Australian Government
Department of Defence

remote undersea surveillance

insights paper

EDTAS emerging disruptive technology assessment symposium

The co-authors of this paper are Ash Colmer – former Army officer and Principal Consultant for Noetic – and Dr Richard Ellem of DSTG. Ash would like to acknowledge the insights that underpinned the development of this paper, that were gathered through a series of interviews with a wide range of subject matter experts from academia, industry, and Defence – in Australia and around the world. Ash would also like to acknowledge the support provided by David Vallance from Noetic in drafting this paper and Defence Science and Technology Group for the review and feedback. This Insights Paper was designed by Noetic's creative design team.

Contents

Introduction

Aim

The aim of the Insights Paper is to present key themes relating to recent and projected developments in the systems and technologies that enable Remote Undersea Surveillance (RUS) and their implications. In particular, the Insights Paper seeks to draw out the many implications for the ADF's future warfighters – the people – who these technologies will support in order to provide a base level of common knowledge to inform EDTAS participants and help engender debate during the symposia. To achieve this, the Insights Paper will describe the context and the present situation regarding RUS technologies. It will describe the current types of technologies that are emerging and how they are intended to support RUS, as well as the risks and challenges the technologies present.

Scope

This paper does not intend to be a definitive list of all aspects of RUS that may be discussed in an unclassified forum. What is presented in this paper is an array of opinion that seeks to promote discussion and potential RUS research objectives for DSTG. Thought Leaders and Subject Matter Experts (SMEs) in academia, industry and Defence were identified by the Sponsor and then approached to participate in an explorative, structured interview. The list of interviewees and contributors is appended to this paper. Some of the opinions presented may not necessarily be aligned with present doctrine, concepts or even policy. The conclusions reached are those of the author, noting the limitations of SME availability and open-source research.

‘America’s undersea dominance is not assured—or permanent. U.S. submarines are the world’s quietest, but new detection techniques are emerging that don’t rely on the noise a submarine generates and may make some traditional manned submarine operations riskier in the future. America’s competitors are likely pursuing these technologies even while growing and quieting their own undersea forces. To affordably sustain its undersea advantage well into this century, the U.S. Navy must accelerate innovation in undersea warfare by evolving the role of manned submarines and exploiting emerging technologies to field a new “family of undersea systems.”’[1]

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[1] Clark, Bryan (Senior Fellow, Center for Strategic and Budgetary Assessments). Statement Before the House Armed Services Seapower and Projection Forces Subcommittee on “Game Changers – Undersea Warfare”, 27 October 2015

context

The Importance of the Undersea Domain

> ‘Protecting Australia’s large exclusive economic zone requires understanding of the maritime environment under our control, sustained presence, and adapting to new technological developments that could increasingly complicate our ability to keep Australian interests safe in the Maritime domain’
>
> - Force Structure Plan, 2020

Australia’s maritime jurisdiction is enormous and diverse, covering 13.6 million square kilometres (or 4% of global ocean areas).[2] It is the third largest in the world after the United States and France, and encompasses the Exclusive Economic Zone (EEZ), extended continental shelf and marine areas adjacent to the Australian continent (including Tasmania, Lord Howe Island, Coral Sea Islands, and Ashmore and Cartier Islands), Norfolk Island, Macquarie Island, Cocos (Keeling) Islands, Christmas Island, Heard and Macdonald Islands, and the Australian Antarctic Territory.[3] Australia’s region of responsibility for maritime search and rescue is even larger and covers over one-tenth of the Earth’s surface.

Australia is a maritime nation. It is the 5th largest user of shipping services in the world. It is heavily reliant on sea transport for the vast majority of its imports and exports with over 99% by volume and 74% by value transported by ship. In 2019 international shipping transported $284 billion worth of exports and $209 billion worth of imports from and to Australia. Coastal shipping is also critical for a substantial proportion of domestic freight[4]. Australia’s growing domestic marine industries contributed $47.2 billion per annum to the Australian economy in 2012 and this is expected to double to more than $100 billion per annum by 2025.[5]

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[2] This includes the Australian continent which covers almost 7.7 million square kilometres with 60,000 kilometres of coastline. The Economic Exclusion Zone (EEZ) off the Australian continent and its territories (excluding the Australian Antarctic Territory (AAT)) covers nearly 8.15 million square kilometres. The EEZ with extended continental shelf (9 April 2008) covers 11.38 million square kilometres. The AAT covers 5.9 million square kilometres with 11,200 kilometres of coastline. The AAT marine areas cover approximately 2 million square kilometres. Australian marine areas include approximately 12000 islands.

[3] Geoscience Australia, Marine Strategy 2018-2023. Geosciences Australia website, https://www.ga.gov.au/. Accessed 7 Apr 21

[4] Inquiry into Australia’s Maritime Strategy, https://www.aph.gov.au/Parliamentary_Business/Committees/House_of_Representatives_Committees?url=jfadt/maritime/report/report.pdf.

[5] Protecting Australian Maritime Trade Report March 2020 (navalinstitute.com.au) https://navalinstitute.com.au/wp-content/uploads/Protecting-Australian-Maritime-Trade-Report-March-2020.pdf

Figure 1 Australia's maritime zones (source: Geoscience Australia)

As highlighted above, Australia's vast maritime expanse is critical for trade, natural resources and many other applications of national significance. Situational awareness and a wide range of activities supported by Navy are essential for the control of the maritime domain and the protecting of these interests. By definition, maritime domain awareness is the effective understanding of anything associated with the maritime domain that could impact its security, safety, and economic, social, environmental or cultural resources. The maritime domain broadly refers to all areas and things of, on, under, relating to, or bordering on a sea, ocean, or other navigable waterway, including all maritime-related activities, infrastructure, people, cargo, and vessels and other conveyances.

A significant challenge for securing the maritime domain is the growing number and increasing capabilities of submarines within Australia's region of interest. The 2016 Australian Defence White Paper predicted that more than half of the world's submarines will be operating in the (wider) Indo-Pacific region within the next two decades. New undersea threats including a diverse range of undersea weapons and autonomous underwater vehicles are emerging with rapidly developing capabilities, systems and technologies that will enable them to operate over increasing ranges and durations.

To address this challenge, the ADF needs advanced undersea surveillance capabilities to deal with the complexity of these emerging threats. Fully integrated sensor systems and networks will be required to provide persistent coverage over wide expanses of ocean. These capabilities will require the capacity to be rapidly and flexibly deployed to areas of interest, and have sufficient endurance, to operate effectively over a range of conditions in deep water and shallow littoral environments. They will need to complement, work cooperatively and integrate with other ADF maritime capabilities and support interoperability with coalition partners.[6]

Undersea surveillance aims to provide awareness and understanding of what is happening in the underwater environment for relevant marine areas of interest and is an essential enabler for undersea domain awareness (UDA). UDA is the component of maritime domain awareness that covers anything that operates within the underwater environment or that can influence the broader maritime domain from underwater and is dependent on both sensing to detect objects within the environment and communication to report these to operators and commanders. From a security perspective, the focus of UDA includes sea lines of communication (SLOC), coastal waters and maritime assets with reference to hostile intent and the proliferation of submarine and other undersea warfare capabilities intended to limit access to the ocean and littoral waters.

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[6] Department of Defence, Strategy/Remote Undersea Surveillance, DSTG Website https://www.dst.defence.gov.au/strategy/star-shots/remote-undersea-surveillance, Accessed 11 March 2021

UDA is required more broadly for:

- Monitoring undersea activities as they relate to scientific research (monitoring, measuring and modelling ocean properties),
- Monitoring commercial activities (resource exploitation and management, exploration, food and aquaculture, and tourism),
- Environmental protection or conservation (ocean ecosystem monitoring, habitat degradation and species behaviour and vulnerability),
- Minimising the effect of natural disasters (monitoring geophysical volcanic, seismic and tidal wave activity),
- Maritime border protection (maritime safety, maritime security and law enforcement, border control and immigration, illegal fishing, drug smuggling, piracy and terrorism),
- Protection of commercial assets (shipping, oil and gas infrastructure), and
- Protection of national critical infrastructure (ports, harbours, undersea cables).

All of these applications require some form of undersea surveillance or monitoring that is customised for each intended purpose. In all cases, the key components required for achieving UDA include characterising the ocean environment (physical, chemical, biological, geological, climatological); sensing the undersea domain for potential threats, resources and activities of interest; making sense of data to plan security strategies, conservation and resource utilisation/management; and formulating and monitoring regulatory frameworks and responses at the local, national and global levels.

