-Dependent Ocean Waveguide.'

known amount of time using, for example, a search of parallel sweeps of the idealized sensor. These search plans are also referred to as ladder search or 'mowing the lawn'. Given the deterministic detection range assumed for the sensor and the assumption of no false alarms, once the exhaustive search is complete, the probability of covering the stationary target and detecting it increases linearly from zero to 100%.

Search for a moving target rather than a stationary one introduces a new source of uncertainty that can best visualized as what the target might do while the searcher is executing the parallel-sweep ladder search. Even if the SSBN maneuvers randomly without knowledge of the searcher that can be used to evade, the probability of it being detected is no longer 100% when the entire area is covered because the SSBN has a chance of moving into an area already covered by the searcher.[28] For this reason, searching for a moving target is represented as the probability of detecting the target as a function of time. The probability of detection increases over time, but unlike the exhaustive search for a stationary target, the probability never reaches 100%. For example, a random search requires about three times as much time as the exhaustive search for a stationary target to achieve a 95% probability of detecting the SSBN and requires more than four times as long to achieve a probability of 99%. This is the simplest possible model for random search for a moving, non-evading target, but already it has implications for the sea-based deterrent: search for SSBNs is an irreducibly random process.

If this simple vignette is expanded to include the more realistic possibility of distracting the searcher with false alarms that must be investigated, or introducing active sonar systems that must be avoided, the time to achieve these probabilities of detection can increase even more.[29]

In this vignette, once the SSBN is detected by the SSN searching for it, the SSN may attempt to trail it continuously. Covert trailing with passive sonar has limitations, however. Trailing a submarine with passive sonar is complicated by the fact that passive sonar provides only the direction to the detected sound source, or perhaps the direction with an uncertain estimate of the distance to the source.

If the trailing SSN or UUV has a comparable or greater speed than the target and can operate at higher speed while remaining covert, tracking using only directional information from a passive sensor can be performed, as was the case during the Cold War when US SSNs could trail Soviet submarines. However, in a situation where both the acoustic advantage and the speed advantage do not exist so the trailing SSN cannot move faster than the SSBN it is trailing and remain stealthy, then passive 'bearings-only'

[28]Alan Washburn, *Search and Detection* (CreateSpace Independent Publishing Platform 2014), 89–90.

[29]Stephen M. Pollock, 'Search Detection and Subsequent Action: Some Problems on the Interfaces', *Operations Research* 19/3 (May-June 1971), 559–86. See also David V. Kalbaugh, 'Optimal Search Among False Contacts', *SIAM Journal on Applied Mathematics* 52/6 (Dec. 1992), 1722–50.

trailing is not reliable for extended covert trailing.[30] The substantial undersea warfare acoustic advantage held by the United States relative to the Soviet Navy during the Cold war is very unlikely to be re-established with respect to China and Russia.

Uncrewed underwater vehicles are unlikely to compensate for the loss of passive acoustic advantages. When only one fixed passive sensor is available, it is in general not possible to derive tracks using only bearing information. If the sensor can maneuver, then it must maneuver with much more agility than the target, and over a long duration would need to be faster than the target and have greater endurance. If this is not possible, then multiple passive, bearings-only platforms are needed.[31] In order for such groups to be effective there must be reliable communication between the coordinated UUVs or UUVs and SSNs. However, the requirement to communicate can make UUVs vulnerable to detection themselves. In addition, passive tracking from UUVs would require them to operate for long periods, with stealth, and at speeds at least as great as the SSBNs they attempt to follow. Since UUVs typically lack the endurance of a submarine, the use of UUVs to provide robust passive, covert trailing against SSBNs is unlikely over the next decade or two. In addition to the requirements for passive tracking, if an SSN trailing an SSBN had to avoid active sonar or other apparent threats in a protected bastion, it would be very difficult to maintain reliable passive tracking.

Trailing an SSBN may not need to begin with a random search if the SSN can begin trailing as soon as the SSBN leaves port, for example. In this case, the entire process of search, detection, and tracking described above is avoided, greatly increasing the confidence of the strategic ASW force.[32] With new technologies becoming available, however, it becomes feasible for the pro-SSBN side to detect and then harass these waiting SSNs. Trailing an SSBN in a region protected by pro-SSBN forces entails risks to the SSN.

Very different technical and tactical problems arise when trailing SSBNs using nearby systems becomes impractical. When the searching system cannot trail the SSBN but must glimpse an area periodically over time from a remote location in the air or in space, finding SSBNs presents different

[30] D. L. Middlebrook, 'Bearings Only Tracking Automation for a Single Unmanned Underwater Vehicle', Master's Thesis in Mechanical Engineering, MIT, 2007. Ch. 5. Experimental Results. https://dspace.mit.edu/bitstream/handle/1721.1/42416/237797318-MIT.pdf?sequence=2.

[31] Xianghao Hou, Jianbo Zhou, Yixin Yang, Long Yang, and Gang Qiao, 'Adaptive Two-Step Bearing-Only Underwater Uncooperative Target Tracking with Uncertain Underwater Disturbances, *Entropy* 23/7 (July 2021), 1–18, 907. https://doi.org/10.3390/e23070907.

[32] The level of confidence in trailing Soviet SSBNs from port throughout their patrols is well expressed by former Commander of the Pacific Fleet Admiral David Jeremiah, when he told interviewers: 'we could do a body count and know exactly where they were. In port or at sea. If they were at sea, N3 had an SSN [on them], so I felt very comfortable that we had the ability to do something quite serious to the Soviet SSBN force on very short notice in almost any set of circumstances'. Christopher A. Ford and David A. Rosenberg, 'The Naval Intelligence Underpinnings of Reagan's Maritime Strategy', *The Journal of Strategic Studies* 28/2 (Apr. 2005), 379–409.

challenges for all of the basic processes of detection, localization, and long-term tracking.

Tracking: Local and Remote

Tracking an unknown number of SSBNs with local sensors in the bastion or remote sensors is a much different process than the search-and-trail vignette described above. Tracking means keeping a continuous estimate of the locations of possible targets in an area over time. When a sensor makes a detection – which may be correct or a false alarm – it can produce a contact report with a location estimate. Location estimates derived from noisy data are typically uncertain and are often reported as a best estimate of the location at a given time with an area of uncertainty (AOU) surrounding it. If a sequence of contacts is produced over time that is consistent with the motion of an SSBN, those contacts can be strung together into a track. The track has an estimate of the location of a hypothetical target using all the information up to the latest contact. The advantages of making detections, producing contact reports to summarize the results, and creating tracks from these contact reports is that the contact data is very much smaller than the original sensor data so contacts can be shared over limited communication channels from different sensors. Tracking methods that fuse the data into tracks before making detection calls can deal with weaker target signals in noise but must share some or all of the raw sensor data, placing greater demands on communication channels. The discussion of tracking below will assume that detection occurs before tracking.[33]

Once a tracking process has been established, there can be many existing tracks which may or may not be associated with actual SSBNs. Each of these tracks will have an estimate of location, perhaps velocity, and AOU estimates based on the quality of the contacts that comprise the track. If there is no new contact for a significant time, the AOUs grow in the absence of new information based on an assumed model for the SSBN motion. Uncertainty about the motion patterns of the objects being tracked is also a factor that reduces the capability of tracking systems.[34]

The problem of associating new contact information with updated track estimates is very difficult and often represents a major challenge in practical trackers. In the presence of false alarms tracking algorithms will produce false

[33]A modern treatment of multiple target tracking is given by Lawrence D. Stone, Roy L. Streit, Thomas L. Corwin, and Kristine L. Bell, *Bayesian Multiple Target Tracking,* 2nd Ed. (Norwood, MA: ARTECH House 2014).

[34]Xueli Sheng, Xiaoyu Want, Hanjun Yu, Longxiang Guo, Jingwei Yin, 'Target Tracking Technology for Reducing False Alarm', 4th Underwater Acoustics Conference and Exhibition, College of Underwater Acoustic Engineering,Harbin Engineering University, 2017. https://www.uaconferences.org/component/contentbuilder/details/9/130/uace2017-proceedings-a-target-tracking-technology-for-reducing-false-alarm.

tracks by associating sequences of false or even correct detections into a plausible track, but one that does not correspond to a real target. False tracks can multiply quickly and are indistinguishable from 'true' tracks associated with actual SSBNs. There may be many possible ways to associate a new contact with existing tracks, further increasing the ambiguity of the tracking picture. Tracking in the ocean with intermittent data, false alarms, missed detections, and deliberate deception is complex, and remains an active research problem.[35]

The performance of tracking algorithms in the presence of false alarms is known to have limits when the false alarm – or clutter – density rises beyond a certain threshold.[36] However, it is impossible to make general statements about the limits of tracking outside of a specific scenario that defines the physical observable, randomness in the environment, the sensor architecture and performance, and target behavior. It is known theoretically that tracking algorithms can become unstable and fail to track targets even with unlimited computing resources if the false alarm density exceeds a certain threshold for that particular system.[37] The ability to estimate the location of a single target over time using a tracking algorithm is known to decay as the probability of detection of the system decreases, the false alarm density increases, and the target speed increases.[38] These are all parameters that are outside the control of the tracking algorithm, and the tracking algorithm cannot compensate for limitations due to noise in the environment or target behavior.

Tracking algorithms can compensate for some levels of false alarms and the uncertainties inherent in the detection process under the right conditions. Tracking an unknown number of targets with multiple sensors tends to improve with the following factors:

- Reliable prior information about the number of targets in the area.
- Sensors with detection probabilities closer to 100% and false alarm probabilities closer to zero.
- Frequent sensor coverage and detection opportunities

[35]A useful survey of target tracking research was published in 2015 by the Laboratory for Science and Technology on Automatic Target Recognition at China's National University of Defense Technology in Changsha, China. See Changzhen Qiu, Zhiyong Zhang, Huanzhang Lu, and Huiwu Lo, 'A Survey of Motion-based Multitarget Tracking Methods', *Progress in Electromagnetics Research B* 62 (Mar. 2015) 195–223. https://www.jpier.org/pierb/pier.php?paper=15010503.

[36]A numerical example of tracking failure due to high clutter density is in Tables 1 and 2 of Sheng, 'Target Tracking Technology', 1017.

[37]B. Belkin, G. Schweiter, and R. Wenocur, 'Predictive Models of Correlator/Tracker Algorithm Performance in the Presence of False Alarms', DFS 88 Tri-Service Data Fusion Symposium, DoD Joint Director of Laboratories Data Fusion Subpanel, Laurel, MD, Mar. 1988, pp. 340–46. https://apps.dtic.mil/sti/pdfs/ADA325998.pdf, see also Yaakov Bar-Shalom and Thomas E. Fortmann, *Tracking and Data Association* (San Diego: Academic Press 1988), Ch. 7, 8.

[38]Belkin, et al., 'Predictive Models of Correlator/Tracker Algorithm Performance', 340–46.

- Multiple sensors that provide independent data about the presence or absence of targets.
- An absence of decoys or other platforms or natural phenomena that produce signals similar to targets.
- Robust communication networks that move sensor information to tracking and data fusion centers with minimum delay.
- Minimum chance of communication disruption by jamming
- The ability to move sensors at will to collect data that can resolve tracking uncertainties, or to add additional sensors as needed.

Conversely, as each of these factors degrades – as would likely be the case over the course of a war – tracking can degrade quickly. Decreasing the probability of detection or increasing the false alarm rate can lead to actually losing the track of the true target altogether. The performance bounds of a tracking architecture can be bounded using principles from statistical estimation theory.[39]

The ability to reposition sensor platforms quickly and to employ additional ones can help resolve difficult tracking problems. Aircraft and surface ships with ASW sensors are useful for collecting more data quickly, but for the anti-SSBN side tracking within a bastion, operating surface and air vehicles inside a bastion area with substantial radar and air defense is difficult. If the pro-SSBN side can maintain sufficient control of the air and sea surface in the bastion, they can deny efforts of the anti-SSBN side to use tracking sensors from ships and aircraft. In addition, the pro-SSBN side will be able to use their own surface and air ASW platforms to search for and track undersea threats. These factors underscore the importance of integrated air defense systems and surface search for bastion defense as a means of providing protection for pro-SSBN ships and aircraft.

Remote tracking from space

An alternative to tracking using sensor platforms within the bastion is tracking using remote sensors that can collect data from space or near-space altitudes. Tracking SSBNs over the course of a prolonged conflict would require day and night sensing capability over the SSBN patrol areas with frequent revisits. Active sensors would be required for such an effort, and they would be observable by the pro-SSBN side. There is no demonstrated sensing technology that can provide the required detection capability, control over false alarms, and revisit time. The enormous challenges and unlikely

[39]Xin Zhang, Peter Willett, and Yaakov Bar-Shalom, 'Dynamic Cramer-Rao Bound for Target Tracking in Clutter', *IEEE Transactions on Aerospace and Electronic Systems* 41/4 (Oct. 2005), 1154–67.

prospects of space or airborne remote tracking will be discussed in a later section.

Communications for tracking systems

Tracking SSBNs using multiple sensors requires reliable communications to move sensor data to computing centers where it can be combined. Tracking on the scale of large ocean bastions can make use of land-based radio communications as well as undersea cables and satellites. Tracking SSBNs over tens of millions of square kilometers in the Atlantic and Pacific Oceans would require many sensors on satellites to provide sufficient revisits over potential SSBN patrol areas. The amount of data required for tracking would depend on the degree to which the sensing data would be processed by computers near the sensor before being transmitted.

The discussion of tracking above assumes a detect-before-track approach to data fusion in which data from each individual sensor is used to produce a detection decision without the benefit of data from other independent sensors. If the signal processing and sensor detection algorithms are integrated on the same platform as the sensor itself, they can produce contact reports that collapse all the data down to a very small data message containing the location, time, uncertainty, and other estimates from the single sensor. While collapsing the sensor data into contact reports reduces the communication requirements by many orders of magnitude, some information is lost.

A tracking paradigm that adopts the track-before-detect methods will typically provide better performance against targets in environments where the background noise is high relative to the potentially detectable signal. Track-before-detect methods are more likely to result in more accurate tracks with fewer false tracks. However, these methods require moving relatively large amounts of data through the communication network, which places great demands on it. In this way, communication links become an integral part of an ASW tracking architecture, and therefore a potential element for disrupting ASW by an adversary.

Technologies and operations: Pro-SSBN and Anti-SSBN

The central thesis of this chapter is that new and existing technologies and operations for undersea warfare can be adapted to protecting SSBNs more rapidly and cost-effectively than threaten them. Protecting SSBNs in bastions or in the open ocean involves competition for surveillance and counter-surveillance over long periods of time. It is not possible to predict exactly how this competition will unfold 20 years into the future, but the technical and operational dynamics will revolve around search, detection, identification, and tracking problems. While the anti-SSBN side seeks to reduce uncertainty about the adversary SSBNs, new technologies can be used by the pro-SSBN side to cloud that picture. A useful starting point is a vignette with two adversaries searching for each other.

Consider the situation of a single SSN searching for a moving SSBN in a bastion. The probability that the SSN detects the SSBN increases with time, but at a steadily decreasing rate. The pro-SSBN side may have little information about whether a hostile SSN is present, but it can use the SSN's search against it. If the pro-SSBN side installs submarine sensors on the seabed or on UUVs, the probability that the SSN encounters the sensor and reveals its presence obeys the same random search relationship. So, the longer the SSN is searching, the higher the probability that it is detected by the pro-SSBN side.

The pro-SSBN side can increase the probability of detecting an SSN with no prior information about its whereabouts simply by using more sensors. The more sensors, the greater the probability of the SSN encountering one of them. This leads to two competing random search processes. The pro-SSBN side can accelerate the search for SSNs using fixed sensors or sensors on UUVs. The anti-SSBN side can allocate more SSNs to the search. There are two possible events: define event A as the SSN is detected by the pro-SSBN side and event B as the SSBN is detected by the SSN. A general result from probability theory provides an important insight: the probability of random event A occurring before random event B is equal to the probability of the event A divided by the sum of the probabilities of the two events.[40] That is, the pro-SSBN side can increase the probability of detecting the SSN before the SSN detects the SSBN by using more sensors. This intuitive result deals only with competing probabilities for the first stage of an ASW search, however.

If the SSBN is discovered first and is trailed by the SSN, this probabilistic picture changes, even if the SSBN is not aware that it is being tracked. The SSBN patrolling in its protected area can deliberately pass through areas with sensors installed by the pro-SSBN side. This behavior will draw a trailing SSN into that sensor's range. What had been a random search for the SSN becomes a definite opportunity for the pro-SSBN side to detect and localize it. Once the SSN is detected and localized, active and passive sensors from the pro-SSBN side can be used to continue to track it from the air, surface, or subsurface and take other actions against it. During the Cold War, analysts in the CIA and elsewhere called this 'delousing'.[41]

[40]Koopman derives this result in the context of a single searcher with two independent sensors and refers to the effect as 'forestalling'. Bernard O. Koopman, *Search and Screening* (Arlington, VA: Military Operations Research Society 1999), 79–81.

