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Non-acoustic Submarine Detection

A Technology Primer

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TYPE Sensor	**CHARACTERISTICS** Vantage/Range, Precision, Persistence	**RISK FACTORS** Intrusive, Clandestine, Action-enabling
DOMAIN Sea, Air, Space	**COUNTRY** United States, China, Russia	

- Non-acoustic submarine detection technologies are those that do not rely on the collection of soundwaves emitted or reflected by a submerged vehicle for location and tracking. Advances in light-based imaging and magnetic detection instruments are increasing the range and precision with which today's ultra-quiet and nonferrous submarines can be located.
- The erosion of submarine stealth poses two major risks. First, advanced deep-water detection technologies threaten current freedom of operation in contested waters. Second, conventional stability may deteriorate as all submarines become locatable targets in naval warfare—including nuclear-armed submarines.
- The act of deploying advanced detection technology is unlikely to disrupt current strategic stability unless an adversary becomes aware of the presence of enhanced sensors and accurate tracking of their vehicles.

Introduction

Emerging non-acoustic detection technologies have the potential to expose the location of ballistic missile submarines (SSBNs)—assets which derive strategic significance from their ability to covertly maintain second-strike capability.[1] Submarines equipped with nuclear missiles, when undetected, can survive an adversary attack and ensure retaliation. Due to advances in stealth submarine technology—including ultra-quiet diesel and nuclear engines, sound-dampening mounts, and stealth paint—most active and passive acoustic methods are incapable of detecting the presence of modern vessels. However, advances in non-acoustic detection tools have the potential to reveal the location of SSBNs. This may enable preemptive action against an adversary's second-strike capabilities and erode confidence in mutually assured destruction. At the same time, significant technological barriers remain to accurately tracking and executing an attack on a submerged target at great depth.

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[1] Keir A. Lieber et al., "The Rise of U.S. Nuclear Primacy," *Foreign Affairs* 85, no. 2 (2006): 42-54, https://www.foreignaffairs.com/articles/united-states/2006-03-01/rise-us-nuclear-primacy.

Non-acoustic submarine detection technologies are those that do not rely on the collection of soundwaves emitted or reflected by a submerged vehicle for location.[2] Significant improvements have taken place with light-based imaging and magnetic anomaly detection (MAD).[3] Modern light-based imaging relies on Light Detection and Ranging (LIDAR) technology. LIDAR works by emitting laser (or LED) pulses and measuring the return time and strength of the reflected light. When deployed on space, aeronautic, or naval platforms, LIDAR can track a submarine's disturbance to the ocean surface or directly image a vehicle. LIDAR is presently limited to sensing depths up to 200 m—projected by some to reach 500 m.[4] MAD instruments closely monitor magnetic fields. When flown over the ocean, a MAD instrument can locate the disturbance to Earth's natural magnetic fields caused by a submarine's metal hull or salt-ion wake. These detection methods function differently: LIDAR can scan broader areas from a greater distance, whereas MAD equipment must be flown at low altitude or submerged.

Both methods—unlike acoustic approaches—may enable the location of the quietest of submarines through direct and environmental disturbance detection. The ability to detect quiet submarines may allow a substantial enhancement to situational awareness in anti-submarine warfare. The detection of conventional attack submarines may allow a naval force to avoid torpedo attack or destroy adversary firepower. The tracking and targeting of SSBNs may allow for the destruction of submarine-launched ballistic missiles (SLBMs) carrying thermonuclear warheads. Quiet, nuclear-powered SSBNs are essential components of the nuclear strike capabilities of the United States, Russia, United Kingdom, France, India, and China.[5]

This primer details the state of the art in non-acoustic detection technologies, discusses their contributions to situational awareness, and assesses their risks to strategic stability.

Methods of Detection

The deployment of non-acoustic technology for submarine detection is not a recent occurrence. Entering the Cold War, the United States and USSR invested in a network of acoustic sensors, or underwater hydrophones, to detect the sounds emitted by submarine engines. Following the deployment of USS *Nautilus*—the first nuclear-powered submarine—in 1954, the United States and USSR began to pursue alternate non-acoustic means to detect quiet nuclear submarines for anti-submarine warfare (ASW).[6] The limited sensitivity of light-mapping and magnetic field sensors at the time hindered efforts to illuminate the quiet depths of the ocean.[7] Now, the once-limited means of non-acoustic detection are being enhanced by improvements in ocean

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[2] There are two forms of acoustic detection. Active sound navigation and ranging (SONAR) emits soundwaves and creates a map of targets based on the measurement of echoes. Passive underwater microphones (hydrophones) listen for the sounds emitted by vessels.