In the Defence context, UDA was highlighted as a priority area in the 2020 Defence Strategic Update. In his launch, the Prime Minister called it the foundation of deterrence: submarines are less likely to enter waters where they can be seen. Freedom of movement in the maritime domain is critical for trade, communications, natural resources and protection of the environment. Undersea surveillance is particularly challenging; the environment is complex and is becoming increasingly congested with a greater density and variety of undersea vehicles and infrastructure.[7]

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[7] Davey, Samuel, RUS EDTAS Scoping Paper, December 2020

The Undersea Battlespace

The undersea battlespace is defined as the environment, factors and conditions that must be understood and controlled to successfully conduct military operations within the underwater environment. Specifically, undersea warfare refers to military operations that are conducted to establish and maintain control of the underwater component of the maritime domain including the delivery of effects into and from within the underwater environment. This includes both offensive and defensive capabilities that enable friendly forces to deliver military effects to achieve the full range of expected missions and to deny an adversary force the effective use of its own underwater platforms, systems and weapons.

Figure 2 Source: Defence Connect

Traditional methods for conducting undersea warfare are reliant on crewed submarine, surface combatant and maritime air platforms to provide both surveillance and response against undersea threats.

These platforms contribute to a variety of established undersea warfare mission areas including:

- Submarine warfare;
- Anti-submarine warfare (ASW);
- Anti-surface warfare (ASuW);
- Mine warfare (MIW);
- Naval special warfare (NSW);
- Intelligence, surveillance and reconnaissance (ISR) (including indications and warnings (I&W) and initial preparation of the environment (IPOE)); and
- Maritime strike and strategic deterrence (delivered from underwater).

In addition, there are a number of new emerging mission areas which are becoming increasingly important, such as:[8]

- Subsea and seabed warfare (SSW);
- Counter-AUV;
- Electromagnetic manoeuvre warfare (EMMW),
- Deception; and
- Non-lethal sea control.

Collectively, these mission areas form the core of ‘full-spectrum undersea warfare’, which is the increasingly multi-domain extension of undersea warfare to achieve control over all dimensions of the undersea battlespace across these current and emerging undersea warfare mission sets and effects. These effects extend from seabed to space and include all physical (maritime (surface, underwater, subsea and seabed), land, air, space) and non-physical (information/cyber, psychological/human, and ‘Robotics and Autonomous Systems – Artificial Intelligence’ (RAS-AI)) domains.

Submarines will continue to be the most potent and capable undersea threat for the foreseeable future. ASW missions are often categorised as ‘local’ (involving a single platform), ‘force’ (involving multiple platforms operating as a task group), and ‘theatre’ level (multiple forces and platforms covering a wide area or region).[9]

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[8] CNO, Report to Congress, Autonomous Vehicle Requirement for 2025, February 2016, p4

[9] D. Finch, Anti-Submarine Warfare (ASW) Capability Transformation: Strategy of Response to Effects Based Warfare, 16th ICCRTS, Paper 103, Quebec, Canada, 21-23 June 2011. D. Finch, Anti-Submarine Warfare (ASW) Capability

[10] Undersea surveillance can be applied through different means to each of these ASW levels. However, providing undersea surveillance for a defined area of interest at a remote location or across a wide area of ocean, referred to as Remote Undersea Surveillance (RUS), in support of theatre level ASW operations are the harder challenges for the RUS Star Shot.[11]

The broader context for the RUS Star Shot and this Insights Paper includes theatre undersea warfare that involves persistent, pro-active, wide area and long duration military operations within the undersea battlespace. This warfare is enabled by command and control (mission data, decision support, modelling and analysis) provided by dedicated shore-based facilities and deployed forces with support from national sovereign government, industry and university capabilities and cooperation or leverage from international partners.

The future force as outlined in the 2020 Force Structure Plan will have significant undersea surveillance capability through Hunter class frigates, Attack-class submarines, and Poseidon maritime patrol aircraft, but Australia’s region of interest is too vast to monitor with crewed platforms alone; theatre level awareness requires a change in paradigm. To supplement this, significant investment in dedicated undersea surveillance projects, including an emphasis on autonomous sensing is being pursued. The Navy Robotics, Autonomous Systems and AI strategy outlines an ‘Evergreen’ approach to this capability with a vision of evolving technology refresh of payload and control systems.[12]

Transformation: Strategy of Response to Effects Based Warfare, 16th ICCRTS, Paper 103, Quebec, Canada, 21-23 June 2011.

[10] W. Toti, The Hunt for Full-Spectrum ASW, USNI 140 (6), June 2014.

[11] Davey, Samuel, Op.cit.

[12] Ibid

Figure 3 - RAAF P-8A Poseidon Maritime Patrol Aircraft

The Government has re-stated its commitment to the delivery of a ‘regionally superior’ submarine capability that is to be ‘fully interoperable with the United States in order to enhance Australia’s own deterrent, and contribute to regional anti-submarine warfare’. Further the undersea domain includes persistent undersea surveillance; undersea combat; command, control, communications; support; sustainment; and training sub-systems.[13]

In addition to the 12 Attack-class submarines, the Government intends to continue with:

- Sustainment, capability enhancements, and life of type extensions to the Collins class submarines, which are halfway through their life, to maintain a capability advantage until the transition to the Attack class;
- Continued upgrades to the submarine combat system and heavyweight torpedo; and
- Facility and infrastructure upgrades to support the expanding submarine fleet.[14]

To further safeguard our undersea capability, the Government will also invest in an integrated undersea surveillance system (including exploration of optionally

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[13] Commonwealth of Australia, 2020 Force Structure Plan, p 37

[14] Ibid, p37

crewed and/or un-crewed surface systems and un-crewed undersea systems), an undersea signature management range, and expanded undersea warfare facilities and infrastructure.[15]

Throughout this Insight Paper we will refer to the United States as a ‘capability benchmark’ for RUS as undersea research and development has been a distinct U.S. military advantage since the end of WWII. However, the wide availability of new processing and sensor technology and the increased exploitation of ocean resources are making undersea expertise more broadly available. This implies that there will be increased undersea competition, even as U.S. forces are likely to retain a significant advantage for the next one to two decades. [16]

The Undersea Environment

The undersea environment is vast and complex, and this imposes significant challenges and physical constraints on undersea warfare operations which are fundamental to the consideration of effective RUS technologies.

Regional ocean environments vary considerably at different geographic locations and with changing oceanographic and atmospheric conditions that evolve over time. In particular, the physical characteristics of the ocean can be very different in deep open ocean basins, constrained water spaces (such as archipelagic seas, islands, reefs and geographic chokepoints) and shallow littoral or coastal waters (with complex seabed structures, rich biological life and freshwater river inflows); and from warm tropical waters through to colder temperate and polar regions. The environment also changes continually through temporal variations over daily, seasonal, annual and longer time scales. There are many influences and drivers for these variations including internal ocean physical structures (surface/internal waves, tides and currents), physical and chemical properties (temperature, density, pressure and salinity), surface properties (atmospheric wind, weather and solar effects), seabed structures and properties (sediment geology), biological features and properties (ecology and biology of marine organisms) and anthropogenic impacts (shipping noise, air guns, active sonar).

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[15] Ibid, p39

[16] Clark Op.cit, p5

Figure 4 Source: Newsco.nz.co

One of the challenges for undersea surveillance is that understanding, modelling and predicting these variations is challenging as it is difficult to measure all of the required physical characteristics over wide areas at different depths and across different time scales. According to Geoscience Australia, the total physical mapping of Australia's ocean floor by multibeam sonar in 2015 had covered only approximately 25 per cent of Australia's marine jurisdiction. Many other physical characteristics required for understanding the performance of undersea surveillance systems are even less well understood.

The ocean environment imposes severe constraints on underwater platforms and systems which are summarised below.

- **Physical operation** – The operation of surface and underwater vehicles is severely impacted by the dynamic nature of the ocean caused by weather effects near the surface, varying ocean currents (that can interfere with navigation and operation), and the impacts of increasing high pressures with depth (that require pressure resistant enclosures for sensitive systems and components). Other physical effects such as marine life growing on the surfaces of platforms, vehicles and systems (biofouling can occur quickly in some ocean environments impacting the operations and performance of some systems components), and the corrosion of materials (particularly metals) by seawater, also provide significant challenges that need to be overcome.