[41]Central Intelligence Agency, Directorate of Intelligence, 'The Soviet Attack Submarine Force: Evolution and Operations Introduction', Intelligence Memorandum, Sep. 1971, Approved for Release 2017/06/14. https://www.cia.gov/readingroom/document/0002013695

Entering and leaving bastions

The decision to operate SSBNs within protected bastion areas will rest on decisions made by the pro-SSBN side over the course of a prolonged crisis or conventional war. There may be reasons to move some part of the SSBN fleet out of the bastion areas into adjacent oceans. For example, this could be seen by the pro-SSBN side as complicating the adversary's problem of using missiles defense against SLBMs that have been launched.[42]

The bastion regions have long perimeters, and there may be an assessment that a few SSBNs could exit the bastion after some period of conventional war that included strikes against anti-SSBN sensors and communication networks.[43] Russia and China are aware of the risks to their SSBNs when they attempt to pass out of bastion areas into open ocean areas. Modern sensor networks operated by Norway in the Norwegian Sea can provide surveillance against Russian submarines, and the Russian military has developed specialized means that can disrupt these surveillance systems.[44]

China is aware of sensors operated by the US and Japan in exits from the South China Sea and East China Sea to the Pacific Ocean.[45] One Chinese report on these sensors in the passage between Miyako and Okinawa provided detailed passive acoustic detection estimates of both fixed and mobile towed passive sensors in that area.

The major passage from the Chinese bastion areas of the Yellow Sea, Bohai Gulf, and the East China Sea to the Philippine Sea is the Miyako Strait, which is about 250 km wide. To quote from this Chinese study:

> 'The actual detection capability of foreign sonar equipment can be obtained according to the key technical parameters of the sonar and combined with the prediction results of the sound field. SOSUS and SQR-19 are taken as examples … to illustrate. SOSUS is the subsurface sonar array with the largest number of array elements, the longest array, and the best submarine detection capability deployed by the United States and Japan in Miyako Waterway. A certain point … in the western Pacific Ocean near the south of Miyako Island was selected for calculation'.[46]

The SOSUS array is a large array typically mounted on the seabed, the long length of which allows for the best rejection of ambient noise as well as

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[42]Zhou, 'Tides of Change,' 30.

[43]See APPENDIX for geography of potential bastion areas.

[44]Thomas Newdick, 'Norwegian Undersea Surveillance Network had its Cables Mysteriously Cut', *The War Zone (The Drive)*, Nov. 11 2021. https://www.thedrive.com/the-war-zone/43094/norwegian-undersea-surveillance-network-had-its-cables-mysteriously-cut.

[45]Desmond Ball and Richard Tanter, *The Tools of Owatatsumi: Japan's Ocean Surveillance and Coastal Defense Capabilities* (Canberra: Australian National UP 2015). https://press.anu.edu.au/publications/tools-owatatsumi.

[46]Jingyi Wang, Xiaopeng Kong, Guangli Cheng and Yanan Chen, 'Research on Detection Range Prediction for Oversea Wide-Aperture Towed Sonar', OES China Ocean Acoustics (COA), Aug. 2021, pp. 57–61. doi: 10.1109/COA50123.2021.9519971. IEEE ExPlore https://ieeexplore.ieee.org/document/9519971.

directional tracking. The AN/SQR 19 TACTAS is an array towed behind a ship travelling at slow speeds. The results of the TACTAS model would apply more to mobile sensors. A summary of the results from the PLA Navy study shown here show how much the detection range can vary according to the speed of the target: slower speeds produce significantly less noise.[47]

	Detection Method	Low-speed submarine	High-speed submarine
AN/SQR 19 TACTAS	Broadband	1–3 km	3–46 km
	Narrowband	1–6 km	4–49 km
SOSUS	Broadband	5–52 km	50–89 km
	Narrowband	30–63 km	52–90 km

Table. Passive acoustic detection ranges of US systems against PLA submarines in the Miyako Strait.[48]

The wide variations in detection range estimates are due to the uncertainties and variations in acoustic transmission loss and ambient noise in the region. Open-source estimates of detection ranges against Soviet submarines from the 1980s showed similar variations.[49] The detection ranges decrease substantially from those in the table if the passive arrays are in shallow waters, where acoustic transmission loss is typically greater. Given that the width of the Miyako Strait is 250 km, the estimates of detection range suggest that a robust set of sensors would be required to reliably detect and track submarines passing through this region. The use of undersea acoustic jamming or direct attacks on sensor communication links would make tracking SSBNs in the Miyako Strait even more difficult.[50]

Underwater Acoustics in bastions

The bastion areas that China and Russia would likely use have depths that range from less than 50 meters to several thousand meters deep. The sound transmission characteristics in shallower waters varies by time, location, and direction, sometimes by more than an order of magnitude. Ambient noise due to human and natural sources also complicates the problem of underwater sensing, especially for covert passive sonar search, detection, and tracking. To put this in some perspective, these variations in the acoustic

[47]Wang, et. al., 'Research on Detection Range'. 2021.
[48]Wang, et. al., 'Research on Detection Range'. 2021.
[49]Tom Stefanick, *Strategic Antisubmarine Warfare and Naval Strategy* (Lexington, MA: Lexington Books 1987) APPENDIX 8.
[50]S. Li, Y. Song, 'Nonparametric Detector Performance for Active Sonar in Ocean Reverberation Background with Multiple False Targets Jamming', International Conf. on Electronic Science and Automation Control (ESAC 2015). Atlantis Press. https://www.atlantis-press.com/proceedings/esac-15/25836895. See also, Xiong, Mengchen, Jie Zhuo, Yangze Dong, and Xin Jing, 'A Layout Strategy for Distributed Barrage Jamming against Underwater Acoustic Sensor Networks', *Journal of Marine Science and Engineering* 8/4 (Apr. 2020). https://doi.org/10.3390/jmse8040252https://www.mdpi.com/2077-1312/8/4/252.

environment can have a larger effect on reducing passive sonar detection range than the impacts of decades of improvements in submarine quieting.

The South China Sea includes the widest range of water depths and sonar conditions of all the Chinese bastion areas. Ambient noise in the deep central sections of the South China Sea can vary by factors of 100 between the winter and summer.[51] Sound propagation can be better in the summer, and there is generally more shipping at that time of year so noise at frequencies below 500 Hz is more influenced by shipping from a larger distribution of ranges both near and far. As a result, low frequency narrow-band detection and identification of SSBNs from SSNs could be made more challenging by the many moving noise sources. The undersea acoustic conditions are similar in the north east South China Sea, about 60 miles west of the center of the Luzon Strait, in 3500 meters of water.[52]

Measurements of the acoustic transmission loss along shelf break east of Hainan Island show the strong effects of direction on sonar effectiveness.[53] The complex bathymetry and variability in bottom type in the downslope direction leads to large changes in acoustic transmission loss across varied paths. The transmission loss can change by 20 to 30 dB for small changes in direction.[54] This level of variability greatly impacts the detection capabilities of sonars operating in this area.

The Yellow Sea is 140 meters deep at its deepest point and has an average depth that decreases gradually from the East China Sea in the south to the Bohai Gulf in the north. Due to a variety of warm and cold currents, the Yellow Sea has a complex acoustic environment.[55] Detection ranges of active sonar vary considerably as the temperatures change over depth and the sound propagation patterns vary. Detection ranges for an active sonar operating at 10 kHz can vary between 3.5 and 5 km, depending on the season and the sonar operating depth. Even longer ranges are possible, but for PLA Navy planners developing plans for detecting submarines and UUVs in the strategically vital Yellow Sea, the design of active detection systems must take account of the variability in active sonar range.

[51] In summer, SCS has strong sound speed minimum so the deep areas have convergence zones. Qiulong Yang Kunde Yang, 'Seasonal Comparison of Underwater Ambient Noise Observed in the Deep Area of the South China Sea', *Applied Acoustics* 172 (Jan. 2021), 107, 672. https://www.sciencedirect.com/science/article/abs/pii/S0003682X20307763.

[52] Yang Shi, et al., 'Long-Term Ambient Noise Statistics in the Northeast South China Sea', *Journal Acoustic Society of America*, 145/6 (June 2019), EL501-EL507. https://asa.scitation.org/doi/10.1121/1.5110740.

[53] Jin Liu, et al., 'Measurement and Modeling of Sound Propagation Over Continental Slope in South China Sea', *Journal of the Acoustical Society of America* 147/3 (Mar. 2020). https://asa.scitation.org/doi/10.1121/10.0000801.

[54] See Figure 2 in: Jin Liu, et al., 'Measurement and Modeling of Sound Propagation'.

[55] Zhan He, and Yang Rijie, 'Analysis of Measured Data and its Effect on Active Sonar Working Depth in the Yellow Sea', International Conference on Electronic Science and Automation Control (ESAC 2015), pp. 8–11 https://www.atlantis-press.com/proceedings/esac-15/25836843.

The Russian bastion area of the Barents and Kara Seas in the Arctic have significant shipping levels resulting in greater ambient noise and reduced detection ranges. Ambient noise in the Barents Sea has been rising about 10 dB every 10 years recently as shipping levels have increased, and the Barents Sea has by far the highest noise levels over the largest area of all the Seas in the Russian Arctic region.[56] Sound propagation can vary greatly in the Barents Sea, as in many shallow water regions. One set of measurements in the Barents Sea at 60 meters depth resulted in significant variability in acoustic transmission loss by frequency over distances of less than 5 miles. These variations are due to local sediment and seabed acoustic properties, and so it is difficult to generalize about sonar detection conditions for a body of water the size of the Barents Sea.[57] Sonar detection ranges may be better in deeper water, but while this may increase the possibility of detecting Russian SSBNs, these sonar conditions can help the pro-SSBN forces using fixed arrays and decoys.

The acoustic transmission characteristics of shallow waters characteristic of Chinese and Russian bastion areas have a filtering effect that changes the strengths of different sound frequencies by different amounts, which in turn can make identifying targets difficult with passive sonar. This filtering effect can make decoy noisemakers more difficult to distinguish from actual submarines at longer ranges due to the fact that signals arriving from long ranges in shallow water lose distinguishing characteristics at high frequencies. Creating a decoy sound recording is likely to be straightforward, since a simple recording of an actual SSBN can be used and looped. Since an SSN hunting for SSBNs in a bastion must rely on passive sonar, this decoy effect of creating false contacts that must be investigated is another advantage to the pro-SSBN side attempting to prolong the search for SSBNs.[58]

Decoys in bastions

As described earlier, the longer anti-SSBN forces must spend searching or trailing in a bastion area, the more chances that pro-SSBN sensing and tracking installations can detect and potentially counter decoys, and the more time this will add to the search.[59] Russia appears to be developing submarine decoys that can be used in bastions to complicate tracking efforts

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[56] Arctic Council, 'Underwater Noise Pollution from Shipping in the Arctic', (May 2021), pp. 10, 37–38, Figures 13–18. https://pame.is/projects/arctic-marine-shipping/underwater-noise-in-the-arctic

[57] Zhi Yong Zhang, 'Modelling Shallow Water Sound Transmission by Using a Simple Analytical Formula based on the Effective Depth Approximation', 2015 Conference of the Australian Acoustical Society, Hunter Valley, 2015. https://acoustics.asn.au/conference_proceedings/AAS2015/.

[58] R. N. Forrest, 'Estimating Search Effectiveness with Limited Information', Naval Postgraduate School, Sep. 1993, p. 13. https://apps.dtic.mil/sti/pdfs/ADA274563.pdf.

[59] Stephen M. Pollock, 'Search Detection and Subsequent Action: Some Problems on the Interfaces', *Operations Research*, 19/3 (May-June 1971), 559–86. And D.V. Kalbaugh, 'Optimal Search Among False Contacts', *SIAM Journal on Applied Mathematics* 52/6 (Dec. 1992), 1722–50.

of attack submarines. One such decoy is the Surrogat, which is a large-displacement UUV.[60] A device like this could be used as a target for training, or as a decoy, or as a search platform for using active sonar. A representative from Russia's Rubin design bureau indicated that an important role for the Surrogate-B is imitate a submarine, creating a 'false trail' as well as using active sensors that a submarine trying to avoid detection would not use. The stated range of the Surrogat-B UUV is 1400 km.[61] Another version of the Surrogat UUV is one that is designed to operate in direct support of submarines.[62] While the operational status and reliability of this system cannot be independently known, the list of functions addresses many of the kinds of capabilities that would be very useful for the pro-SSBN side operating in a bastion.

The Surrogate W has a lithium-ion battery with an advertised range of over 1400 km (800 miles) that can be recharged on a 'mother ship' as well as at underwater docking stations. Within Russian bastion areas such as the Barents Sea and the Sea of Okhotsk, an operating range of 1400 km would enable the Surrogate to transit and patrol large portions of the SSBN operating areas. A fuel cell energy source is reported to be under development.[63] Other features include a mobile communication gateway between the subsurface and the atmosphere:

> The Wingman may perform as a smart gateway between a submarine and the atmosphere, ensuring the covert data exchange and navigation fixes. Having received the data from the Leader, the UUV transfers it to a satellite. The data could be sent immediately or after a fixed period of time or when the UUV reaches a preassigned spot. An interaction with seabed network systems can be organized in the same way.[64]

> Surrogate-W is able to conduct ice reconnaissance under solid ice pack and minehunting in hazardous areas… Working autonomously, Surrogate-W gives the Leader time and space to solve other tasks while the UUV explores the region.[65]

> Acoustic and non-acoustic search systems allow the Wingman to search for ships and submarines independently in specified areas or along vectors. Unlike a submarine, the UUV can acquire targets using overt methods, such as active

[60]Joseph Trevithick, 'Future Ballistic Missile Submarine Concept Unveiled at Russian Army Expo', *The Drive*, 15 Aug. 2022. https://www.thedrive.com/the-war-zone/russias-future-ballistic-missile-submarine-concept-has-guard-drones.
[61]RIA Novosti, 'The Rubin Central Design Bureau Spoke about the Capabilities of the Drone Surrogat-V', 18 Aug. 2022. https://ria.ru/20220818/bespilotnik-1810375120.html.
[62]Central Design Bureau for Marine Engineering Rubin, 'Rubin Design Bureau presents Surrogat-W to perform with a submarine', 16 Aug. 2022. https://ckb-rubin.ru/en/mediacentr/novosti_i_sobytija/signle_news/news/detail/News/rubin_predstavljaet_surrogat_v_dlja_sovmestnykh_deis/.
[63]Rubin Surrogat-W, 16 August 2022.
[64]Rubin Surrogat-W, 16 August 2022.
[65]Rubin Surrogat-W, 16 August 2022.

> sonars, since it is more than difficult to hit a UUV due to its size and maneuverability.[66]

> Another prominent feature of Surrogate-W is its ability to imitate a submarine it covers. The Wingman can lure opposing forces away from the Leader, distract them or take all the heat… The onboard acoustic countermeasures make Surrogate-W able to imitate quite complicated tactical episodes.[67]

All of these advertised features and the implied tactics are potentially useful for the pro-SSBN side.