[3] Other non-acoustic detection technologies have been attempted but have not received significant improvement with emerging technology. These methods include the detection of sloughed paint, radioactive wake, and heat signatures left by traveling submarines.

[4] 200 m LIDAR-detecting capabilities achieved by the U.S. Navy's ALMDS program. Projection expectations based on China's Project Guanlan.

[5] North Korea is developing its diesel-powered Singpo-class SSBN. Israel's Dolphin-class submarine may be capable of deploying nuclear warheads.

[6] Owen R. Cote, "Innovation in the Submarine Force: Ensuring Undersea Supremacy," *Federation of American Scientists*, https://fas.org/man/dod-101/sys/ship/docs/innovation.htm.

[7] Malcolm W. Browne, "IN BATTLE OF WITS, SUBMARINES EVADE ADVANCED EFFORTS AT DETECTION," *New York Times*, April 1, 1986, https://www.nytimes.com/1986/04/01/science/in-battle-of-wits-submarines-evade-advanced-efforts-at-detection.html.

monitoring, light imaging tools, and the rise of "big data" processing. Instruments with enhanced capabilities are also being mounted on new marine and aerospace platforms, such as unmanned vehicles and satellites. Three significant fields of improvement include (1) detection of a submarine's impact on surrounding ocean environments; (2) light mapping of the vehicle; and (3) magnetic field monitoring. These advancements are enabled by improvements in MAD and LIDAR.

Remote Sensing of a Submarine's Environmental Impact

Detecting the environmental disturbance caused by traveling submarines emerged as an early approach for ASW. Initial efforts focused on tracking the surface-level disturbance caused by the dislocation of seawater via Synthetic Aperture Radar (SAR). The 1978 NASA satellite SeaSat proved the ability of space-based SAR to map subaqueous terrain and wave patterns.[8] The strategic implication of advancement in remote sensing of the seas was the detection of the waves left behind as a submarine disturbs the waters through which it passes. Significant among these are the Bernoulli hump (near-wake) and Kelvin waves (far-wake) created by a submarine's turbulence.[9] The detection of the Bernoulli hump—the minute rise in ocean surface height caused by a traveling submarine—is hampered by the inability of radar-based satellites to detect abnormal projections as small as 1 mm.[10] The logarithmic decay of Kelvin waves—the V-shaped wake that trails a marine disturbance—presents similar issues of infinitesimal results when a submarine travels at low speed and high depth. Natural irregularities in ocean surface height caused by weather, currents, and traveling marine animals present further difficulties to accurate detection. Following the launch of SeaSat, the Pentagon blocked the release of precision commercial space radar technology, launching their own intelligence radar satellite in 1988. This precision technology was leaked to China in 1997.[11]

The improvement of LIDAR technology may allow for accurate detection of small variations in ocean height and subaqueous waves. Modern LIDAR is more precise than SAR, capable of measuring changes smaller than 1 cm.[12] NASA is deploying high-resolution laser imaging technology to precisely measure ice, cloud, and land elevation. NASA-Goddard's 2018 ICESat-2 features an Advanced Topographic Laser Altimeter System, which is capable of detecting land-ice elevation with less than 2.5 cm accuracy.[13] The satellite is also capable of tracking ocean-surface height and roughness. At the moment, the deployment of precision-level laser-imaging

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[8] The rise of space-based radar began years before, but SeaSat's success in capturing high-resolution radar imagery over large areas set the path for SAR imagery. Charles Elachi, "Radar Images of the Earth from Space," *Scientific American* 247, no. 6 (1982): 54-61, https://www.scientificamerican.com/article/radar-images-of-the-earth-from-spac/.

[9] The Bernoulli hump occurs as a submarine disturbs the water it enters, causing a subtle rise in ocean height above. The Kelvin wave is caused by the wake that follows any ship, as the turbulence radiates outward.

[10] When a submarine travels at low patrol speed and great depth, the surface level rise becomes inappreciable. For example, an Ohio-class submarine speeding at 10 m/s at a depth of 100 m only produces a 1.6 cm elevation. Refer to: Tom Stefanick, "Strategic antisubmarine warfare and naval strategy" (Washington, DC: Lexington Books, 1987).

[11] William J. Broad, "U.S. Loses Hold on Submarine-Exposing Radar Technique," *New York Times*, May 11, 1999, https://www.nytimes.com/1999/05/11/world/us-loses-hold-on-submarine-exposing-radar-technique.html.