- **Navigation** – Position keeping underwater is challenging as inertial systems are impacted by ocean currents (potentially with complex, changing structures that vary with location and depth), there is limited or no access to GPS (unless operating on or near the surface), and it is much more challenging to exploit bathymetric terrain or to establish a network of navigation beacons for differential positioning over large areas.
- **Communications and network connectivity** – Underwater communications at longer ranges is usually reliant on acoustic methods with limited operational ranges, low bandwidth/data rates, and poor time latency and error performance. At shorter ranges, higher frequency acoustic or optical methods can be used to overcome some of these constraints. In some circumstances, fixed electrical or optical cables to shore or to the surface can be used to avoid these problems however these in turn, often provide different challenges and operating constraints for deployment, reliability, survivability and maintenance.
- **Sensing** – Sensor and signature types that can be exploited in the underwater environment are severely constrained by the physical properties of the ocean. Acoustic sensors are the primary method for long range detection, however, non-acoustic methods such as electromagnetic signals and non-conventional or exotic signatures can be exploited as supplementary detection methods at short ranges for targets operating in shallow water or near the ocean surface in deeper water environments. The underwater acoustic environment is complicated by spatial and temporal variations in temperature, pressure and salinity, which result in a sound speed profile that varies in depth, location and time. This leads to a number of different types of propagation paths or modes that can be exploited for undersea surveillance (as will be described below).

Underwater acoustics is the best mechanism for long-range sensing within the ocean environment.[17] Acoustic signals propagate as compressional waves that can be detected as pressure fluctuations or gradients. The ocean medium and objects or inhomogeneities within it affect the propagation of these sound signals resulting in amplitude, frequency and phase changes that can be exploited to gain information about the ocean environment and any objects within it.

The speed of sound varies with temperature, salinity and pressure (or depth) resulting in a sound speed profile that is highly-dependent on the physical conditions within the ocean environment.[18] Changes in the sound speed profile as a function of depth causes the refraction or 'bending' of propagating sound waves in the vertical direction towards the region with slower sound speed (Snell's law). The structure of the sound speed profile as a function of depth is usually described in terms of a mixed layer near the surface (where the temperature is approximately constant and sound speed increases with depth creating a surface duct), the main thermocline (where the temperature and sound speed decrease with depth), the deep sound channel axis (located at the point of minimum sound speed), and the deep isothermal layer (where temperature becomes constant at approximately 2°C due to the thermodynamic properties of salt water at high pressures and the sound speed increases with depth due to increasing pressure).

The greatest variability and complexity in the sound speed profile occurs near the surface where heating and cooling effects due to seasonal and diurnal changes combined with mixing due to wind and wave activity at the surface influence the structure of the temperature profile within the mixed layer, or where a freshwater layer caused by fresh water outflows, heavy rain or melting ice floats on top of a more dense, saline layer (halocline). Consequently, the sound speed structure varies considerably with latitude and in different regions due to the predominant ocean currents and atmospheric conditions.

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[17] The conductive nature of sea water strongly attenuates electromagnetic signals, the motion of the surface and currents mask hydrodynamic signatures, and other more exotic signatures are either restricted to short-range detection or are difficult to exploit in practice.

[18] The sound speed profile, which is a function of temperature, salinity and pressure (or depth) and has a nominal value of 1500 metres/second (within 1-2% or [1485-1530]), is one of the most important parameters that affects the propagation of sound waves. Density variations also influence acoustic propagation, but these are typically relatively small over large propagation distance except where there are significant changes in salinity such as due to heavy rain, river inflows or ice melt. Sound speed equations are empirical relations that cover typical ocean depths (0-8000 metres), temperatures (-2-30 degrees Celsius) and salinities (25-40 parts per thousand).

These effects can vary considerably with latitude, ocean currents and atmospheric conditions. The strength and depth of the surface duct depends on the amount of mixing, both in magnitude and time duration, and is more pronounced when there are sustained winds and waves or significant weather events such as storms. In calm conditions, diurnal heating and cooling change the temperature profile near the surface resulting in weaker or stronger ducting effects. In polar regions, where there may be ice or sub-zero air temperatures, there is often a strong temperature gradient near the surface resulting in the minimum sound speed occurring at or much closer to the surface and with either no or at best only a weak surface duct.

The attenuation of sound waves through absorption varies with the frequency of the pressure fluctuations resulting in lower frequency sound waves propagating over much longer ranges than higher frequency sound waves.[19] The losses along specific propagation paths are complicated by channelling (or ducting), focusing and shadowing effects within the water column or the seabed that reinforce certain sound frequencies and impose losses (e.g., through 'duct leakage' or dispersion) on other sound frequencies. Reflection and scattering effects associated with the sea surface, sea floor, internal layers, bubbles, particulates, biological life or objects within the water column also play important roles in how sound waves propagate through the ocean.

The combination of the above propagation effects can be described somewhat simplistically in terms of the following propagation paths or modes:

- **Direct path (DP)** – These are propagation paths that connect two points via the shortest path and don't involve any reflection or scattering from the sea surface, sea floor or within the water column. These paths have the lowest attenuation.
- **Surface duct (SD)** – These propagation paths are trapped within the surface duct resulting in multiple recurring reflections from the sea surface. The surface duct is created by surface temperature effects (atmospheric and solar heating, atmospheric cooling and ice) or salinity effects (due to precipitation, river flows, freshwater plumes from subterranean aquifers, or ice melt) combined

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[19] For example, low frequency sound (<1000 Hertz) can propagate over hundreds or thousands of kilometres, medium frequency sound (1000-10000 Hertz) typically propagates out to a few tens of kilometres, and higher frequency sound (>10000 Hertz) is usually only employed for shorter range applications from a few tens of metres out to a few kilometres.

with thermal mixing in the surface layer through the action of wind and waves. Surface ducts typically occur where there is strong mixing due to the action of wind and waves or in arctic and shallow water environments and can have depths of a few metres down to 100 or more metres. These paths typically have reduced attenuation at medium to high frequencies but don’t support lower frequencies, which leak out of the ducted region.

- **Surface and bottom bounces (SB/BB)** – These are propagation paths that involve reflection off the sea surface or sea floor. Combinations of bottom and surface bounce paths are typically periodic with increased attenuation caused by losses associated with reflections from the sea floor, which are highly dependent on the seabed structure and physical characteristics.
- **Convergence zone (CZ)** – These propagation paths extend down towards the sea floor and refract sufficiently so that they are eventually directed back up towards the sea surface without interacting with the sea floor resulting in spatially periodic refocussing near the surface at range intervals of (35-70 km). The CZ paths have less attenuation than bottom bounce and are usually only observed in deep water where they don’t extend below the critical depth (the depth in deep water where the sound speed is the same as it is at the sea surface).
- **Deep sound channel (DSC)** – These propagation paths typically occur in deep water and are due to ducting around the minimum in the sound speed that can be tightly ducted or more CZ-like in structure or a combination of both although the paths don’t extend below the critical depth. Low frequency sound can propagate for hundreds or thousands of kilometres as there no or limited interactions with the sea surface and no interaction with the sea floor.[20]

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[20] At mid-latitudes, propagation within the deep sound channel can occur without any interactions with the sea surface or sea floor. In polar regions, the water is coldest near the surface and the minimum sound speed is either at or close to the surface (ocean-air or ice interface), so this channel is more like a large surface duct with some surface interactions. The depth of the deep sound channel can be close to the surface near the poles, around 1000-1200 metres at temperate latitudes, and as deep as 2000 metres at some places near the equator.

- **Reliable acoustic path (RAP)** – These propagation paths are a special type of direct path that extend upwards towards the sea surface from a point below the critical depth in deep water. The low attenuation and shape of these propagation paths support good upward-looking coverage throughout the water column with direct path or one surface bounce.
- **Shadow zones** – These are regions within the ocean where sound signals do not propagate from a given source location. They typically occur below the surface mixed layer in the regions between the above propagation modes and increase in size with increasing water depth and horizontal range from the source.
- **Shallow water multipath** – In continental shelf regions where the water is shallow, by definition less than 200 metres in depth, only the upper part of the sound speed profile is relevant and propagation paths consist of either a surface duct or multiple surface and bottom bounce paths. The attenuation caused by multiple surface and bottom reflections and multipath fading effects typically reduces the range over which sound propagates. In these environments, low frequency sound can also propagate through the sea floor and back into water column.