Acoustic sensors in bastions

Russia also appears to be developing some sensor arrays to detect SSNs or other undersea vehicles from intruding in the Barents Sea, or other bastion areas in the Arctic and potentially in the Western Pacific. For example, Russia is reported to have been developing a seabed acoustic sensor system, and by 2016 some of these capabilities were revealed to be associated with the Russian Harmony project. The reporting suggests that the Harmony system incorporates both active and passive sensors that can collect data automatically from arrays.[68] Components of this Russian sensing architecture can be deployed by submarines in various areas as needed, and perhaps can even relay data to satellites. 'In 2016, a second serial stationary sonar system, MGK-608 M, was deployed, with the remote part placed at the maximum distance of 160 km from the coastline. At least four such systems are set to be deployed'.[69] The Harmony system was described in 2016 as a sensing system with a control center on Novaya Zemlya.[70] One Chinese study referenced the Russian Harmony system as part of an integrated communication, navigation, and maritime surveillance system-of-systems or 'underwater attack-defense confrontation system'.[71]

Active sonar can be used by the pro-SSBN side in a bastion with few restrictions. When one or more active sources are operated in conjunction with one or more receivers at a different location, the sonar is said to be operating as a multistatic sensor. The sound projector in a multistatic sonar can be detected from a great distance by an attack submarine or UUV, but the

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[66]Rubin Surrogat-W, 16 August 2022.
[67]Rubin Surrogat-W, 16 August 2022.
[68]K. Bogdanov, and I. Kramnik, *The Russian Navy in the 21st Century: The Legacy and the New Path* (Alexandria, VA: Center for Naval Analysispage Oct. 2018) 22–23. https://www.cna.org/reports/2018/10/russian-navy-in-21st-century.
[69]Bogdanov and Kramnik, 'The Russian Navy in the 21st Century', 25.
[70]Alexey Ramm, 'Россия разворачивает глобальную систему морского слежения', *Izvestia*, 25 Nov. 2016. https://iz.ru/news/647107.
[71]Xie Wei, Yang Meng, Gong Junbin, Fan Huili, and Bai Tiechao, 'Underwater Attack-Defence Confrontation System and its Future Development', *Strategic Studies of CAE* 21/6 (June 2019), 71–79. https://www.engineering.org.cn/en/10.15302/J-SSCAE-2019.06.014.

multistatic sonar receivers do not produce a signal and cannot be detected. Multistatic sonars can be fixed on the seabed, dropped from aircraft, and operated from UUVs.[72] Underwater communication networks in conjunction with multistatic sonar can enable distributed active sonar fields in a range of water depths relevant to China's and Russia's SSBN bastions.[73] Networks of multistatic active sonar sources and receivers can provide sufficient information to track submarines or UUVs entering protected bastions with adequate control over false alarms.[74]

China has been deploying undersea surveillance systems near important locations near the South China Sea, Hainan Island, Qingdao, and elsewhere.[75] Short range sensors within bastions can be used to provide initial locations of potentially hostile undersea systems. These initial detections can be used to provide a starting point for search using helicopters or fixed wing aircraft.

An additional complication for anti-SSBN operations in the South China Sea is that China has placed many sensors in the South China Sea that, if operational, would provide data about air and surface operations in those areas.[76] According to one western report,

> In early 2010, for example, the Shore-Based Fiber-Optic Array Underwater Acoustic Integrated Detection System—a key project under the 863 Program to develop China's underwater hydrophone network—was successfully completed. In May 2017, CCTV and the Xinhua News Agency revealed a new plan to invest more than 2 billion renminbi (about $300 million) over the next five years to complete a national underwater surveillance network in the South and East China Seas. Once completed, this surveillance network could greatly enhance China's underwater situational awareness—a key capability for protecting its SSBNs.[77]

China and Russia are developing systems to protect their bastions on similar paths, but this is most likely due to the urgency of protecting their SSBNs with cost-effective means. With such a challenging technical requirement, it would not be surprising if the system designs were so constrained as to evolve in the future along parallel lines, without necessarily any deliberate collaboration. A recent study from a highly-regarded US defense think tank advocates for the

[72]Optimal search patterns for static or mobile multistatic sonar components can be very effective in detecting and tracking quiet submarines. See Alan Washburn, and Mümtaz Karataş, 'Multistatic Search Theory', *Military Operations Research* (MORS) 20/1 (January 2015) 21–38.

[73]Chi Zhang, Fang Xiao, 'Overview of Data Acquisition Technology in Underwater Acoustic Detection', *Procedia Computer Science* 188 (2021), 130–36. https://www.sciencedirect.com/science/article/pii/S1877050921011467?via%3Dihub.

[74]LU Shuping 'Robust Centralized CFAR Detection'.

[75]Lyle J. Goldstein, 'China's "Undersea Great Wall": Beijing Will Build Its Next Line of Defense on the Ocean Floor', *The National Interest*, 16 May 2016. https://nationalinterest.org/feature/chinas-undersea-great-wall-16222

[76]J. Michael Dahm, 'South China Sea Military Capabilities Series', Johns Hopkins University, Applied Physics Laboratory. https://www.jhuapl.edu/work/publications/south-china-sea-military-capabilities-series

[77]Zhou, 'Tides of Change', 56.

US Navy to adopt technologies for decoys, jamming, and uncrewed vehicles to support US SSNs in 'fighting into the bastions' based on many of the technology trends described here.[78] Citing a variety of western sources, the authors of this US study warn that 'Improved adversary defenses could degrade or defeat US undersea operations, preventing US submarines from conducting critical missions such as sinking a Chinese invasion fleet or tracking Russian ballistic missile submarines (SSBNs)'.[79]

Magnetic, electric, and gravity sensors

In addition to effective active sonar systems, non-acoustic systems might also provide useful capabilities for ASW. Submarines produce electric fields in the water and in the air. The underwater electric potential (UEP) and above water electric potentials have been investigated for applications to submarine detection but studies indicate that the range at which the signal of a submarine can be distinguished from naturally occurring noise is on the order of 10s of meters.[80] This is probably not practical for either side as a method of submarine detection, although it is useful in the design of advanced naval mines.

The magnetic anomaly of a submarine also typically falls quickly, but is detectable at about 1000 meters.[81] Higher sensitivity sensors could detect at somewhat larger ranges, but since the magnetic field drops as the cube of the range, a sensor with higher sensitivity would become very easy to deceive with decoys if those decoys could approximate the magnetic anomaly of a submarine. New types of quantum magnetometers have been developed that some claim can detect SSBNs at a range of 6 kilometers.[82] Even if some of the engineering issues such as cooling requirements of quantum sensors could be solved, the most effective use by quantum-enhanced measurements would be for the kinds of sensors useful in protecting bastions.

Gravity measurements have also been considered for detecting submarines. These measure gravity anomalies and would need to have a high enough spatial resolution to distinguish a submarine from a bottom feature

[78] Bryon Clark and Timothy A. Walton, 'Fighting into the Bastions: Getting Noisier to Sustain the US Undersea Advantage', June (Washington DC: Hudson Institute 2023). https://www.hudson.org/fighting-bastions-getting-noisier-sustain-us-undersea-advantage-submarine-bryan-clark-timothy-walton.

[79] Bryan Clark, 'Fighting into the Bastions', 8.

[80] David Schaefer, Christian Thiel, Jens Doose, Andreas Rennings, and Daniel Erni, 'Above Water Electric Potential Signatures of Submerged Naval Vessels', *Journal of Marine Science and Engineering* 7/2 (2019), 53. https://doi.org/10.3390/jmse7020053.

[81] Jiaxin Zhou, Jianjong Chen, and Zhichao Shan, 'Spatial Signature Analysis of Submarine Magnetic Anomaly at Low Altitude, *IEEE Transactions on Magnetics*, 53/12 (Dec. 2017).

[82] Katarzyna Kubiak, 'Quantum Technology and Submarine Near-Invulnerability', Policy Brief from European Leadership Network, 11 Dec. 2020. https://www.europeanleadershipnetwork.org/policy-brief/quantum-technology-and-submarine-near-invulnerability/.

such as a sand wave.[83] Ship and aircraft measurements have resolutions of 1 to 10 km, while measurements from space a typically measured on the order a quarter of a degree.[84] Given the availability of sensors that have similar range such as magnetic sensors, there does not seem to be a distinct advantage in attempting to detect submarines by their effect on the local gravity.[85]

Over the next 20 years, the most cost-effective sensing methods would probably be combinations of multistatic active sensor fields, perhaps with magnetic sensors. These would be effective against both submarines and UUVs operating in bastions. Combining short range sensors at fixed sites or on UUVs with mobile decoys would create a complex environment for hunting SSBNs.

Remote sensing from above the Sea

The prospect of detecting submarines from space or high in the atmosphere has always been a topic of interest when considering hypothetical threats to US SSBNs in the open ocean. Combinations of low earth orbit optical and synthetic aperture radar (SAR) sensing satellites in conjunction with geostationary optical sensors makes it possible to track surface ships due to the strong contrast of ships in the visible spectrum and their radar signature.[86] Satellite constellations are growing rapidly, and commercial satellite companies are using a wide range of sensors including optical, infrared, and synthetic aperture radar capable of supplementing military systems for finding and identifying ships. There are also companies that provide space-based signals intelligence sensors for collecting radio communications and for radio location finding. Combinations of these satellites can revisit most areas of the ocean every few hours or even more frequently, and over the next 20 years it is reasonable to assume that more satellites with more frequent revisit times will become available.

Submarines operating at the surface can be detected by these means, and even if they are submerged and operating at shallow depts and relatively high speeds they can be visible just under the surface and their surface waves

[83]Sand waves over 15 meters in height can be found in the Taiwan Straits and the northern South China Sea. Yuping Yang, Meng Liu, Jingping Xu, and Weikun Xu, 'Migrating Sandwaves Riding on Relict Dunes of Taiwan Shoal, Northern South China Sea', *Frontiers of Earth Science* 10 (Sep. 2022), 10, 75220. doi: 10.3389/feart.2022.975220

[84]Tommaso Pivetta, Carla Braitenberg, and Dora Francesca Barbolla, 'Geophysical Challenges for Future Satellite Gravity Missions: Assessing the Impact of MOCASS Mission', *Pure and Applied Geophysics* 178 (June 2021), 2223–2240. https://doi.org/10.1007/s00024-021-02774-3.

[85]Paul M. Moser, 'Gravitational Detection of Submarines', Pacific Sierra Research Corp. PSR Note, 984. Oct. 1989, p. 11. https://apps.dtic.mil/sti/pdfs/AD1012150.pdf.

[86]Wei Yu, Hongjian You, Peng Lv, Yuxin Hu, Bing Han, 'A Moving Ship Detection and Tracking Method Based on Optical Remote Sensing Images from the Geostationary Satellite', *Sensors* 21 (Nov. 2021). doi: 10.3390/s21227547. PMID: 34,833,622; PMCID: PMC8619672.

are detectable by radar. When submarines operate at slow speeds and substantial depths, their signals become extremely weak. As in all detection problems for which the signal is weak relative to random background noise and clutter, increasing the sensitivity of the signal detection algorithms necessarily increases the false alarm rate, or equivalently, the density of false alarms produced over a given area. As described earlier, if the information from the sensor and detection algorithm is inadequate for tracking, then the tracker algorithms will degrade to the point that they provide no useful targeting information.

The sensors that can operate in day and night are the only ones that can provide continuous data for tracking. Two possible candidates for space-based active sensors are LIDAR and synthetic aperture radar (SAR). Of these, only SAR can reliably function in dense clouds, since LIDAR light is scattered and attenuated in clouds.

Light detection and ranging (LIDAR)

LIDAR is an active sensor that works by emitting a short pulse of laser light into the ocean from above the sea surface and then sensing the returned signal in a sensitive detector that is aimed at the area where the laser entered the water. Backscattered light will return from the ocean surface, objects in the ocean, and the seabed if the water is sufficiently clear and shallow. There has been recent interest in China in developing space-based LIDAR for purposes of measuring the ocean optical properties of the upper layers of the ocean. This has sparked some concern that these systems could be used as sensors for an overall system to detect, classify, and track US SSBNs.[87]

When considering the effectiveness of optical detection from space, it is useful to consider the cloud coverage over the ocean. Cloud base heights during cloud cover events can vary from the sea surface (fog) up to 400 to 600 meters for many types of clouds. Total cloud cover over the Taiwan Strait, for example, varies between 50% to nearly 80%, with some variations over the season.[88] Even brief periods of clouds would prevent updates to SSBN locations from LIDAR which would disrupt the tracking process significantly.

China has initiated an ocean science mission called Guanlan that involves LIDAR sensing from satellites to sample the upper layers of the ocean for optical properties, chlorophyll, and perhaps other ocean properties. Large scale monitoring of ocean optical properties does not require very short revisit times nor does it require a sampling at a very high spatial density.

[87]Evan Lisman, 'Non-Acoustic Submarine Detection', CSIS Tech Primer, On the Radar, 5 Nov. 2019. https://ontheradar.csis.org/issue-briefs/non-acoustic-submarine-detection/.

[88]Caiyun Zhang, et al., "Bridging between SeaWiFS and MODIS for continuity of chlorophyll-A Concentration Assessments off Southeastern China', *Remote Sensing of Environment* 102 (Feb. 2006), 260.

The Chinese scientists perhaps inadvertently stimulated a great deal of interest in the program by describing it as part of a 'step forward toward a "transparent ocean" down to the vicinity of the thermocline'.[89] Models of space based LIDAR detection show the difficulties of detecting from space even with powerful lasers. One published model indicated that to reach the minimum signal-to-noise ratio for detecting backscatter photons from the ocean into space, about 1 Joule per laser pulse would be needed, and in any case a 5 Joule pulse would approach the limit of eye safety.[90] To put this into some perspective, from a low earth orbit, a satellite moving on the order of 25,000 km/hr, or about 7000 meters per second, might require at least 3 LIDAR laser pulses over a submarine in order to detect it from the background. If the submarine is 10 meters in diameter, this would translate to about 2000 pulses per second. At that rate, the laser would need to be about 2 kiloWatts. Laser weapons start around 10 kiloWatts of power. However, any object 10 meters across would produce a false contact, which when fused over time would generate a growing number of false tracks. In addition, since the returned power of a LIDAR signal from significant depths is greatly reduced by the round-trip scattering and attenuation of the incident light, a jamming or deception signal at the ocean surface directed up to the satellite could be relatively weak and still create false alarms or overwhelm and mask the true LIDAR signal. Between the technical demands of an entire system of space-borne, high-power LIDAR, the likelihood of cloud cover, and the relative ease with which decoy targets could be introduced into the ocean, space-based LIDAR does not appear to be an immediate threat to SSBNs in large ocean areas.

Radar to detect subsurface effects

Turbulent wakes, internal waves, and related temperature variations in the water associated with a moving submarine can spread to the point where they reach the surface some distance behind the submarine hull. These physical observables are typically larger if the SSBN is travelling at a high speed and relatively close to the surface. If they create a measurable signal that is distinct from the surrounding surface water, then this signal might be detectable from the surface, the air, or potentially from space. Observables at the surface might be

[89]Ge Chen, et al., 'Concept Design of the "Guanlan" Science Mission: China's Novel Contribution to Space Oceanography', *Frontiers in Marine Science*, 6/194 (Apr. 2019). https://www.frontiersin.org/articles/10.3389/fmars.2019.00194/full.

[90]Zhenhua Zhang, Peng Chen, and Zhihua Mao, 'SOLS: An Open-Source Spaceborne Oceanic Lidar Simulator', *Remote Sensing* 14/1849 (Apr. 2022), 23–24. https://www.mdpi.com/2072-4292/14/8/1849.

- Water motions that affect the motion of the surrounding ocean, and have effects that could be measured by optical sensors, magnetic sensors, or electrical sensors
- Changes in local salinity or temperature profiles in the ocean
- Small currents might change the distribution of floating surface chemical and biological activity into a recognizable pattern. These effects might change the emissivity of the surface in a discernable pattern, or the radar scattering of the surface at particular frequencies and directions.

The turbulence in a submarine wake in a stratified fluid with temperature and salinity varying over depth, creates yet other effects that have been investigated. Detecting variations in the temperature and salinity over the wake can be one possible means of detecting the wake from within the ocean, which would be relevant to trailing.[91] As I have discussed already, however, translating a known physical effect of a submarine to an oceanic-scale operational tracking capability with high reliability requires the detailed specification of an enormous architecture of sensors, communications, and tracking capabilities maintained over many millions of square kilometers.

There has been a deep interest in detecting hydrodynamic effects of submarines from space using synthetic aperture radar since the 1970s. There were many observations of surface effects in SAR images that corresponded to changes in depth and subsurface currents. Both the Soviet Union and the United States applied a great deal of talent and energy to understanding the hydrodynamic effects of the ocean, the ocean surface effects, and the interactions between SAR and the sea surface. Space-based SAR is not significantly attenuated by clouds, as in the case of passive optical sensing and LIDAR. Chinese researchers have been publishing the results of numerical analyses of this problem. The conclusions typically echo what has been publicly released in studies from the United States.

> The results show that under appropriate circumstances, the body induced wake can be identified in SAR image and some information of the body can be retrieved too. However, the chance of detectability decreases dramatically when the SAR platform has a high range-to-velocity ratio, or when the body is moving at small speed, deeper depth or under high wind conditions.[92]

This is a detection mechanism that will likely receive continued attention, although there is no evidence to support the assumption that an individual

[91] Qing Chen, Qunqing Lin, Yimin Xuan, and Yuge Han, 'Investigation on the Thermohaline Structure of the Stratified Wake Generated by a Propagating Submarine', *International Journal of Heat and Mass Transfer* 166 (2021), 120,808. See also Zachary E. Moody, Christopher J. Merriam, Timor Radko, and John Joseph, 'On the Structure and Dynamics of Stratified Wakes by Submerged Propagating Objects', *Journal of Operational Oceanography* 10/2 (Mar. 2017), 191–204.