[12] For more on the capability of modern LIDAR to detect waves, see: Michael J. Allis et al., "Application of LiDAR as a measurement tool for waves," *International Society of Offshore and Polar Engineers,* 2011, https://www.onepetro.org/conference-paper/ISOPE-I-11-402.

[13] "ICESat-2 (Ice, Cloud and land Elevation Satellite-2)," *eoPortal Directory*, https://directory.eoportal.org/web/eoportal/satellite-missions/i/icesat-2.

technology in space is expensive, with ICESat-2 requiring $1.1 billion in funding.[14] Despite advances in ocean surface monitoring, the application of wake-sensing LIDAR for submarine detection has seldom been covered in unclassified literature since the 1990s. Given the highly-classified nature of submarine technology and deployment, it is possible that the U.S. Navy continues to explore such technology.

Another environmental trace left by a traveling submarine is the disturbance of bioluminescent organisms by turbulence. The ocean is full of bacteria, fungi, and algae that emit blue-green light when agitated. Depending on light conditions and the depth from which this luminescence must travel, optical observation can detect the glow from well beyond the ocean surface. In 1918, German U-Boat U-34 passed through a colony of bioluminescent plankton in the Strait of Gibraltar, which led to its detection and subsequent destruction by Allied forces.[15] The U.S. Navy and Soviet scientists explored instrumented bioluminescence observation as early as 1970.[16] Numerous challenges hampered these efforts, including the exponential loss of light traveling through seawater; the dark conditions required for primitive low-light detectors to pick up traces of light; and the inability to distinguish submarine movements from agitation caused by whales and schools of fish. Continuing into the 1990s and 2000s, Russian and American scientists partnered to develop models of a ship's bioluminescent signature. As of 2014, the U.S. Navy is not openly funding further research efforts.[17] It is difficult to tell whether the technology was abandoned or if research continues in the classified realm. Advances in space-based multispectral imaging and associated computing advances may allow for the cost-effective detection and processing of extremely faint light emitted by disturbed bioluminescent organisms.[18]

Direct Detection of a Submarine

Satellite, airborne, and submarine-based light imaging technology allows for the direct detection of a submarine. In addition to surface-level measurements, LIDAR can create maps of subaqueous environments by transmitting light pulses through water. A moving or stationary submarine is detected by either reflecting laser signals abnormally early or by absorbing laser light, creating a hole in the map. Underwater applications of LIDAR are improving with recent advances in bathymetric LIDAR technologies which emit only specific wave-lengths that are least susceptible to absorption by seawater.[19,20] The most significant limitations for airborne LIDAR systems

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[14] Meghan Bartels, "NASA Will Launch a Laser Into Space Next Month to Track Earth's Melting Ice," *Space.com*, August 23, 2018, https://www.space.com/41596-nasa-icesat2-earth-ice-satellite-september-launch.html.

[15] For more on the history of bioluminescence research and applications, see: Robert F. Staples, "The distribution and characteristics of surface bioluminescence in the oceans," *Naval Oceanographic Office*, 1966, p. 10, https://apps.dtic.mil/docs/citations/AD0630903.

[16] A Navy report concluded that early aircraft-mounted low-light image intensifiers would be a promising tool for the detection of submarines traveling at a moderate depth through coastal areas where high concentrations of luminescent organisms exist. Refer to: John Strand et al., "The Antisubmarine Warfare (ASW) Potential of Bioluminescence Imaging," *Naval Reserve Center,* 1980, https://apps.dtic.mil/docs/citations/ADA084124.

[17] Sarah Laskow, "How the Navy Tried to Turn Bioluminescence Against the Soviets," *Atlas Obscura*, January 13, 2017, https://www.atlasobscura.com/articles/how-the-navy-tried-to-turn-bioluminescence-against-the-soviets.

[18] Steven D. Miller, et al., "Suomi satellite brings to light a unique frontier of nighttime environmental sensing capabilities," *Proceedings of the National Academy of Sciences* 109, no. 39 (2012), https://www.pnas.org/content/109/39/15706.

[19] Bathymetric LIDAR relies on blue-green wavelengths, which can penetrate water at greater depths than red wavelengths.