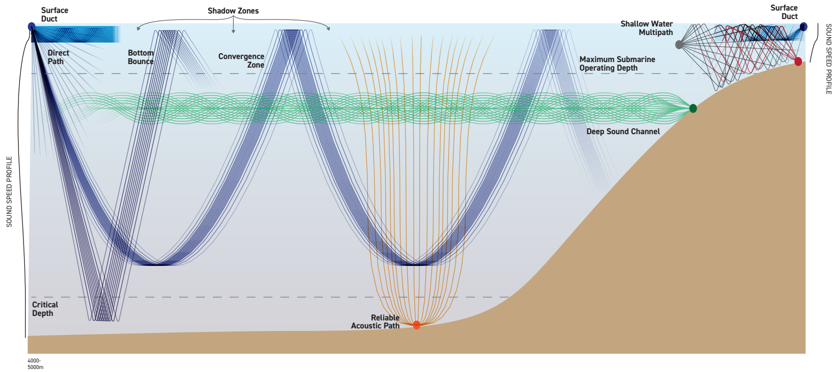

Figure 5 - Sound Propagation Models

The definition of deep water is roughly aligned with the edge of the continental shelf that marks the Exclusive Economic Zone (EEZ) where the 200 nautical mile boundary ends with an approximate water depth of 200 metres. As the water depth increases, more propagation paths or modes are supported and the bottom bounce, convergence zone and deep sound channel become increasingly important for propagation over longer ranges. The water depths that support each of these propagation modes varies considerably with the structure of the sound speed profile, surface and mixing effects, and with the structure and composition of the sea floor. The sea surface is an almost perfect reflector but has small-scale roughness that is time-varying over short time scales due to wind effects and waves that result in structured reflections and scattering from the moving sea surface.

Acoustic propagation near the surface is also impacted by changes in atmospheric conditions and currents that lead to variations in the sound speed resulting from the mixing process, and due to complex interactions with moving clouds of bubbles generated by waves. The sea floor is typically a complex, rough boundary with strongly varying bathymetric features, surface roughness and sediment structures that typically consist of multiple heterogeneous sediment layers with different sediment types, sizes, features and physical characteristics that influence sound reflection, scattering and transmission. Internal ocean processes such as internal waves, currents and small-scale turbulence introduce further small fluctuations in the sound speed profile at different locations and depths that lead to additional variability in propagating sound signals over longer ranges.

The intensity and phase of a sound pressure wave generated by a sound source can be deduced (at least in principle) from the acoustic wave equation however this is typically difficult to implement in practice due to the complexity of the ocean environment. Analytical solutions of the wave equation are not feasible except in simple geometric representations and solutions are often approximated using ray tracing, normal modes, coupled-mode models, parabolic-equation, Green’s function solutions, or finite element methods.

Each of these approaches have different limitations, computational loads and applicability at different frequencies, which impact their usefulness in the modelling of sound propagation in different environments.Sound Navigation and Ranging (sonar) refers to sensors that exploit underwater acoustics for sensing in the underwater environment. These can be passive (i.e., they listen for signals of interest radiated from potential adversary platforms) or active (i.e., they use a sound source or transmitter to emit a sound signal that propagates out to a potential adversary platform and listens for reflected or scattered signals at a receiver. Active systems are further categorised as monostatic (source and receiver are collocated), bistatic (source and receiver at different locations) and multistatic (multiple sources and receivers at different locations).

The detection performance of a sonar system is limited by the available propagation paths or modes that can be exploited by its sensors and the background or ambient noise level received by these sensors. The ambient noise within the ocean results from multiple different types of sources including wind, waves, precipitation or ice near the surface; seismic and geological sources within the sea floor; and currents, biological life (marine mammals, fish, snapping shrimp) and anthropogenic sources (shipping, active sonar and other noise sources) within the water column. This results in background noise that contains both broadband and structured wide-band or narrow band signals over a wide range of frequencies that are highly directional and vary considerably at different locations, depths and times.

For active sonar, unwanted reflections from the sea surface, sea floor and from objects or inhomogeneities within the water column also result in reverberation that increases the received noise at a sensor in the frequency band used by the sound source. In tropical regions, propagation effects, higher surface fluctuations, site-specific sea floor variations, and richer biodiversity can degrade sonar sensor performance by as much as 70% compared to colder temperate and polar regions. The optimal design, employment and performance of sonar systems for platforms or dedicated undersea surveillance requires significant knowledge of the ocean environment to overcome the complexities of these propagation modes and the impact of ambient noise or reverberation within different frequency bands.

Non-acoustic sensing

Non-acoustic signals such as electromagnetic radiation that are typically used for above-water sensing are highly attenuated by sea water due to its conductivity and are only suitable for the detection of surfaced or submerged platforms operating near the surface down to depths of a few metres and up to a hundred (or slightly more) metres. Consequently, non-acoustic sensors are more often employed by air (or space) platforms or as short-range supplementary sensors in underwater applications at close ranges, for objects operating near the ocean surface or in shallow water environments (typically defined as less than 200 metres). Some examples of conventional non-acoustic sensors include:

- Low frequency electromagnetic waves (magnetic and electric fields, magnetic anomaly detection (MAD), communications intercept), and
- High frequency electromagnetic waves (radar, periscope detection, optical, laser, light detection and ranging (LIDAR), infra-red, thermal, night vision, hyperspectral imaging).

There are a range of other non-conventional or exotic signatures of submarines and undersea vehicles that may be exploited (at least in principle) in undersea sensing applications, however, many of these are challenging to employ and operate effectively in practice. These include:

- Gravity (gravitational signatures or anomalies generated by a submarine),
- Hydrodynamics and wakes (pressure waves, hydrodynamic effects, surface and internal wake structures from the movement of a submarine),
- Chemical and nuclear (chemical and nuclear isotope detection within a submarine's wake, anti-neutrinos from the reactor of a nuclear submarine), and
- Biological (bioluminescence from micro-organisms caused by the presence of a submarine).

The Remote Undersea Surveillance Challenge

Remote undersea surveillance (RUS) is defined as the provision of undersea situational awareness over specific and wide area regions of interest beyond the reach of crewed platforms. RUS capabilities operate over extended ranges away from parent (crewed) platforms or in remote geographical locations where it is challenging for an operator to exert any significant control over the operation of the system. It is intended that they will include both deployable surveillance sensor systems and future autonomous vehicles and systems. They will incorporate a range of onboard system components and technologies necessary to complete the mission. These may include sensors, sensor signal processing, detection-classification-localisation-tracking, environmental modelling, communications systems, and command a control (C2) functionality.

The C2 functionality may include operator aids and mission-level decision support functions that would link into a theatre-level C2 system. Maturing all of these system components and technologies to the level of performance required to achieve the desired operational effectiveness, reliability, and survivability in increasingly contested environments is the key challenge for RUS.

Remote undersea surveillance (RUS) is defined as the provision of undersea situational awareness over specific and wide area regions of interest beyond the reach of crewed platforms.

Cost-capability trade decisions will need to be made regarding the mix of large numbers of small, cheaper sensors and platforms versus the relative effectiveness of larger, more capable and more expensive systems. Understanding what the mission scenarios, threats and environments will be, and what the operational concepts required for success are essential for determining the best single or mix of system solutions.

Research to support these decisions is not straightforward as the physics and complexity of the ocean environment imposes significant constraints and challenges on the operation of autonomous systems and sensors that vary considerably with system size; space, weight, power and cooling (SWaP-C) requirements for sub-system components; and the desired operating or sensor coverage area requirements. These are all matters worthy of exploration through the EDTAS process.

SWaP-C

Key considerations for sub-system components – space, weight, power and cooling.

Additional Challenges

In addition to all these complexities, RUS must also consider the impact of climate change, growing congestion in particular parts of the ocean and the evolution of technical and regulatory constraints, especially with regards to autonomous vehicles.

Potential impacts of climate change on the undersea domain

Environmental change may bring with it some additional considerations for undersea surveillance. There will be greater volatility and more extreme weather events that will impact on the resilience of undersea platforms which will require technological improvements to mitigate against mission failure.

Increasing ocean temperature may potentially impact the operation, resilience and survivability of possible RUS platforms. Its effects may include changing the acoustic profile of the sea, changes to sea life and changes in salinity which may enhance the effects of fouling.

Reducing the polar ice caps and resultant higher sea levels may change the location of traditional choke points and observation channels. It will also create more space for underwater vehicles to operate and more area for RUS to observe.