[92] Peng Liu and Ya-Qui Jin, 'Simulation of Synthetic Aperture Radar Imaging of Dynamic Wakes of Submerged Body', *IET Radar, Sonar, and Navigation* 11/3 (March 2017) 481–489. https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/iet-rsn.2016.0297

spaceborne SAR and its processing would have a high probability of detection against SSBNs operating at substantial depths and low speeds while simultaneously having a low false alarm rate. On the other hand, SAR might be useful for detecting high-speed submarines at shallow depths, such as SSNs operating in ocean regions with complex bottom topography that would require operating well above the sea floor.

As in all active sensors, countermeasures against SAR are available. The ability to disrupt synthetic aperture radar returns from the sea surface, especially in bastion areas, is a very active area of research, including in China.[93] The methods of SAR jamming include using high levels of noise to overwhelm the returns to the SAR, and more subtle – and lower powered – deceptive jamming that injects false targets in the SAR return.[94] Deceiving a SAR system with jamming requires very good information about the position of the SAR system itself, and is not a stratightforward technical problem.[95] Given the complexity of SAR countermeasures, and SAR processing itself, it is difficult to predict whether SAR could be used reliably to detect weak signals on the surface in the face of a determined countermeasures effort.

As in all military systems, the capabilities of an individual sensing component does not give rise to a reliable military capability. An oceanic-scale sensing and communication architecture would be needed to make use of any possible detection process. This architecture would need to include data uplink and downlink capabilities as well as logistics and maintenance support. Such architectures are inherently highly visible, and can be made vulnerable.

In contrast with the challenges of using SAR in the open oceans against slow, deep SSBNs, the use of SAR within bastion areas by the pro-SSBN side may be feasible from UAVs or fixed wing aircraft. For example, attack submarines operating against Chinese SSBNs in the relatively shallow waters of the Yellow Sea, parts of the East China Sea, or the Bohai Gulf would be operating relatively near the surface in conditions where surface effects may be detectable from SAR. These SSNs may also need to operate at relatively high speeds to maneuver for passive bearings-only tracking. UAVs equipped with SAR could potentially detect the hydrodynamic effects of submarines in these waters. However, given the large number of surface ship wakes in these regions, a SAR sensor would probably need to be fused

[93]Kaizhi Yang, Wei Ye, Fangfang Ma, Guojing Li, and Qian Tong, 'A Large-Scene Deceptive Jamming Method for Space-Borne SAR Based on Time-Delay and Frequency-Shift with Template Segmentation', *Remote Sensing* 12/1 (Dec. 2019), 1–25, 53. https://doi.org/10.3390/rs12010053.

[94]Kaizhi Yang, Fangfang Ma, Da Ran, Wei Ye, and Guojing Li, 'Fast Generation of Deceptive Jamming Signal Against Spaceborne SAR Based on Spatial Frequency Domain Interpolation', *IEEE Transactions on Geoscience and Remote Sensing*, 60 (Dec. 2021), 1–15.

[95]Frans-Paul Pieterse, Johan C. Smit, and Jacques E. Cilliers, 'On the Importance of the Accuracy of the Estimate of the Radar Position for Fully Coherent Jamming of a Stripmap SAR Sensor", IEEE 2022 International Conference on Radar, Antenna, Microwave, Electronics, and Telecommunications (ICRAMET), Bandung, Indonesia, 2022, pp. 183–88, doi: 10.1109/ICRAMET56917.2022.9991237.

with other sensor data to enable tracking over a longer period. The pro-SSBN side with an air defense system would have a distinct logistical advantage in operating over their bastions.

UUVs: Pro-SSBN and Anti-SSBN

Uncrewed underwater vehicles (UUVs) are being developed for many uses, including antisubmarine warfare, mine warfare, and the use of UUVs as decoys.[96] Autonomy is often considered the most challenging problem for the development of UUVs. Autonomy is an active area of research today, and it must be assumed that in 20 years, there will be significant improvements in autonomy for undersea surveillance. Advances in UUVs will likely be most readily applied to SSBN bastions, given the fact that bastions require relatively short-range transits from logistics support on shore and bastion defense can be effective without necessarily requiring stealth. Bastion areas can be configured with recharging or refueling stations and with communication nodes that can be connected directly to shore.

The challenges of autonomy algorithms grow quickly when the operation of a UUV requires a greater degree of information about the surrounding environment and more complex planning in the face of uncertainty. For pro-SSBN operations in a bastion, UUVs that operate with predetermined patrol plans, or with cooperative algorithms to support networked communication and sensing in known areas, the levels of autonomy are probably within reach in the next 20 years. Minehunting UUVs which execute area search plans are already used for autonomous mine search operations.[97] For the pro-SSBN side continuous minehunting operations over key waterways like SSBN transit lanes between ports and patrol areas would facilitate bottom change detection to help locate any clandestine mine installation by an adversary.[98] These kinds of capabilities would be available to the pro-SSBN side for ongoing search and patrol with active sensors in bastions and SSBN port egress routes.

If UUVs are deployed to operate far from supporting infrastructure on land or at sea, then their autonomy algorithms must be capable of addressing a very wide set of circumstances, including tides, reefs, fishing nets, and variable currents. When SSNs were used to trail Soviet SSBNs in the Cold War,

[96]Robert W. Button, John Kamp, Thomas B. Curtin, and James Dryden, 'A Survey of Missions for Unmanned Undersea Vehicles' (Santa Monica, CA: RAND Corporation June 2009), p. 38. https://www.rand.org/pubs/monographs/MG808.html.

[97]Megan Eckstein, 'What's Ahead for Navy Unmanned Underwater Vehicle Programs?' *Defense News*, 29 Nov. 2022. https://www.defensenews.com/naval/2022/11/29/whats-ahead-for-navy-unmanned-underwater-vehicle-programs/.

[98]Naval Meteorology and Oceanography Command, Public Affairs, 'Naval Oceanography participates in BALTOPS22', 11 June 2022, US Sixth Fleet, https://www.c6f.navy.mil/Press-Room/News/Article/3059896/naval-oceanography-participates-in-baltops22/, See also D. Terracciano, L. Bazzarello, Caiti, A. et al., 'Marine Robots for Underwater Surveillance', *Current Robotics Reports* 1, (2020), 159–167. https://doi.org/10.1007/s43154-020-00028-z.

they were capable of tasks ranging from obstacle avoidance to targeting and launching weapons against SSBNs. They could also navigate in shallow water and under ice, avoiding obstacles while tracking an SSBN using only the bearing information provided by passive sonar. Nuclear-powered attack submarines can travel many thousands of miles, transit at high speeds, and operate for months at sea while the crew continually adapts to new data and new conditions. Long-range and long-endurance autonomy for strategic ASW operations would pose much greater challenges for UUVs, and will be somewhat slower to develop to maturity. For the foreseeable future, autonomy will probably favor the pro-SSBN side.

A review of Chinese sources from 2018 provides a number of references from Chinese military and technical sources regarding the use of UUVs in the pro-SSBN mission.[99] UUVs are considered by Chinese experts as providing a potential undersea communications network for search, detection, localization, and tracking of potentially hostile vehicles in waters critical to the Chinese Navy. Chinese concepts for using undersea communication cables in conjunction with UUVs teamed with SSBNs are discussed in the technical literature, as are concepts for using UUVs as decoys to draw anti-SSBN forces away from SSBNs.[100] Given the short transit distances and availability of ship- and shore-based UUV logistics support, it is plausible that China could keep far more UUVs in the pro-SSBN mission than the US or its allies could keep UUVs in the anti-SSBN mission, assuming expenditures of the same rough order of magnitude.

Many of the concepts for using UUVs in the pro-SSBN mission from Chinese and Russian sources are quite similar. This is likely due to the fact that both the Chinese and Russian Navies are driven to the same technical solutions by the constraints of cost, effectiveness, and the opportunities available to disrupt anti-SSBN missions by taking advantage of the difficulties and uncertainties of ASW search, detection, identification, and covert tracking in protected waters.

In addition to the challenges of autonomy, the other key design issues for UUVs are related to the stored energy source for propulsion and sensing. Modern UUVs with long ranges such as Echo Voyager use batteries and diesel engines for long distance operations simply because there are few fuels that are as easy to store and have as high energy density by weight and volume as diesel fuel and engines.[101] although quieter propulsion systems would be necessary to operate over long periods in protected bastions. Some recent work on UUV energy sources provide an approximate baseline for current capabilities.

[99]Zhao, 'Tides of Change', 66–67.
[100]Zhao, 'Tides of Change', 66–67.
[101]'Inside Boeing's Orca XLUUV for the US Navy', *Marine Technology News*, 13 Feb. 2024. https://www.marinetechnologynews.com/news/inside-boeing-xluuv-634578.

A recent Chinese study from the Dalian Naval Academy evaluated the cruising speed and range of a large displacement UUV using solid oxy-hydrogen energy propulsion. [102] The Chinese study used open-source specifications on a US UUV called Proteus.[103] However, the Chinese analysis applied a new power technology to determine its impact on the US UUV performance. The proposed propulsion system provided for significant increases in distance, but even with these improvements in stored energy, the hypothetical system could travel only 560 kilometers at a speed of 19 km per hour, or about 2780 kilometers at 9.3 km per hour.[104] These results demonstrate that UUVs with ranges of over 1850 km are feasible with current technology. Some reporting suggest that Russia is developing a UUV with Air Independent Propulsion with a potential range of 7400 km using a hydrogen and oxygen system, although no speed data was provided.[105] Over 20 years or more, it is possible that small nuclear-powered propulsion plants could be engineered for UUVs in order to give the UUVs much longer endurance.

China has also been working on using uncrewed air vehicles (UAVs) to support maritime patrol aircraft in the ASW mission. Chinese maritime patrol aircraft patrolling over the northern portion of the South China Sea directly off China's coast have accounted for a large number of China's incursions into Taiwan's Air Defense Identification Zone, an indication of how important the ASW mission is in this area.[106] Chinese maritime patrol aircraft operate at relatively slow speeds and must remain near sonobuoy fields in order to monitor the acoustic returns from the buoys, fuse the data into estimated locations of submarines, identify them with magnetic anomaly detectors, and then possibly attack the submarines with torpedoes. UAVs with long durations could be used to collect the hydrophone data and relay the data to a remote fusion center.[107]

[102]The analysis used information published on the AUVAC website in the US: Autonomous Undersea Vehicle Application Center, AUVAC. MINWARA Undersea Mining. Powerpoint, https://auvac.org/files/uploads/platform_pdf/proteus.pdf. The Chinese reference is: Fangfang Zhang, et al.. Dalian Naval Academy, 'Power Performance Prediction of Large Displacement UUV with Solid Oxy-Hydrogen Energy Propulsion', IEEE 2020 3rd International Conference on Unmanned Systems (ICUS), 27–28 Nov. 2020, Harbin, China.

[103]The powerpoint slides indicated that Proteus has a working depth of 150 ft., dimensions of 308 × 63.5 × 64 inches, weight of 8240 lbs., Cargo volume 170 ft3 Cargo weight in air 3600 lbs, Energy Storage 148 kWh baseline, 296 kWh Extended, and uses a Lithium polymer battery. https://auvac.org/files/uploads/platform_pdf/proteus.pdf.

[104]Fangfang Zhang, et al., 'Power Performance Prediction of Large Displacement UUV'.

[105]Naval News Staff, 'Russia Develops Preliminary Design Of AIP Unit For Sarma UUV', https://www.navalnews.com/naval-news/2021/09/russia-develops-preliminary-design-of-aip-unit-for-sarma-uuv/

[106]The ocean areas south of Taiwan include access from the South China Sea to the Philippine Sea. Radio Free Asia Staff, 'China Sends 21 Aircraft into Taiwan's Air Defense Identification Zone', *Radio Free Asia*, 14 Dec. 2022. https://www.rfa.org/english/news/china/taiwan-incursion-12142022043822.html. See also Olli Pekka Suorsa, 'The Anti-submarine Warfare component of China's Sorties in Taiwan's ADIZ', *The Diplomat*, 4 Nov. 2021. https://thediplomat.com/2021/11/the-anti-submarine-warfare-component-of-chinas-sorties-in-taiwans-adiz/.

[107]Lyle J. Goldstein, 'China is Doing All it Can to Make Sure it Can Kill US Submarines', The *National Interest*, 15 Nov. 2020. https://nationalinterest.org/blog/reboot/china-doing-all-it-can-make-sure-it-can-kill-us-submarines-172600.

UUVs in the anti-SSBN role

If the anti-SSBN side uses uncrewed underwater vehicles crewed submarines, the same dynamics described here apply, except that the uncrewed systems will likely need to operate clandestinely and therefore fully autonomously or in close coordination with US SSNs.[108] If they operate with passive sonars against SSBNs, they will need to conduct bearings-only tracking autonomously over long durations, avoid decoys and counter detection, all while controlling relatively limited stored energy supplies for propulsion and computing. Use of US and allied UUVs in Chinese or Russian bastions are possible, but long-term search, detection, tracking, and communications in the presence of pro-SSBN countermeasures would be difficult. Given the difficulties with sustained tracking using bearings-only passive detection, UUVs do not seem like plausible systems for this task. Over the next 20 years, improvements in uncrewed system autonomy and propulsion is certain to improve for the anti-SSBN side. More plausible uses could be mobile mines or minelaying or intelligence gathering.

The noise produced by UUVs would limit its own ability to perform passive detection by introducing noise from the machinery into the acoustic sensor in the water, or into a sensor directly fixed to the hull of the UUV. This self-noise is difficult to reduce without increasing the size of the UUV, which in turn increases the resistance, which in turn decreases the endurance of the UUV for a fixed energy source. Noise from the UUV can also enable counter-detection: if the UUV attempts to patrol in a militarily-sensitive area, it might be detected by fixed acoustic sensors, or could be lured to a sensor by a decoy. Research and development for detection and localization of UUVs is active in the United States.[109] It is also active in China and often deals with the special problems of detecting UUVs in shallow waters, where they probably have the greatest value for pro-SSBN and anti-SSBN operations. [110] Over the next 20 years it is likely that detection and tracking capabilities against UUVs at short range will prevent extensive clandestine mapping of defensive undersea sensors, communications, and transit routes within pro-SSBN bastions.

[108]UUVs could be used for clandestine mapping of sensing networks prior to any crisis. Bryan Clark 'Fighting into the Bastions', p. 9.

[109]John Gebbie, Martin Siderius, and John S. Allen III, 'Aspect-Dependent Radiated Noise Analysis of an Underway Autonomous Underwater Vehicle', *The Journal of the Acoustical Society of America* 132/5 (Nov. 2012) EL351-EL357. See also Kristen Railey Kita, Supun Randeni, Dino DiBiaso, and Henrik Schmidt, 'Passive Acoustic Tracking of an Unmanned Underwater Vehicle Using Bearing-Doppler-Speed Measurements" *The Journal of the Acoustical Society of America* 151/2 (Feb. 2022) 1311–1324.

[110]Jiangqiou Li, Li Jiang, Hongyu Chen, Ye Zhang, and Yuchao Xie, 'Propeller Feature Extraction of UUVs study based on CEEMD Combined with Symmetric Correlation', MATEC Web of Conferences 336, 02006 (2021), CSCNS2020. https://www.matec-conferences.org/articles/matecconf/abs/2021/05/matecconf_cscns20_02006/matecconf_cscns20_02006.html, Also, Xiang Pan, Jingning Jiang, Si Li, Zhenping Ding, Chen Pan, and Xianyi Gong, 'Coherent and Noncoherent Joint Processing of Sonar for Detection of Small Targets in Shallow Water', *Sensors* 18/4 (Apr. 2018), 1154. https://doi.org/10.3390/s18041154.

Use of uncrewed systems in the tens of millions of square kilometers of US SSBN patrol area in the Atlantic and Pacific are limited more directly by the energy requirements of long UUV patrols. Due to the likely energy limits of uncrewed systems, UUVs designed to trail SSBNs in the open ocean would require many covert trailing systems that could be used in sequence – one passing on the task of trailing to another in a relay. However, the course of such a relay would be unknown to the trailing systems in advance – they would have to follow the SSBN wherever it went. Therefore, the relay could take place at any random location over hundreds of square kilometers. UUVs with longer ranges are available using diesel engines, but these noisy engines are susceptible to acoustic detection in the deep ocean. If small nuclear reactors are developed for UUVs, they will need to incorporate all of the sound quieting features of the most modern submarines, and this will drive up the size, procurement cost, and maintenance costs of any hypothetical long-endurance UUV. They will approach modern SSNs in design and life-cycle cost, but without the capabilities of a crewed SSN. Since they will not have the quietness of US SSBNs, they will be high-risk, low-payoff investments that do not appear to be practical.