[20] "Bathymetric LiDAR," *USGS*, https://wwwbrr.cr.usgs.gov/gstl/project-lidar.html.

are turbidity (water clarity) and weather, both of which can exponentially increase the rate of refraction of laser pulses, thus decreasing the strength and accuracy of LIDAR.[21]

In addition to space- and aerial-based remote sensing, compact LIDAR sensors aboard submarines and Unmanned Underwater Vehicles (UUVs) may vastly improve sub-to-sub detection. Small UUVs could be deployed in swarms, reducing risk of significant loss in adversary waters and enhancing capability to scan broad areas with multiple LIDAR sensors. Industry demand for advanced LIDAR sensors for autonomous vehicles is pushing Silicon Valley-based Velodyne, the leading commercial LIDAR manufacturer, to develop new hyper-sensitive pint-sized mapping devices.[22] Engaged in commercial competition, Velodyne claims that its mass-produced sensors will hit the market priced at $300,000-$400,00 a piece. A team at the Georgia Tech Research Institute designed compact bathymetric LIDAR systems, which, at half the size and weight of older systems, could be mounted on moderately-sized Unmanned Aerial Vehicles (UAVs) or UUVs. Operating unmanned vehicles for mapping purposes could save considerably on the costs of manned naval reconnaissance. At the moment, UUV-enabled tracking is limited by engineering challenges in UUV propulsion, power, and communications.[23] Efforts to employ this research for U.S. ASW have not been covered in public record.

Magnetic Detection

MAD represents a significant area of advancement in ASW. MAD operates on the disturbance caused by the ferromagnetism, the permanent magnetic force of a submarine's metal hull, which can be detected and localized in a systematic search pattern. MAD is particularly attractive because it does not require a submarine to be in motion. First developed in 1917, MAD devices became common on ASW patrol aircraft by World War II. However, MAD was severely limited by the lack of range associated with airborne fluxgate sensors (often less than a mile) and an inability to accurately distinguish between sources of magnetic anomalies—like shifts in the Earth's electromagnetic fields, solar radiation, and shipwrecks. Further, modern submarine hulls are constructed with nonferrous metals such as titanium[24] or contain electromagnets that are 99 percent effective in masking magnetic signature.[25] However, further advances in technology may render MAD a useful tool despite these obstacles.

The deployment of new highly-sensitive magnetometers may enhance MAD operations. The conventional fluxgate sensor, while easily deployed, is limited in its sensitivity and ability to filter out magnetic background noise.[26] Experimentation with alternative magnetometers has risen in recent decades. Texas-based Polatomic's laser-pumped helium magnetometer promises 20 to 30 times greater sensitivity than the fluxgate sensors

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[21] John Olav Birkeland, "The potential of LIDAR as an antisubmarine warfare sensor," *University of Glasgow*, November 2009, http://theses.gla.ac.uk/1252/1/2009birkelandmphil.pdf.

[22] Jamie Condliffe, "Lidar Just Got Way Better—But It's Still Too Expensive for Your Car," *MIT Technology Review*, November 28, 2017, https://www.technologyreview.com/s/609526/lidar-just-got-way-better-but-its-still-too-expensive-for-your-car/.

[23] Andrew Reddie and Bethany Goldblum, "Unmanned Underwater Vehicle (UUV) Systems for Submarine Detection," *On The Radar*, https://ontheradar.csis.org/issue-briefs/unmanned-underwater-vehicle-uuv-systems-for-submarine-detection-a-technology-primer/.

[24] The titanium hull was pioneered by the Soviet Alpha-class submarine in 1977. In 2005, Sweden's stainless-steel Gotland-class submarine made headlines for evading U.S. MAD sensors in a training mission.

[25] For further information on the demagnetization (degaussing) of submarines, see: R.A. Raveendra Varma, "Design of Degaussing System and Demonstration of Signature Reduction on Ship Model through Laboratory Experiments," *Physics Procedia* 54 (2014): 174-179, https://www.sciencedirect.com/science/article/pii/S1875389214005318.

[26] R. H. Koch, J. G. Deak, and G. Grinstein, "Fundamental limits to magnetic-field sensitivity of flux-gate magnetic-field sensors," *Applied Physics Letters* 75, no. 24 (1999): 3862-3864, https://aip.scitation.org/doi/10.1063/1.125481.

currently deployed on the U.S. Navy's ASW aircraft.[27] Polatomic received a $2.8 million grant from the Department of Defense in 2010 for research on the Lightweight Laser Magnetic Gradiometer, along with several smaller grants for compact magnetometers to fit aircraft and UUVs.[28]