There may be some benefits in the ADF better understanding how these changes may provide advantage. We don't really know for certain what is happening. More research and modelling is required to understand what these climate changes will produce and what their impact will be on our future undersea capabilities.[21] We know that the ocean temperature is rising, but how many places has this been measured? We know that polar ice is melting and that we will have less ice and more water, but is this part of a longer-term cycle? Has it happened before - before we started measuring things? Understanding the effects of these changes is a key enabling research area for RUS that has potential benefits for both Defence and the greater global good.[22]

Data will be required to constantly validate the climate change models we build for undersea surveillance and in particular, autonomous systems. The data requirement will be very large, and we will need innovative ways for collecting it. This may include, underwater vehicles, satellites and even 'crowd sourcing' all ships which collect raw data as part of their daily operations. How it is transmitted from the collection nodes, how it is processed and who owns it are questions to be resolved. How the findings from the processing of this data are managed and shared between nations, allies, commercial entities and others will also need to be addressed.[23]

Potential impacts of increased congestion on the undersea domain

Increased shipping traffic, sensors and commercial applications may cause significant issues for undersea surveillance in the future. While the ocean is a large place and there is plenty of empty space, the proliferation of under- and above sea users will provide challenges for undersea observation and surveillance. We see this already at high-traffic ports and transit routes for example, where there is a lot of commercial, industrial and recreational activity. Autonomous systems interacting with non-autonomous systems in a congested undersea environment creates a number of issues that will be further exacerbated for the military who will need to understand what each entity is and whether it is friend or foe, or more confusingly, something in between.[24]

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[21] Marouchos, Andreas, Interview with Ash Colmer, 1 Feb 21
[22] Hale, Gary, Interview with Ash Colmer, 2 Feb 21
[23] Scourzic, Daniel, Interview with Ash Colmer, 23 Feb 21
[24] Marouchos, Andreas, Op.cit

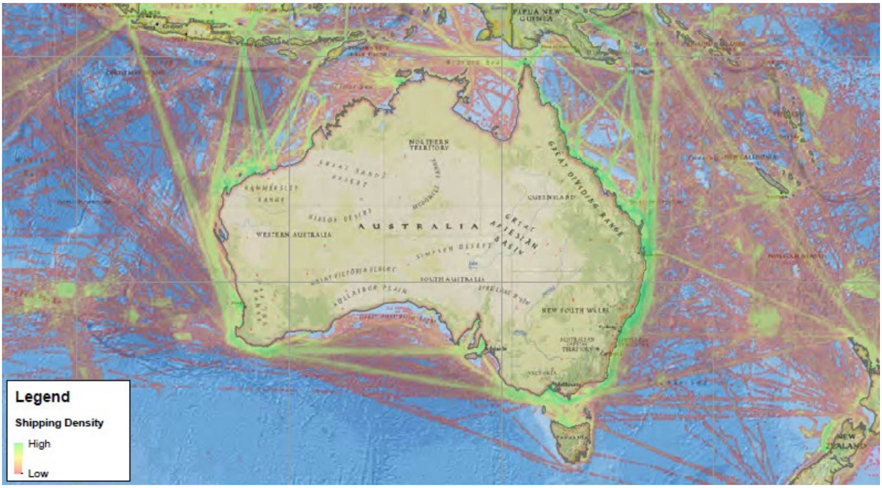

Figure 6 - Marine Traffic around Australia

Furthermore, such autonomous systems will have more objects to avoid and will require complex avoidance routines that may impact on their ability to achieve the mission. An adversary could take advantage of pre-programmed Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) compliant avoidance manoeuvres by sending a relatively low cost vessel to perform blocking manoeuvres that force the autonomous platform to continuously perform avoidance evolutions. At the other end of the technology spectrum, the most serious enemy of underwater autonomous platforms is the “cheap and simple” fishing net. Such nets, if specifically designed for the ‘capture’ of autonomous platform, may be the most effective countermeasure of the future.[25]

Potential Impacts of Legal and Regulatory Constraints

Like most emerging capabilities, the evolution of legal and regulatory requirements for undersea capabilities, and particularly those for autonomous or un-crewed platforms, are potentially a step behind the realisation of what these capabilities are endeavouring to achieve. Such platforms must comply with standard shipping.

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[25] Scourzic, Daniel, Op.cit

According to the Australian Maritime Safety Authority (AMSA):

> 'Currently, these vessels are subject to the same regulatory framework as other vessels, including for survey standards and crewing requirements. This is because the definitions of 'vessel' in the Navigation Act 2012 and the Marine Safety (Domestic Commercial Vessel) National Law Act 2012 are very broad.' [26]

While AMSA acknowledges that there must be some flexibility when considering how to regulate emerging technology, the responsibility lies with Defence to ensure compliance.

As well as the more obvious navigational requirements, RUS technologies may also be affected by a range of constraints such as the use of low frequency active sonar which may impact on sea life and particularly marine mammals. Additionally, a sea full of small 'disposable' un-crewed or autonomous vehicles may create a problem similar to 'space junk' which may have regulatory authorities poorly disposed to such concepts especially for toxic materials or pollutants.

RUS STaR Shot Mission

Amidst this context the RUS STaR Shot will develop technologies for persistent, agile, and robust undersea situational awareness over specific and wide area regions of interest beyond the reach of crewed platforms. It will focus on game changing sensing technology; automation of platforms, data, and networks; and decision superiority in a dynamic natural and contested human environment. This autonomous sensing and evolving Australian sovereign industry capability is vambitious and will not be achieved with current technology.

> The central mission of the RUS STaR Shot is to lead the creation, maturation and transition of game-changing sovereign technology for the surveillance and decision making aspects of the Undersea Combat and Surveillance Program.[27]

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[26] Australian Maritime Safety Authority Website, https://www.amsa.gov.au/vessels-operators/domestic-commercial-vessels/autonomous-vessels-australia, accessed 21 Apr 21

[27] Davey, Samuel, Op.cit

Potential Technology Horizons

The RAN's RAS-AI Strategy discusses developmental possibilities for autonomous systems across three 'technology horizons': today's technology; those that appear likely in the near-term; and those that will likely require significant development out to and beyond 2040.[28] While future timelines for R&D are problematic, for RUS purposes, we will consider the following horizons:

- **Horizon 1 (approximately 2020-2030)** – where we will seek to extend platform and fixed/mobile surveillance capabilities with new autonomous and deployable sensor systems that provide increased operational reach. There will be an increasing focus on developing core enabling system technologies and on the integration of C2 and communications at strategic, operational/force and local levels. This period will also see increasing surveillance and response capabilities that may challenge future platform operations (particularly for surface and air). It will also extend the scope of the maritime domain (undersea, surface and air) to include space and information/cyber.
- **Horizon 2 (approximately 2030-2040)** – will begin to see the integration of platform and surveillance capabilities with maturing autonomous systems and deployable sensors that are more independent and operate at extended distances from platforms. There will be an increasing focus on developing and integrating core system capabilities and on networked C4ISR at all levels. This will occur amidst increasing adversary surveillance and response capabilities that extend further into the undersea, space and information/cyber domains. The scope of the maritime domain will more extensively leverage the undersea (subsea and seabed), space and information/cyber domains.
- **Horizon 3 (approximately 2040-2050)** – will see fully integrated, distributed networks of platforms, sensors and response options. There will be an increasing focus on networked operation and the control of systems and an increasing focus on networked C5ISREW at all levels.

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[28] Royal Australian Navy, RAS AI Strategy 2040, p 10

What Follows…

Having now looked at the context within which RUS operates we will turn our attention to the capabilities that will potentially support it. Section Two provides a broad discussion of current and evolving sensors and systems while Section Three focusses on autonomy and the potential for un-crewed undersea vehicles (UUVs). Section Four introduces some ideas for disrupting the current trajectory of undersea surveillance capabilities and discusses some more novel concepts and technologies. It also discusses how Australia might go about mobilising its full RUS potential across Defence, industry and academia.

undersea surveillance systems & technologies

Undersea surveillance systems aim to detect, classify and localise submarines or other undersea vehicles to provide undersea domain awareness and provide cueing for tactical ASW response forces. This is achieved using a combination of dedicated surveillance sensor systems that provide wide-area search and cueing, and tactical platforms that can further localise and respond to potential undersea threats.

Traditional ASW Systems

The standard tactical ASW platforms include maritime patrol and response aircraft, submarines and surface combatants with hull-mounted, towed or deployed sensors that are used to detect, localise and respond to submarines or other undersea threats. These response options may include periodic monitoring, track and trail, or prosecution using torpedoes, mines or depth charges.