If many UUVs are used collaboratively to trail, the numbers required grow very quickly. In order to have enough trailing systems available in the area of a random SSBN patrol they would need to be able to signal for another trailing system to take over. Given an assumed ability of the covert trailing systems to communicate over a range of 10 kilometers – a high estimate that would require a loud source – there would need to be UUVs distributed over 10 million square kilometers on a grid with spacing of 10 kilometers. With this spacing there would need to be on the order of 100,000 trailing systems dispersed throughout the patrol area ready and continuously waiting to covertly pick up the trail as another system dropped off. The maintenance of this many systems ready to operate would require many more in overhauls and in transit over thousands of miles. This is an impractical approach, so a long-term covert trailing effort would be expensive and only marginally effective. It is important to keep in mind that the controlling factor on the number of UUVs required is not their range, but rather their covert communication range. These calculations for an anti-SSBN architecture based on UUVs assume a 10 km communication range, which is not likely to be covert and could be detected by the SSBN.

The pro-SSBN activities of protecting bastions could make use of UUVs given their multiple possible military missions of intelligence, surveillance, reconnaissance, mine countermeasures, oceanography, auxiliary communication and navigation, UUV-based sensing, and logistical support. These are all functions that are extremely valuable in defending SSBN bastions, and could be adopted by the US in regions near the SSBN bases. This would require a significant cultural shift in US thinking about SSBN security, but could be considered in the long term future. Advances in UUVs capable of sensing and patrolling for submarines are most likely to be applied to the pro-SSBN mission first. On the other hand, the deployment of sensors or mines, and relatively simple search patterns could be accomplished using UUVs.

The use of uncrewed surface vehicles (USVs) allows for much greater flexibility in propulsion, communications, and sensing. Since USVs would be more detectable than UUVs, they would be more vulnerable in an anti-SSBN role in an adversary bastion than they would be performing pro-SSBN missions in a bastion where the pro-SSBN side had adequate air defense and control of the sea surface. Their flexibility and greater range does allow them to operate in contested regions in the pro-SSBN role together with seabed sensors, maritime patrol aircraft, and UAVs.

Naval mines

Naval mines are very potent weapons that have reached a high level of sophistication. Even less sophisticated mines can have potent tactical effects. Mines can damage interior systems and people well before they sink a submarine, and can be effective at ranges of several tens of meters, depending on the size of the explosive charge and the water depth.[111] The PLA has placed additional emphasis on using sea mines including mobile sea mines in the ASW mission.[112] China and Russia have large arsenals of naval mines that could be used to threaten SSNs attempting to search within SSBN bastions. These minefields operated by the pro-SSBN side could be controlled remotely and would create a risk to SSNs or even UUVs approaching SSBN transit routes from ports.[113] Mines can be effective if installed in the relatively shallow waters of the Chinese bastion regions, and China has significant stocks of remote-controlled mines.[114] Controllable minefields are much easier to maintain over time in confined areas near shorelines such as the Bohai Gulf or near Hainan Island. Remote control mines could be adapted to the pro-SSBN bastion defenses by China near sensitive ports and chokepoints.

The anti-SSBN side could attempt to lay active minefields near SSBN ports if submarines or UUVs could get close enough to place the mines in the likely

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[111] Bogdan Szturomski, 'The Effect of Underwater Explosion on a Ship', *Scientific Journal of the Polish Naval Academy*, 2/201, (2015), 57–73. https://www.infona.pl/resource/bwmeta1.element.baztech-158366f3-0986-47bf-a3ad-21819dc55273.

[112] Gabriel Collins, Andrew Erickson, Lyle Goldstein, and William Murray, 'Chinese Evaluations of the U.S. Navy Submarine Force', *Naval War College Review* 61/1 (Dec. 2008). https://digital-commons.usnwc.edu/nwc-review/vol61/iss1/6.

[113] Scott Truver, 'Taking Mines Seriously: Mine Warfare in China's Near Seas', *Naval War College Review* 65/2 (Apr. 2012), 11–13. https://digital-commons.usnwc.edu/nwc-review/vol65/iss2/5/.

[114] Andrew S. Erickson, Lyle J. Goldstein, and William S. Murray, 'Chinese Mine Warfare: A PLA Navy "Assasin's Mace" Capability', US Naval War College, China Maritime Studies Institute. See Table 1. https://www.andrewerickson.com/2009/08/chinese-mine-warfare-a-pla-navy-assassins-mace-capability/.

paths of SSBNs. If mines near the transit routes of SSBNs and other ships could be controlled remotely, they could be sown in large numbers over time and would be a potent maritime threat over the course of a conventional war.

Finding and disabling mines using mine countermeasures technologies (MCM) is a time-consuming task. Given the potential threat from mines, and the difficulty in eliminating them, their impact on naval warfare, ASW generally, and perhaps even strategic ASW over an extended wartime period is under-appreciated.

There is no simple way to prevent mines from being installed in the era of improving UUV technology. The pro-SSBN side would benefit greatly from maintaining information about the seabed and the ocean around SSBN routes. Continuous undersea monitoring with side-scan sonar, electro-optic sensors, and other sensors along SSBN egress routes would provide prior information about changes in the bottom. UUVs can be very useful when applied to localized mine detection and localization operations when sufficient time is available.

Deploying mines in sufficient numbers to have a significant impact on naval operations requires extensive minelaying capabilities, and access to large stores of mines. The logistical challenge of deploying mines and replenishing minelayers makes them a more viable weapon for use near the coasts. Over the next 20 years, the use of remote-controlled minefields in shallow waters may favor the pro-SSBN side in Chinese and Russian bastion areas.

Some operations Analysis

Simple examples of strategic ASW campaigns with a few calculations can put some of the ideas described above into context. I will describe one case of an anti-SSBN campaign by the US against an SSBN bastion that is sufficiently general to apply to either a campaign against Chinese or Russian SSBNs. This baseline analysis will then serve to briefly demonstrate how much more uncertain and costly an anti-SSBN campaign would be against the US SSBN fleet.

A campaign of strategic ASW can begin in several stages of a crisis or conflict. If it begins prior to conventional war, the anti-SSBN side can potentially begin tracking or trailing SSBNs as soon as they leave their ports. However, the pro-SSBN side can concentrate sensors and platforms to find submarines or UUVs in those critical areas. In the 1970s, the CIA determined that the Soviet Navy was aware of US proposals to trail ballistic missile submarines and expected to confront Western submarines in routes leading to the open sea.[115] The CIA also assessed that the Soviet Navy likely viewed

[115]'Soviet Antisubmarine Warfare: Current Capabilities and Priorities', Directorate of Intelligence and Directorate of S&T, Sep. 1972, p. 14, Approved for Release: 2017/06/14 https://www.cia.gov/readingroom/docs/DOC_0005512850.pdf.

their own ability to trail western SSBNs as a 'risky and unworkable scheme' in part because those western submarines 'would be given extensive delousing to remove potential trailing submarines'.[116] Delousing, or searching behind one's own SSBNs for hostile trailing SSNs – can be effective for finding threats to SSBNs prior to wartime simply because very little search effort is required.

If strategic ASW operations were to be delayed until the beginning of a conventional war, then less initial information would be available to the anti-SSBN side since SSBNs would have been sent out to sea. If they were not already trailed by the anti-SSBN side, a search would be required, so it is important to consider the probability of success of a search over time. I will consider the simplest case of a search with no prior information about the location of the target of the search, in this case one or more SSBNs.

The Russian SSBN patrol areas are assumed to include the Barents Sea, Kara Sea, and Sea of Okhotsk which altogether encompass about 3 million square kilometers in very round numbers. These ocean areas are adjacent to the Arctic and North Pacific Oceans so they are probably lower bounds, but I will use them to illustrate the order of magnitude of the search problem. Chinese SSBN operating areas are assumed to include parts of the South China Sea closer to China, perhaps half of the East China Sea closest to China, the Yellow Sea, and the Bohai Gulf. The total of these areas is also about 3 million square kilometers. If we assume that five SSBNs from Russia (of about 10 projected) and five from China (of about 8 projected) have left their ports to patrol in these 3 million square kilometer areas I can use the same approximate numbers for this example of strategic ASW search against both Russia and China.

For the US, assume that there are 10 SSNs allocated to each of the Chinese SSBN areas and the Russian areas. Assume a US SSN detection range against both Chinese and Russian SSBNs that has a 100% probability of detection and no false alarms out to a range of 10 kilometers. As the US SSN searches it can sweep that distance to both sides and therefore has a sweep width of 20 kilometers.[117] Assume further that the SSN search speed is 10 kilometers per hour to minimize radiated sound and to enable navigation in the relatively shallow waters of some of these bastion areas. Now assume that the SSBNs patrol in non-overlapping regions of their respective bastions, and that the US SSNs have prior information on what those patrol regions are.[118] Also

[116]Ibid., 50.

[117]Based on the Chinese analysis of the SURTASS sonar cited earlier. I have selected a range closer to the minimal one since the Chinese analysis assumed deeper water in the Miyako Strait that is more conducive to long range detection. J. Wang, X. Kong, G. Cheng and Y. Chen, 'Research on Detection Range Prediction for Oversea Wide-Aperture Towed Sonar', 2021 OES China Ocean Acoustics (COA), 2021, pp. 57–61, doi: 10.1109/COA50123.2021.9519971. IEEE ExPlore https://ieeexplore.ieee.org/document/9519971.

[118]Assume that the five SSBNs operate in separate regions of the same size, 600,000 square kilometers each, and that the US knows the boundaries of these five areas and allocates two SSNs to search each area.

assume that there are no attempts to find or counter the SSNs within these bastions. Now consider just one ASW operation, since the assumptions are identical, and consider a few cases.

If the SSBNs are stationary and the SSNs conduct an exhaustive search of the area, it would take 63 days for all five of the SSBNs to be detected with a probability of 100%. These assumptions are unrealistically favorable to the anti-SSBN side, but they indicate the scale of the search problem. If the SSBNs are moving at a few kilometers per hours – enough to introduce the conditions of a random search – it would take about 180 days to detect each of the five SSBNs within their separate – and known – patrol regions, with a probability of 95%.

It is straightforward to look into one more level of uncertainty in these five searches. Given that the searches for each of the five SSBNs are independent, the probability distribution of successfully detecting any given number of SSBNs is binomial. Dedicating 10 attack submarines to search for 5 SSBNs under the assumptions above yields a probability of detection all 5 SSBNs of 77% over 180 days. Considering a shorter time frame, say 60 days, the probability of detecting all 5 SSBNs drops to about 10%, and there is a 28% chance that only one or two of the five SSBNs are detected.

These numbers illustrate the fact that if a strategic ASW campaign is executed over the course of a war that unfolds over time in an unpredictable way, then the most plausible option is to trail SSBNs continuously beginning in peacetime using SSNs. This requires the dedication of a very large portion of the available SSNs available for a complex and perhaps very long duration.

This dynamic was succinctly captured in 2018 statements from a retired senior US Navy intelligence officer in describing the feasibility of strategic ASW against China's SSBN fleet.

> given the presumption the PRC has already begun ballistic missile submarine patrols and to mitigate the risk of a sea-launched nuclear ballistic missile attack against the U.S., the U.S. Navy must be able to -"hold at risk" all adversary nation's patrolling SSBNs, at all times. Hold at risk means that every time a PLAN SSBN departs on a strategic nuclear patrol, the USN must follow closely enough to be ready to sink them if they ever attempt to launch a nuclear tipped ICBM towards our shores. Chinese boomers are not so loud that when a crisis begins we will with high certainty be able to find these boomers.[119]

The pro-SSBN side can leverage this limitation by using a combination of decoys to divert the search, using active sonar fields to detect the SSNs or

[119]Captain James E. Fanell, U.S. Navy (Retired), 'China's Global Naval Strategy and Expanding Force Structure: Pathway to Hegemony', House Permanent Select Committee on Intelligence, Hearing on 'China's Military Expansion' May 17, 2018.

divert the search, and to initiate delousing operations against the SSNs themselves.[120]

Searching for US SSBNs in the Atlantic and Pacific Ocean patrol areas that are an order of magnitude larger than the Chinese and Russian bastions would require an order of magnitude longer, and are clearly not threats to US SSBN retaliatory capabilities. Reliable sensing and localization from space using active sensors that can function at night and through clouds to track SSBNs shows little promise of success over the next 20 years. Any serious effort to build such an oceanic-scale surveillance and tracking architecture against SSBNs would be highly visible. Concerns about active submarine sensors over the oceans could be addressed using a number of deception and jamming techniques that could be cost effective.

Artificial Intelligence in ASW

Before concluding this paper, it is important to address a topic that has taken on a central role in public predictions future vulnerability of US SSBNs: the presumed ability of artificial intelligence to solve the many challenges of antisubmarine warfare.

Artificial intelligence algorithms based on very large, deep neural networks have achieved stunning results in the areas of learning to operate in simulation environments such as games or computer simulations of combat. They have also made tremendous advances in classifying very high dimensional data such as images, video, and sounds and have made rapid strides in automatically synthesizing new data from patterns derived from very large training data archives. As of this writing, the most newsworthy applications of deep neural networks are those applied to generating text, software source code, and music based on huge internet-derived text databases.

In applications to the confrontational information environment of undersea warfare, there have been many efforts to apply deep neural network-based algorithms to problems in passive sonar, active sonar, classification, direction-finding, and other critical functions. Reviews of this work suggest that the most successful applications of deep neural networks to submarine detection and tracking are those that combine these deep neural network algorithms with understanding of ocean physics and other advanced signal processing methods that are not based on the artificial intelligence or deep neural network methods. When adequate data is available to train classifiers,

[120]The effect of false alarms on merely slowing the search depends approximately on the product of the frequency of encountering a false alarm each hour and the average time required to investigate that false alarm to determine it is not a real target. If this product is much less than unity, then false alarms by themselves do not have a large impact on the probability of detection as a function of time in a search. See Stephen M. Pollock, 'Search Detection and Subsequent Action: Some Problems on the Interfaces', 571.

they can improve performance in particular tasks over more conventional classifiers, although there is no comprehensive analysis available of how robust these methods are to the variations in undersea noise and sound propagation over time and location. Published reports of deep neural network-based detection or signal recognition algorithms still exhibit degradation at low levels of signal relative to background noise.

For fixed sensors operating in known locations in bastion areas, the availability of continuous data about the background as well as additional 'ground-truth' information about operations in local ocean areas probably yields a somewhat greater improvement for pro-SSBN use of deep neural networks. Thus, if deep neural network-based AI algorithm yield improvements of other methods, it is more likely that these improvements benefit the pro-SSBN side which can maximize the data collection in their protected SSBN bastions.

The effectiveness of deep neural network generative systems for producing fake data of any kind has led two RAND researchers to suggest that generative AI applied to military deception will prove to be "AI's Killer App'.[121] For data such as communications, submarine radiated sound, or other deceptive signals that could be effective in undersea warfare, the application of generative AI could be effective. This would suggest again that AI could be applied as readily if not more so to the pro-SSBN mission. However, since some of the deceptive measures associated with decoys are already relatively straightforward, such as playing a recording of a submarine into an amplified underwater acoustic source, the application of deep neural network based generative algorithms is more likely to be an improvement, rather than a revolutionary advance.

Conclusions

This chapter has explained the ASW processes of search, detection, and tracking and shown how existing and emerging technology will tend to favor the pro-SSBN side. I have emphasized the probabilistic nature of ASW search and the complexity of multi-target tracking in the presence of noise and false alarms, since these are some of the essential sources of uncertainty in ASW. Clever operations, logistical advantages, and technology will enable the pro-SSBN side to increase uncertainty about their SSBN fleet more quickly and cost-effectively than the anti-SSBN side can sweep it away. The following sections summarize my conclusions about the prospects for SSBN security for the United States, China, and Russia.

[121]Edward Geist and Marjory Blumenthal, 'Military Deception: AI's Killer App?' *War on the Rocks*, 23 Oct. 2019. https://warontherocks.com/2019/10/military-deception-ais-killer-app/.

US SSBN Security

The US will continue to leverage its geographic and oceanographic advantages to keep the extraordinarily stealthy SSBNs of the Ohio and Columbia classes secure in the Atlantic and Pacific Oceans. This does not mean that adversary attack submarines can be ignored as a threat to US SSBNs as they leave port to begin patrols, however. Relatively quiet Russian submarines now patrol in the Atlantic and the Pacific, and while these submarines would be highly unlikely to detect and track US SSBNs, the US maintains measures to protect them as they transit to the open ocean.[122] It is always possible that over the next 20 years, the US Navy could choose to adopt some of these pro-SSBN measures to disrupt the potential threats to SSBNs near its ports.