Scientists have also experimented with molten potassium and superconducting quantum interference devices (SQUID). SQUID systems are capable of exceptional sensitivity. Yet are hindered by excessive white noise collection and extreme operating requirements—they function best at cryogenic temperatures. The Intrel Service Company holds a U.S. patent for a Mechanical Expansion Amplifier (MEA) enabled magnetometer, which claims to offer a non-cryogenic yet ultra-sensitive capability to detect underwater changes in Earth's magnetic field.[29]

Array deployment further enhances ultra-sensitive magnetometers. When a pair (or more) of MAD sensors move across an area, magnetic gradiometry—the mapping of magnetic signatures—is enabled. With an array of sensors capturing multiple axes, continuous streams of data can be processed by advanced computer algorithms which filter out natural fluctuations in electromagnetic fields. A Japanese-led research project from 2000 demonstrated success with a calibrated three-axis SQUID MAD device, capable of suppressing magnetic noise from aerial motion and detecting surface vessels with extreme accuracy.[30]

State of Play: Non-acoustic Technologies

Of the aforementioned methods, states are openly pursuing MAD and LIDAR systems. These selected efforts, as detailed below, do not preclude the possibility of clandestine development of other non-acoustic technologies—projects likely to be classified.

The Chinese Academy of Science made headlines in August 2017 for the development of a "quantum sensing" SQUID array. The academy claims to use a large number of antennae with superconductive computer chips cooled by liquid nitrogen. Ultra-sensitive arrays collect mass data on multiple axes which is then fed into quantum computing models to filter out anomalies created by airborne motion and solar storms. Researchers estimate that this application of quantum sensing SQUID arrays could detect a submarine from 6 kilometers, allowing for more remote sensing.[31] The depth at which this quantum technology will penetrate is not reported, though the press from this article suggests an insurmountable tech advantage for the Chinese in pursuit of a magnetically transparent ocean—an unlikely reality given the Japanese proof-of-concept nearly two decades ago.[32]

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[27] For more on Polatomic's advances, see: G. Kuhlman, R. Slocum, and J. Manning, "Battlefield Applications for the Polatomic 2000 Magnetometer/Gradiometer," *Polatomic Inc.,* February 25, 2002, https://apps.dtic.mil/dtic/tr/fulltext/u2/a409283.pdf.

[28] "Polatomic, Inc.," *SBIR/STTR*, https://www.sbir.gov/node/277898.

[29] James Kuzdrall, "Magnetometer Underwater Detection Range, A Mechanical Expansion Amplifier Application," *Intrel Service Company*, July 11, 2018, http://www.intrel.com/mea/mag/mea_app_mag_rng_sum.pdf.

[30] M. Hirota et al., "Magnetic detection of a surface ship by an airborne LTS SQUID MAD," *IEEE Transactions on Applied Superconductivity* 11, no. 1 (March 2001): p. 884-887, https://ieeexplore.ieee.org/document/919486.

[31] Stephen Chen, "Has China developed the world's most powerful submarine detector?" *South China Morning Post*, June 24, 2017, https://www.scmp.com/news/china/society/article/2099640/has-china-developed-worlds-most-powerful-submarine-detector.

[32] M. Hirota et al., "Magnetic detection of a surface ship by an airborne LTS SQUID MAD."

The U.S. Navy has been quiet about their development of MAD SQUID detectors but funded Virginia-based Cortana in 2009 to research the detection of magnetic field disturbances left in the salt-ion wake of a submarine. Detection of trace magnetic disturbances in ion wakes would likely require a level of extreme precision, necessitating U.S. mastery of SQUID technology.[33] As of 2011, this research received an expanded $748,606 research contract from the Department of Defense, suggesting promise for early research and development. The Department has not released further funding information.

In 2010, the U.S. Defense Advanced Projects Research Agency (DARPA) called for exploration of blue laser technology for communications and mapping at extreme depths.[34] Northrop Grumman's Airborne Laser Mine Detection System (ALMDS)—which uses bathymetric lasers mounted aboard a Seahawk helicopter to search for underwater mines at depths of up to 200 m—achieved initial operational capability in 2017.[35] The location of relatively small sea mines at such depths suggests potential submarine detection capabilities. The development and deployment of the ALMDS system is currently funded by the U.S. Navy. Initial development of three deployed units was contracted to Northrop Grumman for $124.5 million in 2005 and expanded by $15.1 million in 2018.[36]

The Chinese Guanlan Project, publicized in October 2018, aims to use a satellite-based high-powered laser to scan vast areas at target depths of 500 m—exceeding the indefinite U.S. Navy *Ohio*-class depth rating of more than 240 m.[37] There are doubts that such goals are possible given current laser power limitations. The project intends to scan such remarkable depths across areas as wide as 100 km. Further, the Chinese researchers claim that the masses of laser-collected data from this project will feed through its upcoming "Deep Blue Brain" quantum supercomputer for rapid processing.[38] In September 2019, Chinese researchers published their findings on newly-developed non-linear crystals which can facilitate high-energy laser emissions in the German chemistry journal *Angewandte Chemie.*[39] This technology may enable more powerful LIDAR scanning at depth.