Maritime patrol aircraft use a variety of sonobuoys for acoustic detection. These consist of active sources and/or passive sonar sensor arrays connected to a surface float with a radio-frequency transmitter for relaying acoustic data back to the aircraft. Sonobuoys are air-deployed, usually in large numbers to cover a trip-line/barrier or an area of interest. The acoustic sources and sensors can be deployed to several different depth settings to support submarine detection within the surface duct or below the mixed layer. These typically operate at low-medium frequency (100-10,000 Hertz) with some omni-directional capabilities at lower frequencies down to a few tens of Hertz. In addition, a number of non-acoustic sensors including magnetic anomaly detection (MAD), electro-optic (EO), infra-red (IR), electronic support measures (ESM), radar (including periscope detection), and electronic or communication signals intelligence can be used for the detection of submarines operating on or near the sea surface.

Figure 7 - Sonobuoy Deployment

Submarines use a variety of hull-mounted arrays (bow, flank, intercept, high-frequency active) and towed sensor arrays for navigation, safety and the detection of undersea, surface and air threats. The acoustic arrays operate across a wide range of frequency bands from very low-very high frequencies (10 Hertz – 100 kHz). The flank arrays located along the sides of the submarines hull and the towed array which are typically 100-200+ metre long acoustic arrays towed on long cables behind the submarine provide the best low-frequency directional responses for long-range detections.

Surface combatants use a hull-mounted array (bow or underneath the hull) and towed sensor arrays for the detection of undersea threats. The hull-mounted arrays are typically active, operating at medium-frequency bands (2-10 kHz) for detecting undersea threats within the surface duct. The towed arrays are typically 100+ metre acoustic arrays towed on long cables operating at low frequencies (50-2000 Hertz). These are supplemented with active sources operating at 1-2 kHz that can be towed in-line with the receiver array or as separate variable depth sonar (VDS) towed acoustic sources. Additional towed array modules operating at medium frequencies (1-10 kHz) are also used for torpedo detection. Many surface combatants also have embarked helicopters that provide similar sensor capabilities including sonobuoys and some of the non-acoustic sensors for detecting submarines operating outside the detection coverage of the ship. Helicopters also employ dipping sonars that are lowered down into the water whilst hovering at low altitude, which provide additional medium frequency (1-4 kHz) active detection capabilities.

All of these tactical acoustic sensors typically rely on very low-medium frequencies (10-10,000 Hertz) to exploit direct path, surface duct, bottom bounce and convergence zone detections in deep or shallow water to provide local area coverage around the platform or sensor field. Cooperative sensor processing across multiple tactical platforms and sensors such as bistatic or multistatic active processing or passive sensor fusion from multiple sensors can be used to provide wider area coverage.

Current and Developing Surveillance Systems

Given the unclassified status of this paper, it makes sense to begin an examination of undersea surveillance sensor capabilities from the perspective of the United States Integrated Undersea Surveillance System (US-IUSS) based on available open-source material.

The US-IUSS is a mature capability that was conceived in 1949, became operational on 18 September 1954, and recently celebrated its 66th anniversary. The system consists of an evolving mix of fixed, mobile, and deployable undersea surveillance systems with dedicated shore-based processing, analysis, reporting and command functions that provide the US Navy with its primary means for detecting non-allied submarines at long ranges in support of fleet undersea domain awareness and tactical cueing for ASW response forces.

US-IUSS capabilities were extensively developed, expanded, and continuously upgraded throughout the Cold War period in response to an evolving Soviet submarine threat. Recent decades have seen a renewed focus and re-invigoration of US-IUSS capabilities due to continued increases in the numbers and diversity of potential submarine and undersea threats associated with the resurgence of Russia, emergence of China, and the proliferation of new submarine and undersea capabilities within many other countries.

These surveillance sensors typically use very low-low frequency acoustics (10-1000 Hertz) that are designed to exploit the deep sound channel, reliable acoustic path and/or convergence zone detections for long-range detection and cueing in deep water, and direct path, surface duct and bottom bounce in shallow water. Distributed combinations of fixed, mobile or deployable sensor systems are typically used to provide wide-area, persistent and adaptable sensor coverage with the mix and types of systems selected based on the operational scenarios, threat posture, locations and environmental conditions.

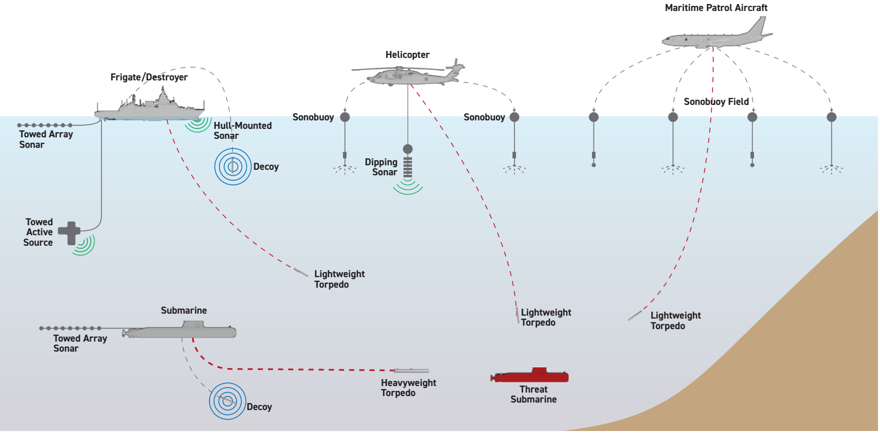

Figure 8 - Traditional ASW Operations

What follows is an overview of the sensors, systems and platforms that have previously been, are currently or are expected to come into service in the future.

Fixed Surveillance Systems

The Fixed Surveillance System (FSS) function was provided by the Sound Surveillance System (SOSUS). SOSUS consisted of a network of large, passive acoustic line arrays that were deployed on the seabed to exploit the long-range propagation of low frequency sound within the deep sound channel. The initial array variants employed a group of up to three large-aperture (~300 metre) line arrays with a total acoustic aperture of 1000-2000 metres that were deployed on the edge of the continental shelf or on seamounts (at depths of up to 1200 metres) to listen out into large ocean basins.

SOSUS was deployed at strategic locations in the Atlantic and Pacific oceans to provide wide-area acoustic sensor coverage; initially near continental US, Canada, and the Caribbean (1954-1963) to provide homeland defence; and increasingly further forward, in the Aleutian Islands (Adak), Marianas Islands (Guam), Midway Islands, Hawaii, Iceland, United Kingdom and other classified locations (1963-1974) to provide indicators and warnings of adversary submarine deployments at key strategic, forward choke points. Additional SOSUS sites and installations beyond 1974 have not been disclosed and are classified special projects. This changing strategic posture resulted from improvements in Soviet submarine capabilities, specifically the continued acoustic quietening; introduction of long-range, submarine-launched ballistic missiles that could engage the continental US at increasingly large stand-off ranges; and the subsequent shift in Soviet ballistic missile submarine patrols from the North Atlantic to a bastion strategy within Soviet territorial waters.

Each SOSUS array was directly connected via undersea cable to a dedicated shore station known as a Naval Facility (NAVFAC) that provided processing, analysis, reporting, and support functions. Technology improvements allowed these arrays to be deployed at increasingly longer distances from the shore station extending from a few tens to a thousand nautical miles or more and allowed remoting via secure land or satellite communications to a smaller number of larger shore facilities that gradually consolidated these functions from 1974-2009.

The US currently has only two dedicated shore facilities located at Naval Ocean Processing Facility (NOPF) Dam Neck, Virginia (for Atlantic Ocean operations) and NOPF Whidbey Island, Washington (for Pacific Ocean operations).

Figure 9 - SOSUS NAVFAC in Pembrokeshire, UK

Modernisation and evolution of the SOSUS system through to 1996 has been well-documented in open-source reports and articles. Sensor array and cable technologies were updated through five generations of commercial undersea telecommunication cable technologies. Sensor signal repeaters, conditioning hardware, and processing systems evolved in-parallel with the sensor and cable technologies with a gradual transition from analogue to digital electronics, custom to commercial electronics hardware, dedicated signal processing to more flexible software-based processing using Commercial-Off-The-Shelf (COTS) computer hardware, and paper-gram to computer-based displays.

The most recent acknowledged variant of SOSUS known as the Fixed Distributed System (FDS) was designed to be a scalable network of much longer seabed arrays with distributed sensors that cover an extended area on the seabed in deep or shallower water, which look upward to detect submarines transiting through this region.

Only two FDS arrays were procured and deployed from 1993-1996 due to funding cuts in the post-Cold War period each at a cost of approximately US$1B per array in 1994. While SOSUS and FDS are older systems they are still representative FSS exemplars. Ongoing development and upgrade programs for these systems beyond 1996 are classified and not much is openly known except that funding continues to be allocated for the modernisation and improvement of these systems.