Space-based architectures for surveillance of US SSBNs over millions of square kilometers would require a large number of mainly active sensors revisiting critical ocean areas on a regular basis. It is critical for the US to continue to investigate the physics of the ocean and test new sensor concepts in order to avoid missing some new combination of physical phenomenology, sensor combinations, data fusion, and tracking architectures that might yield some ability to track US SSBNs. However, the global sensing and communication architectures required to establish a reliable long-term surveillance threat against US SSBNs would be visible and could be countered using all manner of deception, jamming, and decoys well in advance. With strong support for research in oceanography, sensors, and signal processing, as well as SSBNs and their crews, US SSBNs at sea are essentially invulnerable now and will likely remain so for the next 20 years and beyond.

China's SSBN Security

It appears that China is developing systems capable of increasing the probability of finding SSNs that enter their bastion areas. In the event of an intense crisis or conflict, Chinese SSBNs could go to sea and the PLA Navy could put in place defensive measures against US SSNs such as decoys, mines, and surveillance systems in these bastion areas. If SSBNs are not continuously trailed over the course of their patrols or some other means to track them is not available, the time required to search for them is likely to stretch into many months and be highly uncertain. As this search time increases, the opportunities for pro-SSBN countermeasures grows.

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[122] Sam LaGrone, 'NORTHCOM: Russia Close to Persistent Nuclear Cruise Missile Attack Sub Presence off US Coasts', 23 Mar. 2023, *USNI News*, https://news.usni.org/2023/03/23/northcom-russia-close-to-persistent-nuclear-cruise-missile-attack-sub-presence-off-u-s-coasts, also Richard A. Moss, 'Russia Basks in Cold War Glory', *US Naval Institute Proceedings*, 146/10/1,412 (Oct. 2020). https://www.usni.org/magazines/proceedings/2020/october/russia-basks-cold-war-glory

In a crisis scenario, there would be an increased demand for US SSNs from the Pacific Fleet to support many tasks unrelated to strategic ASW. The most prominent example is that SSNs would be key elements in any military capability to deny the Chinese Navy from operating in a scenario involving a threat to Taiwan. In addition, it is likely that US SSNs would be used in such a crisis to monitor key locations from the Bering Strait to Russia's Kamchatka Peninsula, to the coasts of North Korea. US SSNs will also be called on to protect US aircraft carriers and critical logistics ships from attacks by Chinese submarines and ships in the Philippine Sea, to Hawaii, and to the continental US.

Although there is no evidence in China's military policy writings that the PLA sees a benefit to placing its SSBNs at risk in order to draw in US attack submarines,[123] the fact remains that US attack submarines allocated to the strategic ASW mission of trailing Chinese SSBNs will not be available for these other urgent missions. The survivability of Chinese SSBNs will be somewhat conditional on decisions by the US to deploy SSNs in direct support of conventional warfighting objectives.

Future developments in uncrewed systems such as UUVs or USVs for anti-SSBN operations in bastions do not appear to have an overwhelming advantage against countermeasures that could be developed against them. Uncrewed air and surface vehicles would likely face direct attacks as long as China was able to use surveillance radars over their bastions. Uncrewed undersea vehicles would need to transit relatively frequently in and out of bastion areas, and would be subject to all the delousing measures and deception measures that would be used against SSNs. Uncrewed systems are not likely to pose a large threat to Chinese SSBNs operating in bastions.

Russia's SSBN Security

Most of the technical arguments for China's SSBN survivability apply also to those of Russia so I will not repeat them here. It is worth addressing the rapidly changing geopolitical environment in Russia's Arctic bastion areas. The most recent intelligence threat assessments from both the United States and Norway indicate that because the war in Ukraine has weakened Russia's conventional capability, it's nuclear capabilities have taken on greater importance.[124] In this context, the Russian SSBNs in the Northern Fleet are an critical nuclear capability, leading to increased importance on the defense

[123]Zhao, 'Tides of Change', p. 15.
[124]ODNI, 'Annual Threat Assessment of the U.S. Intelligence Community', 6 Feb. 2023, p. 14, https://www.dni.gov/files/ODNI/documents/assessments/ATA-2023-Unclassified-Report.pdf. and 'FOKUS 2023, The Norwegian Intelligence Service's Assessment of Current Security Challenges', https://www.etterretningstjenesten.no/publikasjoner/focus.

of the northern bastion and the Barents Sea in addition to carrying out longer SSBN patrols in the Barents Sea.[125] Russia's SSBNs and some attack submarines are already relatively difficult to track covertly using US SSNs, and Russia appears to be investing in the kinds of undersea systems to disrupt NATO surveillance, to enhance its own undersea surveillance, and to provide decoys for SSBNs.

With the accession of Finland into NATO, the most sensitive bases supporting SSBNs in the Russian Barents Sea and the White Sea are now within 200 kilometers of NATO territory. While Norway has typically constrained the use of its territory and airspace for intelligence gathering against Russian installations on the Kola Peninsula near Norway, Finland now does allow the US to fly intelligence-gathering flights in Finnish territory to collect data from Russia.[126] Thus, Russia is likely to continue to focus efforts on securing its Northern Fleet region in order to protect the SSBNs operating there.

In the Pacific, Russia's excessively broad interpretation of the United Nations decision regarding its continental shelf in the Sea of Okhotsk, as well as the increasing militarization of the southern Kuril Islands have resulted in a more militarized perimeter around that bastion.[127] With the greatly expanded presence of NATO near Russia's Barents Sea bastion, the protection of the Sea of Okhotsk for Russian SSBNs is likely to continue to remain an important part of Russia's strategic nuclear basing. As in the case of China, the degree to which the US can threaten Russian SSBNs depends to a large extent on the level of commitment that the US makes early in a crisis to attempting to trail Russian SSBNs. As the pro-SSBN technologies improve and become more cost-effective, it is less likely that a moderate commitment of US SSNs to the anti-SSBN mission over the course of an extended conflict would have a decisive impact on eliminating Russia's SSBN fleet.

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[125]FOKUS 23, p. 21.
[126]Jo Inge Bekkevold, 'Europe's Northern Flank is more Stable Than You Think', *Foreign Policy*, 28 July 2023. See also Thomas Nilsen, 'U.S. Surveillance Jet Makes First Mission up to Northern Finland', *Barents Observer*, 25 Mar. 2023. https://thebarentsobserver.com/en/2023/03/us-surveillance-jet-makes-first-mission-northern-finland.
[127]Ike Barrash, 'Russia's Militarization of the Kuril Islands', CSIS Blog, 27 Sep. 2022. https://www.csis.org/blogs/new-perspectives-asia/russias-militarization-kuril-islands.

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U.S. Department of Defense Military and Security Developments Involving the People's Republic of China 2024, Annual Report to Congress, Washington, D.C., 2024, 104.

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APPENDIX: Chinese, Russian, and US SSBN Operating areas

China's SSBN bastions

The Department of Defense summary of China's SSBN forces was provided in the 2022 Military and Security Developments Involving the People's Republic of China:

> "The PRC likely began near-continuous at-sea deterrence patrols with its six operational JIN class SSBNs, which are equipped to carry up to 12 CSS-N-14 (JL-2) or CSS-NX-20 (JL-3) SLBMs … The fielding of newer, more capable, and longer ranged SLBMs such as the JL-3 gives the PLAN the ability to target the continental United States from littoral waters allowing the PLAN to consider bastion operations to enhance the survivability of its sea-based deterrent. The South China Sea and Bohai Gulf are probably the PRC's preferred options for employing this concept".[128]

In late 2024, the DoD assessed publicly that "the PRC probably fielded the extended-range CSS-N-20 (JL-3) SLBM on the PRC's JIN-class SSBN, giving the PRC the ability to target CONUS from littoral waters and enabling the PLAN to consider bastion operations to enhance the survivability of its sea-based deterrent."[129] According to the head of the US Strategic Command, Admiral Charles Richard, Chinese SSBNs are said to be "now capable of continuous at sea determined patrols with their JIN-class submarines from a protected bastion in the South China Sea and more are coming. They have a true nuclear command and control system".[130]

China's SLBMs

Estimates of the range of the JL-3 missile vary from around 9,000 km to about 10,000 km.[131] At 10,000 km range of the JL-3 missile would be capable of targeting much of the western part of the US from both the South China Sea or the Bohai Gulf.[132] However, given the rapid development of Chinese strategic weapons and the value of operating within these regions, it is reasonable to assume that they will be able to strike a larger portion of the continental US from these ocean areas within the 20-year timeframe of this paper.

The concept of China using the Yellow Sea and Bohai Gulf as bastion areas for SSBNs appeared in the 1980s when US intelligence services considered how China would operate their Xia-class SSBNs in the face of Soviet ASW efforts. At that time, the targets were assumed to be mainly on Soviet territory, so these bastion areas would allow the shorter-range missiles to strike Soviet targets.[133] Today, the heavy shipping activity in

[128]The 2020 version of the same DoD document did not include the final sentence about likely bastion areas in the South China Sea and the Bohai Gulf. U.S. Department of Defense, 'Military and Security Developments Involving the People's Republic of China' (2022), 96.

[129]U.S. Department of Defense, 'Military and Security Developments Involving the People's Republic of China 2024', Annual Report to Congress (2024), 104.

[130]Senate Armed Services Committee, Nuclear Weapon Council, USSTRATCOM Testimony, 4 May 2022. US Strategic Command Commander Admiral Charles Richard. https://www.stratcom.mil/Media/Speeches/Article/3022885/senate-armed-services-committee-hearing-nuclear-weapons-council/.

[131]US DoD, 'Military and Security Developments Involving the People's Republic of China, 2023', (2023), 59,

[132]Timothy Wright, 'China beyond minimum deterrence: Reading Beijing's Nuclear Developments', *IISS Blog,* 13 Jan. 2023. https://www.iiss.org/blogs/military-balance/2023/01/china-beyond-minimum-deterrence-reading-beijings-nuclear-developments.

[133]CIA Directorate of Intelligence, DECLASSIFIED. 'China Rethinks its Nuclear Submarine Program', Dec. 1984. https://www.cia.gov/readingroom/document/cia-rdp85t00310r000300090003-2

the Bohai Gulf combined with its very shallow depths makes it a possible, but likely only a small part of the operational seas for Chinese SSBNs.

During any crisis or conflict, there will be military operations in the air, sea, and land in the South China Sea, the Taiwan Straits, Yellow Sea, East China Sea, and the seas to the east toward the Philippine Sea. This overlap between conventional military operations and strategic nuclear forces is one of several factors that distinguishes China's basing of nuclear weapons at sea the open ocean patrols of the US SSBN fleet. Attack submarines from the US or its allies operating in the Chinese bastions may encounter Chinese SSBNs inadvertently.

Characteristics of Chinese Bastions

The ocean regions immediately off the coast of China have depths between 100 and 200 meters deep for a distance of between 180 and 370 NM from the coast, as shown in Figure A1. To get a sense of the depth scale it is helpful to keep in mind that SSBNs and SSNs are typically over 100 meters long and 10 meters or more in diameter. Nuclear-powered submarines can operate below the surface in such depths but must navigate above or around bottom features, and generally must avoid coming close to the bottom. Nuclear submarines require a continuous flow of cooling water in order to condense the steam produced by the reactor. If they draw cooling water from inlets near the bottom of the hull, they must avoid getting intakes too close to sediments that could be pulled into their circulating pumps and pipes. Non-nuclear submarines do not have this constraint and can rest on the bottom for days at a time.[134]

Chinese SSBNs appear to be primarily based on the southern part of Hainan Island at the Yulin Naval Base, shown in Figure A2.[135] From this base they have direct access to the South China Sea passing by the Paracel Islands. The deepest section of the South China Sea lying north of 10 degrees North latitude has an area of about 380,000 square miles. The deep region of the South China Sea extends northward and eastward toward Taiwan and the gap between Taiwan and the Philippines.

The acoustic properties vary widely in the waters adjacent to China due to the variations in depth from shallow water to deep water, the intensive shipping, and other factors. The Taiwan Strait is about 60 to 70 meters deep in most places and has a great deal of shipping. To the north of Taiwan are the East China Sea, the Yellow Sea, and Bohai Gulf as shown in Figure A3 The semi-enclosed Bohai Gulf has an average depth of only 18 meters with portions that are between 25 and 50 meters deep. [136] It has an area of about 28,000 square nautical miles. Nuclear submarines can operate in parts of the Bohai Gulf, but their ability for these submarines with diameters close to 13 meters to completely submerge is highly restricted by the shallow depths and the requirement to keep cooling water intakes away from bottom sediments.

[134]Dr. Milan Vego, 'The Right Submarine for Lurking in the Littorals', *US Naval Institute Proceedings* 136/6/ 1,288 (June 2010). https://www.usni.org/magazines/proceedings/2010/june/right-submarine-lurking-littorals.

[135]Mike Yeo, 'Satellite Imatges Reveal Chinese Expansion of Submarine Base', *Defense News*, 21 Sep. 2022. https://www.defensenews.com/naval/2022/09/21/satellite-images-reveal-chinese-expansion-of-submarine-base/

[136]Xinyu Guo, Byoung-Ju Choi, and Fangli Qiao, 'Circulation', in Joji Ishizaka, et al., (eds.), *Oceanography of the Yellow Sea and East China Sea*, PICES Scientific Report No. 62, 2021, p. 3.

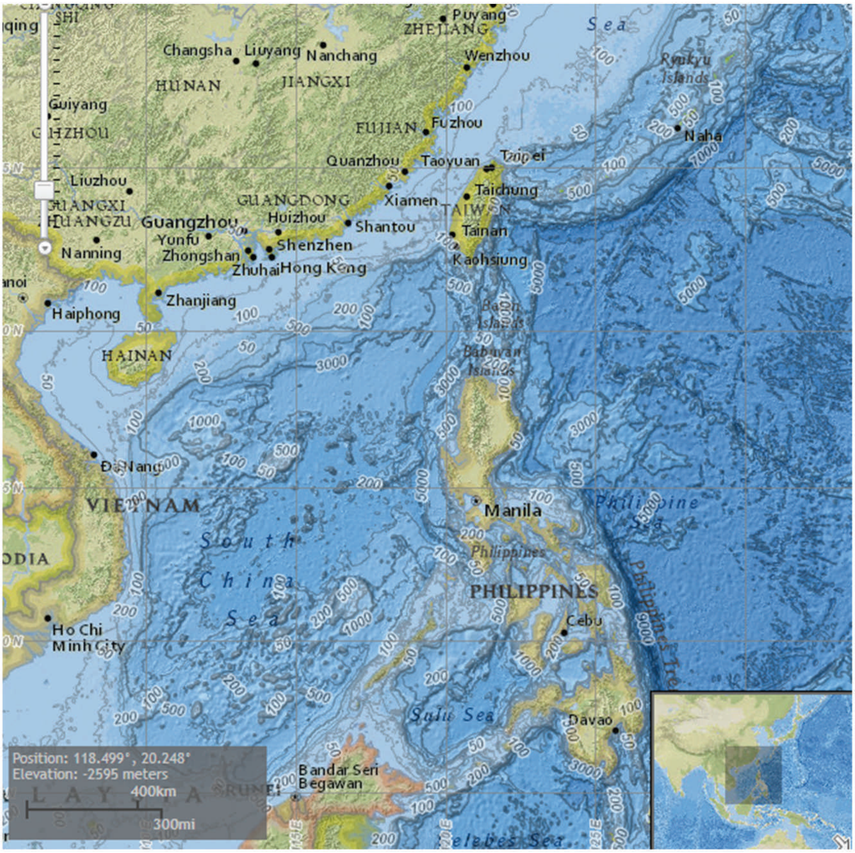

Figure A1. South China Sea to East China Sea. Source: National Centers for Environmental information, NOAA online. https://www.ncei.noaa.gov/maps/bathymetry/.

There is a very high shipping density in the Bohai Gulf as due to the fact that 4 of China's top 10 ports (Tianjin, Tangshan, Dalian, and Yinkou) are there.[137] The northern part of the Bohai Gulf is at least partially frozen from December through March, and in January and February the northern part of the Bohai Gulf can be covered in 20,000 square kilometers of ice between 10 and 40 centimeters thick.[138] The very northern part of the Bohai Gulf is home to an important Chinese submarine construction site, and there has been at least one test launch of the JL-3 missile from the Bohai Gulf.[139] Operating SSBNs in the Bohai Gulf is feasible throughout the year, even in the presence of the relatively thin ice.

To the south and east of the Bohai Gulf is the Yellow Sea which was mentioned by the DoD as another potential SSBN operating area. The Yellow Sea has an area of

[137]Yu Yan, Wei Gu, Andrea M.U. Gierisch, Yingjun Xu, and Petteri Uotila, 'NEMO-Bohai 1.0: A High-Resolution Ocean and Sea Ice Modelling System for the Bohai Sea, China', *Geoscientific Model Development* 15 (Feb. 2022), 1269–1288. https://doi.org/10.5194/gmd-15-1269-2022.
[138]Yu Yan, 'NEMO-Bohai 1.0'.
[139]National Air and Space Intelligence Center (NASIC), *2020 Ballistic and Cruise Missile Threat* (2020), 30.