Effects on Situational Awareness

The U.S. submarine fleet has long benefitted from being the largest, most advanced, and quietest in the world. Thanks to early mastery of sound-deadening technology, U.S. attack and SSBN submarines have remained undetected by adversary SONAR. The spread of powerful non-acoustic detection technology may pose a significant threat to this supremacy in the open seas. An adversary with a well-developed network of advanced non-acoustic sensors could locate and track the 14 Trident II *Ohio*-class SSBNs,[40] increasing the likelihood that

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[33] "Hunting submarines with magnets," *The Economist*, November 12, 2016, https://www.economist.com/science-and-technology/2016/11/12/hunting-submarines-with-magnets.

[34] Michael Clooney, "DARPA seeks radical ocean surveillance technology," *Network World*, January 7, 2010, https://www.networkworld.com/article/2233040/security/darpa-seeks-radical-ocean-surveillance-technology.html.

[35] Katherine Owens, "Navy laser mine detection now operational," *Defense Systems*, March 2017, https://defensesystems.com/articles/2017/03/28/helolaser.aspx.

[36] "$124.5M for 3 Airborne Laser Mine Detection Systems (ALMDS)," *Defense Industry Daily*, September 15, 2005, https://www.defenseindustrydaily.com/1245m-for-3-airborne-laser-mine-detection-systems-updated-01162/.

[37] It is likely that the Ohio-class and other U.S. submarines have deeper, classified operating depths.

[38] Chen, "Has China developed the world's most powerful submarine detector?"

[39] Stephen Chen, "Could these crystals be the next leap forward in China's laser technology?" *South China Morning Post*, September 4, 2019, https://www.scmp.com/news/china/science/article/3025642/could-these-crystals-be-next-leap-forward-chinas-laser.

[40] The 14 Trident II Ohio-class submarine are the only U.S. submarines equipped with nuclear warheads. Each holds 20 strategic Trident II submarine-launched ballistic missiles (SLBMs).

they—and all currently-undetectable submarines—can be targeted at the outbreak of war. Even with today's advances, the ability to continually track and attack numerous deployed SSBNs within a short period of time would require a massive leap in ASW capabilities.

Advances in non-acoustic submarine detection technologies have the potential to greatly increase situational awareness of submarine locations in adversary coastal areas, as well as the open ocean. Should technologies such as the advanced LIDAR promised in China's Guanlan Project prove capable of penetrating depths as far as 500 m, submarines at traditionally-safe depths will no longer remain stealthy. The ability to detect submarines at great *range* from satellites or wide-sweeping aerial sensors requires far fewer resources than flying less-sensitive detectors across vast areas, making submarine detection more cost-effective than ever. Further, space-based non-acoustic detectors are *stealthy, resilient*, and *persistent*, making it difficult for an adversary to detect and disable. Less-stealthy UUVs may also increase situational awareness by collecting information on adversary ships and submarines.

If developed and deployed, significantly advanced non-acoustic detection technology can increase a nation's vantage to monitor their surrounding waters for adversary attack vehicles. The ability to secure coastal waters and ports protects conventional naval operations and shipping from the threat of a torpedo or missile attack. This is important for securing strategic areas such as the Arctic Ocean, where Russian submarines avoiding tracking under ice shelves could be located by aerial MAD systems. New technology may also increase Chinese vantage in the contested waters of the South China Sea, where China intends to create an "Undersea Great Wall," threatening freedom of operation.[41]

Risk Factors for Strategic Stability

The proliferation of advanced non-acoustic submarine detection technology may pose significant challenges to prevailing strategic stability. The tracking of SSBNs may enable preemptive action against a state's second-strike capabilities, degrading the assumption of mutually assured destruction. Further, the acquisition of advanced detection technologies may encourage states to pursue intrusive search efforts in adversary waters. Should an adversary become aware of the clandestine deployment of SSBN-threatening technology, they may indiscriminately target suspect platforms, reducing conventional stability.