Key attributes of FSS are that they consist of large, distributed networks of sensors that are expensive and must be strategically placed to exploit long-range ocean acoustic propagation characteristics in relevant adversary submarine operational areas to be useful. Sovereign access and control of these ocean territories and a high-level of secrecy throughout the deployment, operation, and maintenance of FSS sensor arrays is essential to prevent potential adversary awareness that would allow them to counter, avoid, exploit or destroy them. In addition, dedicated ocean surveying and cable support ships are essential for installing and maintaining the fixed cables and sensor arrays throughout their operating life.

Mobile Surveillance Systems

The Mobile Surveillance System (MSS) function is provided by several variants of the AN/UQQ-2 Surveillance Towed Array Sensor System (SURTASS) employed on dedicated Tactical Auxiliary General Oceanographic Surveillance (T-AGOS) ships. SURTASS provides mobile and relocatable detection, tracking and reporting of submarine contacts at long ranges and is primarily used in deep-water areas not covered by FSS.

Figure 10 – T-AGOS Ship, USNS Impeccable

SURTASS research and development commenced in 1973 with Initial Operating Capability achieved in November 1984. The original SURTASS towed array consisted of a very long (1600 metre) passive acoustic line array containing a large number of hydrophones that was operated at speeds of 3-10 knots at depths of 150-460 metres. The SURTASS processing system adopted a hybrid approach that supports both on-board processing and the transfer of beam-formed data via a dual Super High Frequency Satellite Communications (SHF SATCOM) link to a shore processing system for display, analysis, and reporting. This approach balanced SATCOM bandwidth limitations with a desire to avoid larger vessel and crew sizes.

A dual AN/WSC-6(V) SHF SATCOM system is the current operational system used to transmit passive sonar data to either NOPF location for processing, analysis, and reporting.

Continued technology upgrades have introduced new array and processing improvements through to the current operational TL-29A Twin-Line towed arrays that were developed from 1993-2005 and introduced into service from 2006.

The TL-29A consists of two identical, long (800 metre) passive acoustic line arrays towed side-by-side with variable separation, to provide enhanced detection and operating performance, particularly in shallower water and littoral regions. TL-29A array technology is essentially the same as the TB-29A COTS compact towed array used on US Navy submarines.

An adjunct AN/WQT-2 Low Frequency Active (LFA) acoustic array was developed from 1988-1992 to address the reducing passive acoustic detection ranges against newer, quieter Soviet submarines. The original LFA system contains a large (155 tonne) active vertical line array consisting of 18 projectors operating at 100-500 Hertz. This system required significant fleet and environmental impact testing throughout 1992-2003 before being introduced into service on USNS Impeccable in 2004-2006. A smaller (64 tonne) Compact Low Frequency Active (CLFA) variant with comparable operating characteristics was developed from 1999-2008 and introduced into service from 2008-2011. The CLFA system continued operational testing during 2011-2016 to address technical, operational, and environmental issues, and is currently operational on three Victorious Class T-AGOS vessels. All active sonar data transmitted from LFA/CLFA and received on TL-29A is processed on-board the ocean surveillance ship due to bandwidth limitations in current SHF SATCOM links.

Specialised ocean surveillance (T-AGOS) ships are used to tow the SURTASS arrays. All current T-AGOS ships have specialised Small Waterplane Area Twin Hull (SWATH) designs to provide stability during low-speed towing operations in high sea-states. The US SURTASS fleet from 1984-2004 consisted of 18 mono-hull Stalwart Class ships (2262 tons) that were routinely deployed in the Atlantic and Pacific Oceans, the Mediterranean Sea, and the North Sea, with re-supply and replenishment ports at forward base locations. The current US SURTASS fleet consists of four Victorious Class T-AGOS/SWATH ships (3396 tons) introduced from 1991-1993 and one Impeccable Class T-AGOS/SWATH ship (5362 tons) introduced in 2001 that primarily operate out of Yokosuka (Japan), Guam (Marianas Islands) and other ports of opportunity in the Western Pacific. A new class of up to seven larger T-AGOS(X)/SWATH ships (~8600 tons) are currently being designed for introduction into service from 2025. In addition, a containerised, passive-only, expeditionary SURTASS system (SURTASS-E) for employment on Vessels of Opportunity (VOO) was developed from 2017-2019 to provide increased numbers of ocean surveillance ships as a de-risking strategy prior to the introduction of T-AGOS(X).

The Japanese Maritime Self Defense Force currently has three Hibiki Class T-AGOS/SWATH ships (2900 tons) fitted with SURTASS systems that were introduced into service in 1991, 1992 and 2020. The ‘rough order of magnitude’ (ROM) cost of a SURTASS/LFA equipped ocean surveillance ship is $500 Million.

The combination of FSS (SOSUS and FDS) and MSS (SURTASS/LFA or CLFA) forms the core of current US-IUSS capabilities.

Deployable Surveillance Systems

The Deployable Surveillance System (DSS) function is much less mature and covers a wide variety of different system types and concepts that have been explored and evolved over the past few decades to supplement existing FSS and MSS capabilities. Numerous Defense Advanced Research Projects Agency (DARPA), Office of Naval Research (ONR), Naval Undersea Warfare Center (NUWC), Naval Information Warfare Center (NIWC), and other Government and Industry research and development programs have studied deployable undersea sensors, distributed netted sensors, undersea communication and navigation networks, autonomous vehicles with various undersea sensor and communications payloads, and the undersea constellation. Many of these programs have supported the ongoing development and experimentation of related concepts, systems and component technologies that have allowed these to be adapted, matured, and evolved over time.

Current DSS are grouped into four main families:

- **Shallow Water Surveillance Systems (SWSS)** – These consist of a variety of sensor systems that can be deployed on the seabed, moored or floating to exploit direct path, surface duct or multipath channels in shallow water environments (< 200 metres). Some of these systems use short-range non-acoustic sensors such as magnetic, electric field and optical sensors to supplement the acoustic sensors to provide more robust detection, classification and localisation.

- **Advanced Deployable System (ADS), AN/WQR-5** – A smaller, more rapidly deployable version of the FDS seabed array system that was developed as a theatre-deployable acoustic surveillance system which provides continuous acoustic coverage over wide ocean areas for an extended duration to enable surveillance and cueing for tactical response forces. The ADS consists of multiple passive acoustic line arrays that can be deployed in different configurations for tripline, barrier or area coverage for detecting submarines, ships, or mine-laying operations in shallow water littoral environments. Several ADS variants were matured under consecutive development programs from 1992-1999, 2000-2004 and 2004-2009 with each system reaching operational testing and having operational suitability in some scenarios but not successfully transitioning into operational service. The estimated ROM cost for these systems is $50+ Million.
- **Autonomous Off-Board Surveillance Sensor (AOSS)** – A SPAWAR/ONR program to develop a 100-metre-long array consisting of 14 hydrophones, 3 magnetometers and an electric field sensor packaged within an ‘A’-size sonobuoy-like container for deployment from aircraft or surface ships to provide ASW and ISR barriers in shallow littoral environments for up to 90 days. Contact and track data was transmitted acoustically to a receiver buoy for RF uplink to aircraft or satellite. The system was designed for the detection of submarines, surface ships, aircraft, and mine-laying operations. This program was conducted in the mid-1990’s.
- **Deployable Autonomous Distributed System (DADS)** – An ONR program to develop seabed sensor nodes containing acoustic and magnetic sensors that are distributed on the seafloor and connected via serial cables to cooperatively detect and track submarines and surface ships in shallow water environments. Initial development from 1999-2000 with an advanced development model built in 2004 for testing and analysis in 2005-2006. An ONR Littoral ASW Future Naval Capability program in 2005-2007 sponsored further development of DADS with at-sea testing conducted in 2008-2009.

  + **Seaweb** – A SPAWAR and Naval Postgraduate School (NPS) program to develop a shallow water underwater sensor network with a focus on networked acoustic communication and command of undersea sensors, vehicles, and other components. Initial development was conducted in 1998-2001 with ongoing development and experimentation continuing through to present.
  + **Persistent Littoral Undersea Surveillance Network (PLUSNet)** – An ONR program with multiple institutions to develop a semi-autonomous controlled network of fixed bottom and mobile sensors for undersea surveillance in shallow water littoral zones. Initial development from 2005-2007 with ongoing development and experimentation through to at least 2016.