Figure A2. Hainan Island. The Yulin Naval base is near the southern tip. Depths in meters. Source: National Centers for Environmental information, NOAA online. https://www.ncei.noaa.gov/maps/bathymetry/.

about 100,000 square NM and has average and maximum water depths of 44 and 140 m, respectively.[140] Winter ice is present in the northern part of the Yellow Sea, but as in the Bohai Gulf, it is rarely heavy. The Yellow Sea contains crowded shipping lanes with hundreds of cargo ships and fishing boats present at any given time.[141] In fact, the entire coastline of China out to the South China Sea is crowded with ships of all sizes, each one contributing ambient noise that has been doubling every decade in recent years.[142] If this trend continues for the next 20 years the ambient noise levels in these

[140]Xinyu Guo, 'Circulation', 3.

[141]ShipTraffic.net, 'Yellow Sea Ships Marine Traffic Live Map', http://www.shiptraffic.net/marine-traffic/seas/Yellow_Sea.

[142]Jukka-Pekka Jalkanen, Lasse Johansson, Mathias H. Andersson, Elisa Majamäki, Peter Sigray, 'Underwater Noise Emissions from Ships During 2014–2020', *Environmental Pollution*, 311 (Oct. 2022), 119,766, (https://www.sciencedirect.com/science/article/pii/S0269749122009800)

Figure A3. Bohai Gulf and northern Yellow Sea. Source: National Centers for Environmental information, NOAA online. https://www.ncei.noaa.gov/maps/bathymetry/.

areas could increase by a factor of four, while the noise levels of new classes of submarines are likely to decrease.

The East China Sea is less than 200 meters deep from the coast eastwards to the Senkaku Islands (Diaoyutai Qundao) as shown in Figure A4. To the east is a band of very deep water just to the west of the Japanese Ryukyu Island chain. These islands run from the north of Taiwan to Miako Islands, to Okinawa and northward to the south of Japan. East of the Ryukyu Island chain is the deep basin of the Philippine Sea. These coastal waters of China as well as the Philippine Sea have been the subject of extensive research over the past four decades, much of it relevant to underwater acoustics and therefore antisubmarine warfare.[143]

While in port, SSBNs are often surfaced and vulnerable to attack by several means. China uses submarine tunnels to hide them, but it is not known how well protected

[143]Peter F. Worcester, et al., 'The North Pacific Acoustic Laboratory Deep-Water Acoustic Propagation Experiments in the Philippine Sea', *Journal of the Acoustical Society of America* 134/4 (Oct. 2013), 3359–75. https://doi.org/10.1121/1.4818887

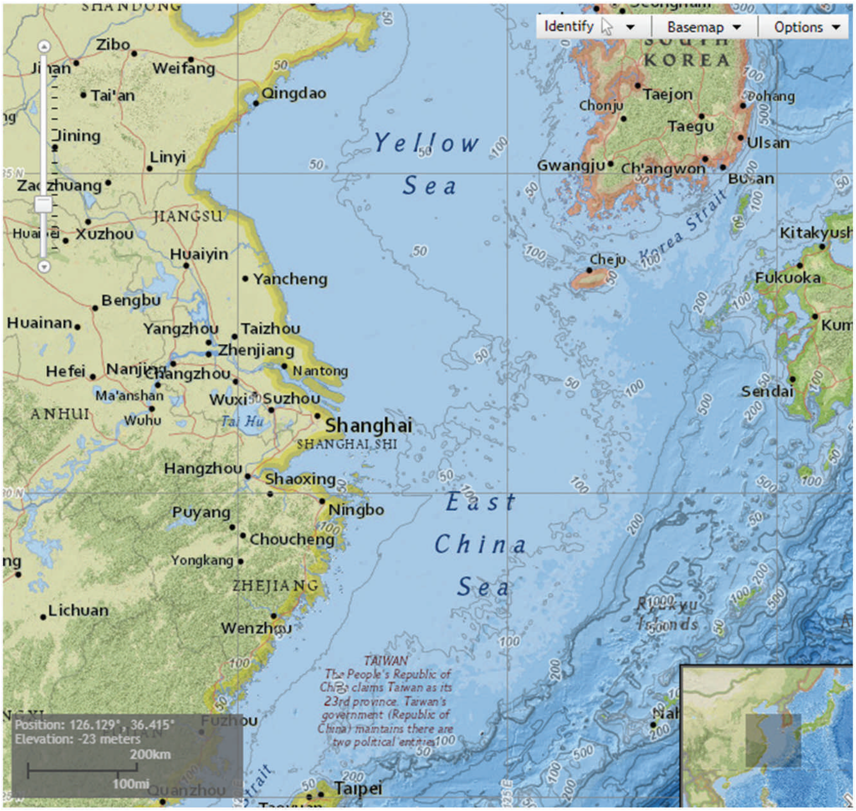

Figure A4. East China Sea and Yellow Sea. Source: National Centers for Environmental information, NOAA online. https://www.ncei.noaa.gov/maps/bathymetry/.

from attack these would be.[144] Chinese SSBNs leaving their base on southern Hainan Island must travel about 500 km to reach the deeper parts of the South China Sea. At a slow speed of 5 knots, this would take less than three days and would cross several dense shipping lanes. If SSBNs were to travel from Hainan northward to the Bohai Gulf, they would also traverse extremely dense shipping lanes including the Taiwan Straits for a distance of about 3,300 km, a trip of two weeks at a slow speed of 5 knots.

Given the relatively long transit time between the SSBN base and the Yellow Sea bastion, some facilities to support SSBNs in the Yellow Sea and Bohai Gulf are used. Facilities where JIN-class SSBNs have been observed include the Bohai Shipyard near Huludao in the northernmost part of the Bohai Gulf, where these submarines are built. They are replenished and prepared for missile launch tests at the Xiaopingdao naval

[144]Brad Lendon, 'Satellite Photos appear to show Chinese Submarine using Underground Base', *CNN World*, 21 Aug. 2020. https://www.cnn.com/2020/08/21/asia/china-submarine-underground-base-satellite-photo-intl-hnk-scli/index.html

base near Dalian. A third location in the Bohai-Yellow Sea region is the North Sea Fleet base at Jianggezhuang near Qingdao.[145] These facilities provide opportunities for JIN-class SSBNs to operate for long periods in this region without requiring the transit back to Hainan Island in the south.

Maritime Assets to support SSBNs

China operates a very large number of aircraft, ships, and SSKs that can operate in the Bohai Gulf, Yellow Sea, East China Sea and South China Sea to support ASW against anti-SSBN submarines and UUVs entering these waters. China does not have a robust long-range, deep water, offensive ASW capability as of this writing, but 'by prioritizing the acquisition of ASW capable surface combatants, acoustic surveillance ships, and fixed and rotary wing ASW capable aircraft, the PLAN is significantly improving its ASW capabilities'.[146] The majority of the Chinese SSBN bastion areas are within a three-hour flight from Chinese territories.

The PLA Navy maintains about 40 destroyers and 40 frigates with some ASW capability in helicopters and sonars. China also maintains a number of fixed-wing and rotary-wing aircraft with ASW capabilities. These are multi-mission systems that can be used to respond to initial detections of submarines produced by sensors that are installed in the ocean, or search over limited barriers to detect submarines attempting to pass through ocean passages. They can also search large ocean areas in the absence of initial submarine detection and location information, but open ocean search with no prior information about submarine locations is relatively inefficient.

China has been upgrading their ASW aircraft that can contribute greatly to protecting the extended shallow coastal seas from SSNs trying to operate there. The newest Z-20 helicopters can use sonar and other sensors to detect submarines, and are replacing older models of helicopters. These helicopters can operate from some classes of surface ships as well as from land. Fixed-wing maritime patrol aircraft for ASW and other missions are also being produced under the designation KQ-200 or Y-8Q. This maritime patrol aircraft is driven by turboprops and often operates over the northern part of the South China Sea where the depths drop from the shallow seas of the Taiwan Straits. It has been suggested that this region is used by both Chinese and US maritime patrol aircraft because it is a favorable location to find submarines in the northern part of the South China Sea, and is an ideal route for monitoring critical sea lanes of communication.[147] A sizable fraction of PLA aircraft incursions into Taiwan's Air Defense Identification Zone (ADIZ) have included some Y-8Q (KQ-200) aircraft flying across the south-western corner of the ADIZ which overlaps the northern access to the deep water of the South China Sea.[148]

China has a number of SSNs and SSKs that can be used in various roles to support bastion defense. In addition, China has a substantial number of *Yuan*-class attack submarines powered by air independent engines that make the submarines less

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[145] Hans M. Kristensen, 'China SSBN Fleet Getting Ready – But for What?' Federation of American Scientists Blog, 25 Apr. 2014, https://fas.org/blogs/security/2014/04/chinassbnfleet/.

[146] DoD, 'Military and Security Developments', 2022, p. 53.

[147] Olli Pekka Suorsa, 'The Anti-submarine Warfare component of China's Sorties in Taiwan's ADIZ', *The Diplomat*, 4 Nov. 2021. https://thediplomat.com/2021/11/the-anti-submarine-warfare-component-of-chinas-sorties-in-taiwans-adiz/.

[148] Radio Free Asia Staff, 'China Sends 21 Aircraft Into Taiwan's Air Defense Identification Zone', *Radio Free Asia*, 14 Dec. 2022 https://www.rfa.org/english/news/china/taiwan-incursion-12142022043822.html.

dependent upon air supplies than diesel-electric submarines, as well as minimizing vibrations thereby making the submarines quieter.[149] The Yuan-class SSK appears to have been designed for deep-water operating areas such as the approaches to Taiwan, and has sonar and air-independent propulsion (AIP) that will improve its abilities against ships.[150] China has reportedly been developing quieter propulsion systems for nuclear submarines, which could reduce the noise levels of SSNs as well as future SSBNs.[151]

The Chinese naval force structure will change in the next 20 years, and some improvements in submarine quieting is likely, though the degree is not known. However, even noisier submarines can be useful as decoys, as the CIA speculated in the mid-1980s, when the Chinese Han SSN was considered a possible decoy to draw Soviet ASW forces away from searching for the Xia-class SSBNs, with which the Han-class shared many design features.[152] Autonomous UUVs can also operate as decoys by broadcasting sounds that are characteristic of submarines.

Russia's SSBN Bastions: Top Priority for the Russian Navy

The Russian armed forces have prioritized defense of strategic nuclear weapons in bastions as did the Soviet Union during the Cold War. Today, as then, there are two Russian SSBN bastions: in the northwest Pacific and in the Arctic. The SSBN base near Petropavlovsk on the Kamchatka Peninsula allows SSBNs direct access to the North Pacific Ocean and to the Sea of Okhotsk after a short voyage to the south along the coastline. The SSBN base on the Kola Peninsula adjacent to Norway and Finland provides direct access to the Barents Sea, Kara Sea, and the central Arctic Ocean. The Office of Naval Intelligence indicated that Russian submarines operated in 'strategic bastions' after the dissolution of the USSR and into the 1990s.[153] Russian force structure and support infrastructure is much more robust in the Arctic bastion than the Northeast Pacific one, although Russia continues to develop its air defense and other naval systems on the Kuril Islands in order to support military operations in the Sea of Okhotsk.[154] While Russia lacks the capability to maintain a bastion in the Sea of Okhotsk that is as robust as the one in the Barents region, Russia's increasing maritime cooperation with China in the region does improve its overall military posture in the northeast Pacific.[155]

[149] https://nationalinterest.org/blog/buzz/chinas-aip-stealthy-submarine-force-worry-us-navy-172869.

[150] CAPT Christopher P. Carlson, USN (Ret), 'Esssay: Inside the Design of China's Yuan-Class Submarine', *US Naval Institute Proceedings,* 31 Aug. 2015. https://news.usni.org/2015/08/31/essay-inside-the-design-of-chinas-yuan-class-submarine

[151] James Holmes, 'Deathly Quiet: The Navy Can't Kill China's Submarines if it Can't Find them', *The National Interest*, 17 Aug. 2021. https://nationalinterest.org/blog/reboot/deathly-quiet-navy-can%E2%80%99t-kill-china%E2%80%99s-submarines-if-it-cant-find-them-191921.

[152] CIA Directorate of Intelligence, DECLASSIFIED. 'China Rethinks its Nuclear Submarine Program', Dec. 1984, https://www.cia.gov/readingroom/document/cia-rdp85t00310r000300090003-2

[153] Smithsonian Institution, National Museum of American History. 'Submarines in the Cold War', These charts were prepared by U.S. Naval Intelligence and declassified for this exhibit; https://americanhistory.si.edu/subs/work/missions/warfare/index.html#.

[154] Mathieu Boulègue, 'The Militarization of Russian Polar Politics', Chatham House Research Paper', (June 2022), 21–25. https://www.chathamhouse.org/sites/default/files/2022-06/2022-06-06-militarization-russian-polar-politics-boulegue_0.pdf.

[155] Mathieu Boulègue, 'The Impact of the War Against Ukraine on Russia's Arctic Posture: Hard Power on Vulnerable Ice', Wilson Center Polar Institute, June, 2024, pp. 7–8. https://www.wilsoncenter.org/sites/default/files/media/uploads/documents/RussiaArctic_Boulegue.pdf.

Today, strategic ballistic missile submarines as well as surface ships armed with long-range conventional Kaliber and other weapons in Russian bastions remain a central part of Russian military strategy. 'The [Russian] navy's strategic nuclear forces' duty during peacetime and their use during war remains the indisputable priority'.[156] The second priority is 'the comprehensive support of navy strategic forces with surface ships, submarines, coastal missile forces, naval aviation, and intelligence resources'.[157] Russia has shifted many of its naval exercises from the Norwegian Sea to the north and east with greater focus on the Barents Sea, which may well reflect a greater emphasis on protecting its sea-based strategic nuclear forces.[158] These strategic nuclear priorities largely overlap with other important maritime missions of the Russian navy, including protecting conventionally armed ships carrying long-range missiles and 'protection and facilitation of maritime economic activities'.[159]

Characteristics of Western Pacific Bastion

The Russian Pacific Fleet has its headquarters at Vladivostok in the Sea of Japan (Figure A5). The Sea of Japan is enclosed by North and South Korea, Japan, and Russian territory including the island of Sakhalin. Russia maintains its SSBN base to the north on the Kamchatka Peninsula that forms part of the boundary of the Sea of Okhotsk. Russian SSBNs are based at the Rybachiy Nuclear Submarine Base near Petropavlovsk with direct access to the Pacific basin. There are currently three Borei SSBNs based there, but this is expected to increase to five.[160] The first two submarines capable of launching the long-range thermonuclear Poseidon torpedo are also expected to be based on Kamchatka.[161] While the SSBN base has access to the North Pacific Ocean, SSBNs can also travel about 460 NM to the south to enter one of several gaps in the northern Kuril Island chain to enter the Sea of Okhotsk.

The Sea of Okhotsk has an area of over 1.5 Million square kilometers, and has an average depth of over 800 meters. The northern portions of the Sea of Okhotsk are covered with ice during the winter months, and icebreakers must operate there to enable year-round shipping. The maximum sea ice coverage in the Sea of Okhotsk is around one million square kilometers.[162]

Russia has been militarizing the Kurile Islands, in particular the islands just to the north of Japan that have been disputed since WWII. In 2014, the United Nations Commission on the Borders of the Continental Shelf made decided in favor of a Russian application to extend its continental shelf borders in the Sea of Okhotsk.[163] Since then, Russia has also been

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[156]K. Bogdanov, and I. Kramnik, 'The Russian Navy in the 21st Century: The Legacy and the New Path', (Alexandria, VA: Center for Naval Analysis Oct. 2018), 22–23. https://www.cna.org/reports/2018/10/russian-navy-in-21st-century

[157]Bogdanov and Kramnik, 'The Russian Navy in the 21st Century', 22.

[158]Kristian Åtland, Thomas Nilsen, and Torbjørn Pedersen, 'Bolstering the Bastion: The Changing Pattern of Russia's Military Exercises in the High North', *Scandinavian Journal of Military Studies* 7/1 (Sep. 2024), 145–160.

[159]Bogdanov and Kramnik, 'The Russian Navy in the 21st Century', 22.

[160]IISS Military Balance 2023, page 196 and Hans M. Kristensen and Matt Korda, 'Russian Nuclear Weapons, 2022', Bulletin of the Atomic Scientists, 78/2 (2022), 108.