Nuclear-armed SSBNs are an essential component of the U.S. nuclear triad. SSBNs lurking near enemy shores provide the most responsive option for the deployment of a nuclear first-strike. More importantly, nuclear-armed SSBNs are the most survivable leg of the U.S. nuclear deterrence strategy.[42] Unlike land-launched and bomber aircraft weapons, the undetected nuclear-armed-submarine can endure a full-scale nuclear attack. The deployment of up to half of strategic U.S. thermonuclear warheads on several undetectable submarines at any given time dramatically reduces the incentive for an adversary first strike. At the moment, it is unlikely that any power could destroy or disarm the undetected Trident-armed *Ohio*-class submarines. The stability-enhancing secure second strike promised by SSBNs could, however, be compromised by advanced detection technology, as an adversary tracking the precise locations of these vehicles is incentivized to seek and destroy them along with a first-strike land attack. Thus, by enabling preemptive action, enhanced non-acoustic detection of stealthy SSBNs could adversely affect prevailing nuclear deterrence and mutually assured destruction.

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[41] Lyle J. Goldstein, "China's 'Undersea Great Wall'," *The National Interest*, May 16, 2016, https://nationalinterest.org/feature/chinas-undersea-great-wall-16222.

[42] Nuclear Posture Review, *Department of Defense*, 2018, https://media.defense.gov/2018/Feb/02/2001872886/-1/-1/1/2018-NUCLEAR-POSTURE-REVIEW-FINAL-REPORT.PDF.

Space-based and aeronautical ASW technologies are stealthy, as the instruments can be mounted on non-suspect vehicles, such as scientific satellites. The operation of aerial detection systems, such as plane- or helicopter-mounted MAD technology, is generally unfettered over the open ocean, where it is more difficult to initiate tracking, but may be intrusive in restricted coastal zones. However, it is difficult for an adversary to determine the precision with which these—historically inaccurate—tools threaten their submarine forces. As such, the act of deploying advanced detection technology is unlikely to disrupt current strategic stability unless an adversary becomes aware of the enhanced sensors aboard and accurate tracking of their vehicles. For this reason, advanced non-acoustic detection operations are best kept clandestine. If an adversary discovers accurate tracking of their submarines, there is an increased incentive to act against the marine, aeronautic, and space-based vehicles upon which the sensors are deployed. This incentive reduces the stability of conventional military operations over open-waters, which may be targeted indiscriminately as a perceived threat to the survivability of a nation's submarine fleet.

The clandestine deployment of ASW, LIDAR, or SAR sensors on aeronautic platforms, if discovered by an adversary, may reduce strategic stability in space. Indiscriminate targeting of suspect satellites could result in the destruction of communications, intelligence, and defense space infrastructure, leading to the erosion of stability. Further, the accidental destruction of Nuclear Command, Control and Communications (NC3) equipment by an adversary could endanger U.S. nuclear response capabilities and prompt considerable retaliation.

The increased threat against detected vehicles may also cause a paradigm shift in the operation of manned submarines. For example, the use of advanced sensing technology could incentivize large manned submarines to stay offshore longer. A 2015 Center for Strategic and Budgetary Assessments report analyzing a post-stealth ASW scenario suggested that large submarines may take a strategic backseat to Unmanned Underwater Vehicles (UUVs), which can launch from secure locations and risk reduced losses if detected and attacked by an adversary in coastal waters.[43] In this scenario, the manned submarine functions akin to a supercarrier, deploying detectable UUVs into high-risk waters to detect, track, and potentially attack enemy subs. There is little open discussion of equipping such UUVs with nuclear arms. This model risks increased action from adversaries, who will have a lower threshold to counterforce operations when attacking an unmanned and lightly-armed vehicle. It leaves SSBNs and other large manned submarines to limit their mobility on patrols, avoiding detection at great depths and rising only for an attack or a return to base.

It is important to note that, even when detected, submarines are very difficult to target and destroy. In a 2018 Lawfare essay, RAND's Austin Long discusses these difficulties in the context of targeting a SSBN located by SLBM launch. In addition to the difficulties faced in deploying weapons to reach a located adversary submarine, the targeted vehicle can move several miles in any direction while the weapon travels. To ensure a large enough blast area to damage a submarine, an adversary would have to deploy several extremely powerful warheads. Further, Long highlights that a 2008 National Research Council report noted "the Navy long ago developed techniques to protect SSBNs after missile launch."[44]

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[43] Bryan Clark, "The Emerging Era in Undersea Warfare," *Center for Strategic and Budgetary Assessments*, 2015, https://csbaonline.org/research/publications/undersea-warfare/publication/1.

[44] Austin Long, "Location, Location, Location: Evaluating Risks to Submarines from Low-Yield Warhead and Submarine Missile Launch Detection," *Lawfare*, March 11, 2018, https://www.lawfareblog.com/location-location-location-evaluating-risks-submarines-low-yield-warhead-and-submarine-missile.

Concluding Remarks: Risk versus Reward

Non-acoustic submarine detection technologies provide substantial enhancements to situational awareness in ASW. Advances in LIDAR and magnetic detection instruments are increasing the range and precision with which today's ultra-quiet and nonferrous submarines can be located. Tracking adversary submarines can protect naval and shipping operations from covert attack. Further, these emerging sensors can monitor broader areas than their less-sensitive predecessors, reducing conventional deployment costs. Emerging space-based technology is less intrusive than aircraft-based sensors, reducing the potential for anti-access conflict. With passive and active acoustic SONAR detection being generally ineffective for the past several decades, the space, aircraft, and marine deployments of non-acoustic instruments pose a challenge to the status quo of non-detection for attack and ballistic missile submarines.

The erosion of submarine stealth, however, poses two major risks. First, advanced deep-water detection technologies threaten current freedom of operation in contested waters, such as in the South China Sea. This will restrict submarine operation to adversary waters further offshore, altering the course of "deterrence patrols," which circulate SSBNs within close-striking distance for rapid attack and avoidance of missile defense radars.[45] Second, conventional stability may deteriorate as all submarines become locatable targets in naval warfare—inadvertently leading to the perilous destruction of a nuclear-armed vessel.[46]

Moreover, if an adversary develops the technological capability to accurately track the location of SSBNs, they may attempt to attack and destroy vessels prior to a strike. However, such a feat would require an unforeseen leap beyond the current limitations of both detection and attack technologies. Only if an adversary could locate and destroy all patrolling adversary submarines armed with thermonuclear weapons would deterrence to a nuclear first-strike be significantly affected.

If detection technology rapidly advances and ocean transparency becomes a reality, there are considerable military and political implications. Presently, it is unclear from public documents whether the United States has advanced capability to track adversary SSBNs. Further, it is reported that adaptability to adversary ASW is rarely discussed—even considered "taboo"—in U.S. Naval and congressional reports on continued SSBN operation.[47] The arms control regime must also adapt to weakened stability as the secrecy of SSBNs erodes. With the practicality of treaty-limited SSBNs threatened, nations may pursue a substantial build-up in alternative arms, such as fitting conventional submarines with undisclosed nuclear missiles, to negate the effects of precision tracking.[48] Some suggest an international treaty to regulate the ocean's secrets, akin to the Treaty on Open Skies, which governs the frequency and resolution of aerial imaging of military forces and activities.[49]

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[45] Tong Zhao, "Tides of Change: China's Nuclear Ballistic Missile Submarines and Strategic Stability," *Carnegie Endowment for International Peace*, 2018, p. 14, https://carnegieendowment.org/files/Zhao_SSBN_final.pdf.

[46] While detection is possible, determining the class or clandestine arms of a vehicle is not. For example, American forces were not aware that the Soviet Foxtrot-class submarine targeted during the Cuban Missile Crisis was armed with a nuclear weapon.

[47] For more on policy considerations, see: James Moltz, "Submarine and Autonomous Vessel Proliferation: Implications for Future Strategic Stability at Sea*," Naval Postgraduate School*, December 2012, p. 2, https://calhoun.nps.edu/handle/10945/34355.

[48] Under the 1992 START II agreement, the number of Russian and U.S. SSBNs was limited to 14—resulting in the conversion of 4 of the 18 Ohio-class vehicles into conventionally-armed nuclear power submarines (SSGNs) by 2002. In compliance with the 2010 New START agreement, the remaining fourteen nuclear armed vehicles lost four of their 24 launch tubes, bringing the total to 280 deployed launch tubes across the U.S. fleet.

[49] For a thorough discussion of ocean-transparency risks, refer to: Elizabeth Mendenhall, "Fluid Foundations: Ocean Transparency, Submarine Opacity, and Strategic Nuclear Stability," *Journal of Military and Strategic Studies* 19, no. 1 (2018), p. 150, https://jmss.org/article/view/58291/pdf_1.

While the opacity of the ocean has obscured the whereabouts of vital strategic forces for several decades, developing technologies present a challenge to the status quo.

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