[161]Kristensen, 'Russian Nuclear Weapons', 131.

[162]Japan Meteorological Agency, Sea Ice in the Sea of Okhotsk (Online), https://www.data.jma.go.jp/gmd/kaiyou/english/seaice_okhotsk/series_okhotsk_e.html

[163]Olena Snigyr, 'Current Russian Practices in Maritime Zones', *Beyond the Horizon*, International Strategic Studies Group, 25 Oct. 2019. https://behorizon.org/current-russian-practices-in-maritime-zones/

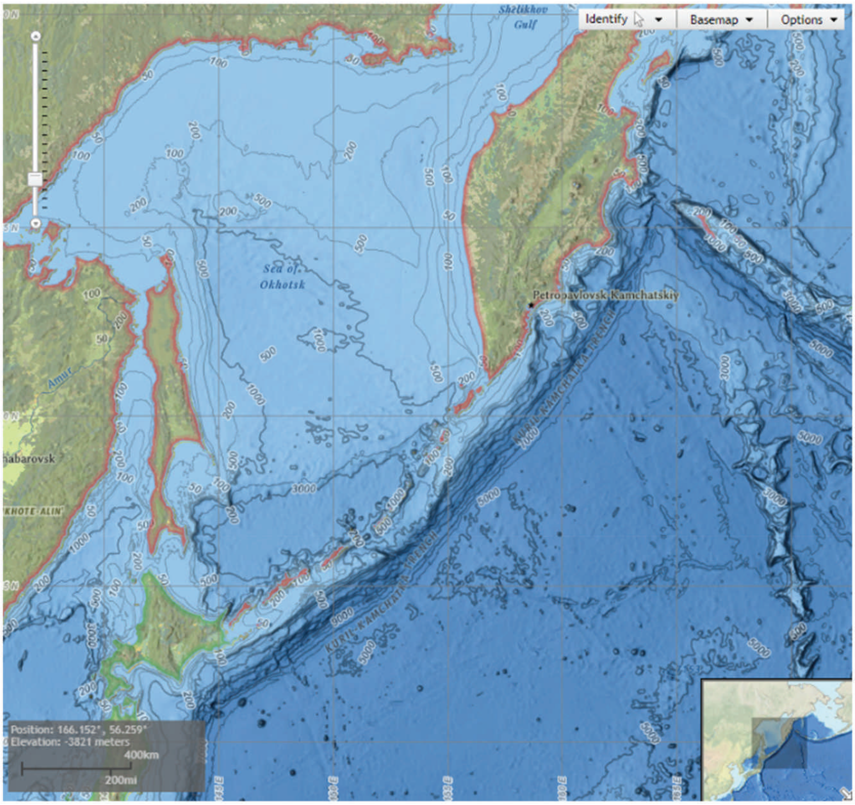

Figure A5. The Sea of Okhotsk and the Kamchatka Peninsula, base for Russia's SSBNs in the Pacific. Source: National Centers for Environmental information, NOAA online. https://www.ncei.noaa.gov/maps/bathymetry/.

increasing their military infrastructure on other islands in the Kurils, such as Matua, which is closer to the Kamchatka Peninsula than to Japan.

Russian SSBNs based on the Kamchatka Peninsula operate in a location that has some attributes of an open-ocean access. This geography can cut two ways: if Russian SSBNs can be trailed by US SSNs or UUVs as they leave port, they may be at risk for some period of time. Russia may use deceptions or harassment of these undersea threats provided they can be detected, which is probably only likely at short ranges. One possibility is for Russian SSBNs to traverse to the Sea of Okhotsk and navigate within a sensor field that can detect a trailing SSN or UUV.

Characteristics of Arctic Bastion

The headquarters of the Russian Northern Fleet are at Severomorsk, in the Murmansk Oblast. There are 8 SSBNs and 19 tactical submarines that include nuclear and conventionally powered versions based in the Russian Northern Fleet. [164] Russian SSBNs operate from several bases on the Kola Peninsula which provides access to the Barents Sea and Kara Seas with their combined areas of over 1.5 million square kilometers. The perimeter of these ocean areas is adjacent to the Arctic Ocean and is 2400 kilometers long. Even by drawing a boundary from the Kola Peninsula to the Island of Novaya Zemlya, and from there around the Kara Sea to the mainland, the perimeter is over 1100 NM long. Given the long perimeters to these Russian bastion areas, it is difficult for Russia to monitor NATO forces entering the bastions. As described earlier, the bastion is best thought of not as a thoroughly protected region, but rather as an area in which the probability of detecting and tracking anti-SSBN forces rises significantly due to underwater surveillance.

The largest Russian naval exercise since the Cold War was mainly conducted off the coast of Norway and the entrance to the Northern Fleet SSBN bastion of the Barents Sea in August 2019. The exercise included the largest Russian submarine operation since the 1980s incorporating a mix of attack submarines and SSBNs in the Barents Sea.[165] Russian SSBNs have also operated in the central Arctic Ocean. The Borei-class Russian SSBNs in 2016 patrolled for two months under the Arctic ice from its home port of Gadzhiyevo near Murmansk on the Kola Peninsula.[166]

Maritime Assets to support Russian SSBNs

The Russian SSBN bastions comprise layers of defense based on fixed sensor installations that provide detection and track information to anti-submarine forces such as Russian SSNs, surface ships, and ASW aircraft. Bastion defenses also incorporate minefields.[167] The priorities for Russian shipbuilding have reflected the importance of bastions and the SSBNs and long-range conventional missiles, such as Kaliber, that operate there. Russia began rebuilding their submarine forces with the Borei (Dolgoruky class SSBNs and the Yasin (Severodvinsk) class attack submarines.[168] Russia will have 8 or 9 Severodvinsk (Yasin) SSNs within 5 years, and US officials appear to rank them as nearly as quiet and capable as many US SSNs.[169]

The Russian naval strategy of protecting bastions appears to have shaped the rebuilding of its surface navy also. Procurement of surface ships emphasized frigates, corvettes, and smaller ships which could operate well within bastions, carry long range missiles, and also provide antisubmarine warfare capabilities if required to protect the SSBNs.[170] While Russia has increased the number of fast patrol boats, corvettes, and submarines over the past 15 years, it has also reduced the number of larger cruisers, destroyers and frigates over the same period.[171] Over the next 20 years, the Russian navy is likely to continue to

[164]IISS Military Balance 2023, p. 193. https://www.iiss.org/en/publications/the-military-balance/the-military-balance-2023/.

[165]CDR SG Geir Arne Hestvik and CAPT Todd Bonnar, 'Conflict 2020 and Beyond: A Look at the Russian Bastion Defence Strategy', NATO Combined Joint Operations from the Sea Centre of Excellence,15.

[166]Thomas Nilsen, 'NATO: Russian submarine activity equals cold war levels', *The Barents Observer*, 3 Feb. 2016. https://thebarentsobserver.com/ru/node/396.

[167]Office of Naval Intelligence, *The Russian Navy: A Historic Transition* (Dec. 2015). ×. https://www.oni.navy.mil/ONI-Reports/Foreign-Naval-Capabilities/Russia/.

[168]Office of Naval Intelligence, 'The Russian Navy', 17–18.

[169]Joseph Trevithick, 'Russia's Newest Submarines are "On Par with Ours" according to Senior American General', *The Drive*, 16 June 2021. https://www.thedrive.com/the-war-zone/41105/russias-new-cruise-missile-submarines-are-on-par-with-ours-says-senior-u-s-general.

[170]ONI, 'The Russian Navy', 19.

[171]CDR SG Geir Arne Hestvik, 'Conflict 2020 and Beyond', 15.

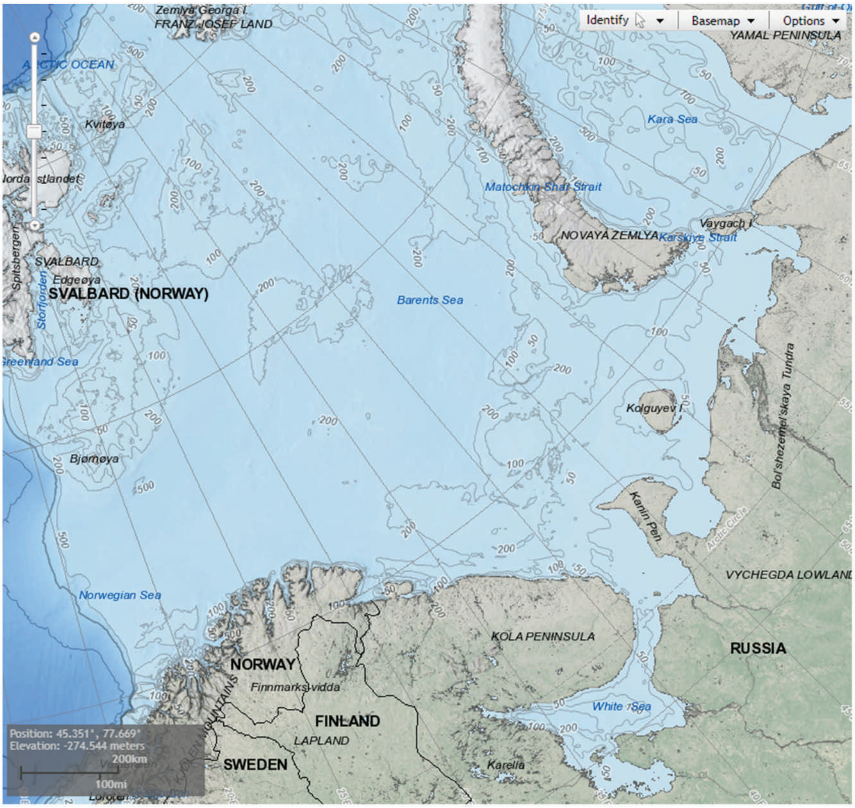

Figure A6. Barents and Kara Seas, with access to the Arctic Ocean. Source: National Centers for Environmental information, NOAA online. https://www.ncei.noaa.gov/maps/bathymetry/.

shift towards smaller, less expensive ships that are nonetheless relevant to defending bastions and carrying long-range missiles.

As in China, ASW aircraft continue to be a part of the forces deployed in bastions. Fixed wing aircraft have long ranges and can rapidly respond to contact reports from undersea sensors to localize intruding submarines. The Russian Navy continues to operate the IL-38 May maritime patrol aircraft, a design that was first produced in the 1960s. These aircraft have a range of about 1,360 NM and have been updated with new ASW equipment.[172] The KA-27 helicopter is also available in some ASW variants. For ASW aircraft to be effective, they require protection from potentially hostile aircraft. Shortfalls in credible MPA like IL-38N "will substantially restrict the effectiveness of Russia's own ASW and force its commanders to make hard choices between using assets like SSNs in offensive roles or protection of their bastions. "[173]

The Russian Navy also has a group of special-mission naval forces in its Main Directorate of Deep-Sea Research 10th Department (GUGI). Based in Murmansk where the Northern

[172]ONI, 'The Russian Navy' 30.
[173]Dr. Sidharth Kaushal, 'Interactive Summary: The Balance of Power Between Russia and NATO in the Artic and High North' RUSI, 12 Apr. 2022. https://rusi.org/explore-our-research/publications/whitehall-papers/interactive-summary-balance-power-between-russia-and-nato-arctic-and-high-north

Fleet is also based, GUGI maintains special nuclear-powered submarines including large submarines that can carry deep submersibles.

> GUGI is a separate force, co-located with the Northern Fleet in Murmansk. This de facto second navy maintains a growing force of modified nuclear-powered submarines, able to serve as mother ships for deep-diving submersibles, and a fleet of ocean-going deep-sea research ships. GUGI's vessels work on undersea infrastructure, map communications cables lying on the ocean floor, and conduct various special missions for the Russian General Staff. Of particular note are GUGI's modified submarines designed to deliver novel nuclear weapons, like the Poseidon nuclear-powered torpedo (previously known as Status-6). According to official Russian statements, and seemingly leaked documents, Poseidon is a nuclear-armed, and nuclear-powered, long-range weapon intended to take out coastal cities or economic infrastructure in a retaliatory strike.[174]

It is not clear how well the forces of the Russian GUGI are integrated with the missions of bastion defense, but they may be capable of contributing to some missions. These missions might include installing seabed sensors to support the surveillance of the bastions for the pro-SSBN tasks, or disrupting sensors and communications that could be used by anti-SSBN forces.

US SSBNs and Ocean Access

The United States operates six Ohio-Class SSBNs from Kings Bay, Georgia (Figure A7) and eight from Kitsap, Washington in the Pacific Ocean (Figure A8). These regions open to the deep ocean and are not close to any potentially threatening nations. This will continue to allow the US Navy to operate SSBNs in a way that is likely to deny an adversary the opportunity to reliably search, identify, and track SSBNs with high confidence over an extended crisis or conventional war.

With respect to ocean access, the US East coast near King's Bay has a relatively broad continental shelf of about 200 meters depth that stretches about 150 km offshore at which point the ocean depth increases. The continental shelf off the coast of Washington is only 13 to 64 kilometers wide. SSBNS travel from Bangor, near Kitsap through the Juan de Fuca Strait to the Pacific. The boundary between the US and Canada in fact runs through the center of the Strait.

The technological challenges of threatening US SSBNs in large ocean areas are enormous. US SSBNs patrol at sea on average of 77 days.[175] The officially stated range

[174]Michale Kofman, 'The Role of Nuclear Forces in Russian Maritime Strategy', in Rory Medcalf, Katherine Mansted, Stephan Frühling and James Goldrick (eds.), *The Future of the Undersea Deterrent: A Global Survey* (Canberra: ANU National Security College 2020), 35. https://nsc.crawford.anu.edu.au/publication/16145/future-undersea-deterrent-global-survey,

[175]US Navy, Fleet Ballistic Missile Submarines (SSBNs), https://www.navy.mil/Resources/Fact-Files/Display-FactFiles/Article/2169580/fleet-ballistic-missile-submarines-ssbn/,

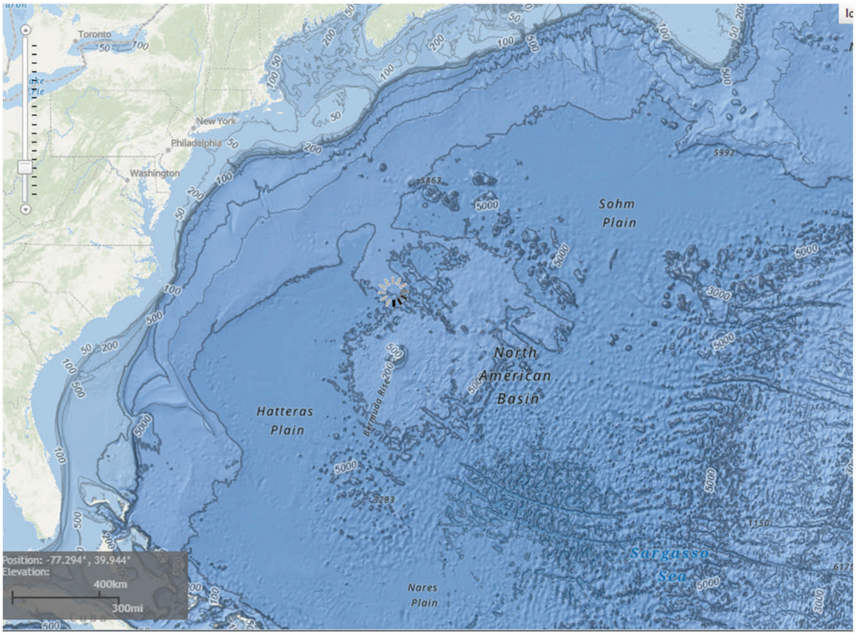

Figure A7. East Coast of United States and North Atlantic Ocean. Source: National Centers for Environmental information, NOAA online. https://www.ncei.noaa.gov/maps/bathymetry/.

Figure A8. Juan de Fuca Straits and access for US SSBNs to the North Pacific Ocean. Source: National Centers for Environmental information, NOAA online. https://www.ncei.noaa.gov/maps/bathymetry/.

ranges of over 7,000 NM.[176] Variations in range estimates are due to assumptions about weapons loading. Assuming a range of 5,500 NM, US SSBN can reach eastern China and western Russia from regions in the Pacific with areas well over 10 Million square NM. From the North Atlantic, these missiles can reach all of Russia and western China. With several SSBNs at sea at any given time, this means that the areas in which the SSBNs can operate can exceed 20 million square nautical miles spread over two oceans.

[176]Hans M. Kristensen and Matt Korda, 'United States Nuclear Weapons, 2023', *Bulletin of the Atomic Scientists* 79/1 (2023), 28–52. doi: 10.1080/00963402.2022.2156686