- **Deep Water Passive (DWP) Surveillance Systems** – These consist primarily of vertical line arrays deployed on the seabed in very deep water (below the critical depth) to exploit reliable acoustic path propagation. These systems provide upward-looking coverage over a large search area with at least 20-30-kilometre diameter.[29] Processed sensor data is transmitted either via optical fibre cable to the shore or surface, or underwater communication links to the surface (e.g., to a wave glider communications node) for reporting to a command node. For underwater communications links, onboard (autonomous) sensor processing is essential to reduce the communications bandwidth requirements.

  + **Reliable Acoustic Path Vertical Line Array (RAP VLA)** – A Navy Small Business Innovation Research contract in 2008-2009 for an air or ship deployed, distributed, passive sonar sensor system that exploits deep-water reliable acoustic path propagation. NAVSEA sponsored further development in 2009-2010.
  + **Transformational Reliable Acoustic Path System (TRAPS)** – A fixed passive sensor node designed to achieve scalable, large-area coverage by exploiting reliable-acoustic path propagation from the deep ocean floor. This is an expendable, low size, weight and power node that communicates to a stationary surface node via wireless acoustic modems with secure radio frequency reach back to a shore facility via satellite. Initially developed under a DARPA program, Distributed Agile Submarine Hunting (DASH) that

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[29] One source indicates 30-60 kilometre, but this may be with surface bounce paths.

aimed to develop a scalable number of collaborative unmanned sensor platforms to detect and track submarines over large areas in deep and shallow water in 2011-2013. Two separate prototypes SHARK (see below) and TRAPS transitioned into ONR programs from 2014-2017 and are now commercial prototypes. A 3-year production contract was awarded to Leidos in June 2019.

Figure 11 - TRAPS Deployment

- **Deep Reliable Acoustic Path Exploitation System (DRAPES)** – An ONR FNC program to develop prototype RAP VLA systems in 2016-2020 that are smaller and more easily deployable than in previous programs.
- **Deep Water Active (DWA) Surveillance Systems** – These systems are deployed as a distributed network of sensors on the sea surface that are designed to exploit convergence zone paths in deep water environments. They extend the concept of a sonobuoy with a larger system that can be deployed from surface vessels to provide longer-range detections and longer endurance than standard sonobuoys.
    - **Deep Water Active Distributed System (DWADS)** – A distributed active sonar system optimised for use in deep water to exploit convergence zone detections. Initial development was conducted in 2008-2010.

- **Mobile Passive/Active Systems (MPAS)** – These systems consist of autonomous surface (e.g., waveglider) or underwater vehicles with sensor and communication payloads that can be repositioned for cued surveillance and are designed to operate cooperatively with other autonomous vehicles and sensor systems to provide persistent surveillance in deep or shallow water environments.
    - **Submarine Hold at RisK (SHARK)** – An unmanned underwater vehicle designed to provide a mobile active sonar platform to track submarines in deep or shallow water environments after initial detections are made. Initially developed under the DARPA DASH program in 2011-2013 and ONR programs from 2014-2017 this is now a commercial prototype (as per TRAPS above) for Applied Physical Sciences and Bluefin Robotics.
    - **Sensor Hosted in Autonomous Remote Craft (SHARC)** – This is a wave glider (wave and solar powered autonomous ocean robot) with an ISR sensor package and communication links to support the exchange of data between shore, aircraft, or surface vessels to sub-surface vessels. Initial wave glider development from 2007-2009 with sensor integration in 2014 and is now a commercial prototype for Liquid Robotics/Boeing.

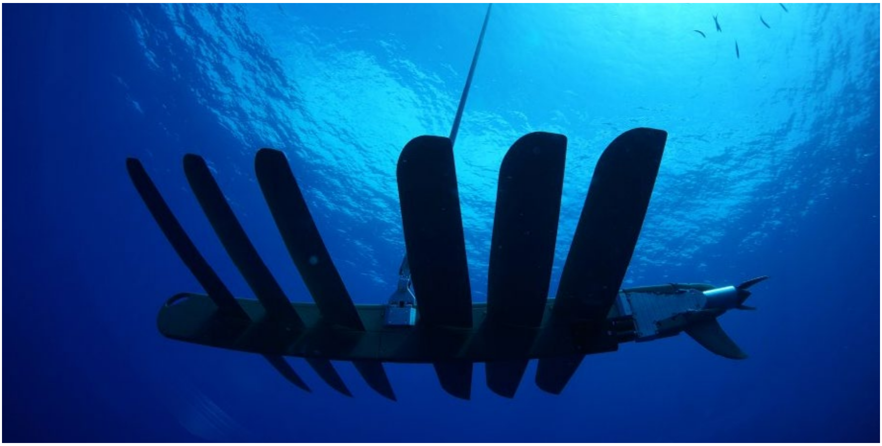

Figure 12 - SHARC at Sea

These DSS have technology and system readiness ranging from early developmental systems through to mature system prototypes. Key drivers for these DSS candidates are reduced costs and increased adaptability for deployment in a wider range of ocean environments and operational locations that are either not suitable or impracticable for FSS, MSS or tactical ASW forces. None of the above DSS candidates have matured into fully operational systems within the US-IUSS. However, there has been a recent convergence into several distinct classes of surveillance sensors with multiple exemplars of mature system prototypes and technology components that have high technology and system readiness. DSS capabilities need to be affordable, scalable and effective; capable of proactive deployment and operation with good survivability; and must provide persistent, wide-area coverage in a range of diverse ocean environments.

The Affordable Mobile Anti-Submarine Surveillance System (AMASS) is an ONR program to develop a Deployable Family of Systems (DFoS) that is focused on affordable solutions for flexible and responsive wide-area surveillance and includes the DWA, DWP and MPAS systems listed above. The initial phase of this program was first announced in February 2020. This program consolidates and builds upon previous prototype systems that have been developed under various US R&D programs over the past two decades.

Integrated Common Processor

The Integrated Common Processor (ICP) provides common processing, display and analysis functions for all fixed, mobile and deployable undersea surveillance sensors within the US-IUSS. Initial ICP development by Lockheed Martin and General Dynamics was conducted from 2003-2007 with installation at NOPF Whidbey Island in 2007, NOPF Dam Neck in 2009, and on SURTASS vessels in 2008-2009 replacing several older legacy processing systems for FSS and SURTASS. Ongoing upgrade contracts with Lockheed Martin in 2010-2017 and 2017-2022 are continuing to improve ICP functionality and deliver new processing hardware and software updates.

ICP is a derivative of the AN/BQQ-10 Acoustic Rapid Commercial-Off-The-Shelf Insertion (ARC-I) system used on United States Navy (USN) submarine sonar systems that has been augmented for IUSS requirements. Functional improvements are delivered through Technology Insertion (TI) hardware upgrades to provide improved processing hardware every 4-6 years and new passive and active sensor or communication hardware when required; and Advanced Surveillance Build (ASB) software upgrades to provide new processing functionality including improved automation, processing and display enhancements every 2-3 years. Other mechanisms such as SBIR grants and fleet-driven rapid prototyping for urgent operational needs through ONR, DARPA and NUWC are also used to support the development of new functionality for the ICP.

Undersea Warfare Decision Support System

The AN/UYQ-100 Undersea Warfare Decision Support System (USW-DSS) is an undersea warfare (USW) command and control system that enables networked-ASW forces to collaboratively plan, coordinate, establish and maintain a common tactical picture, and execute tactical control for USW missions. This provides the sea combat commander, theatre ASW commander, and ASW commander with an integrated command and control capability across all ASW platforms. The system provides networked decision-making tools in an open architecture environment that enables the near real-time sharing of key tactical data between ASW platforms and support nodes within a battlespace to reduce the search-to-detect-to-engage timeline and provide improved ASW effectiveness. The system automates and distributes many of the legacy operator and command tasks that were previously performed manually. Current applications include environmental analysis, collaborative search planning, force management, sharing a common tactical picture with networked tactical decision aids, sensor tracks and sensor metrics, automated and manual cross-platform track fusion, search execution measures of effectiveness, graphics storage and recall, and ASW briefing support.

The USW-DSS is installed in US carrier strike group platforms, SURTASS ships, embarked destroyer squadron staffs, and select shore nodes including NOPF, Commander Task Force and Theatre Undersea Warfare Operations Centres. The system interfaces with common operational picture systems such as Global Command and Control System-Maritime (GCCS-M) and Link-11/16, and shares ship, sensor, and track data from the AN/SQQ-89 Surface Ship ASW Combat System on destroyers or the CV-TSC Tactical Support System on aircraft carriers to generate and share a single, composite track picture capable of fire control. The system leverages open architecture and COTS computing environments with an iterative development program. Decision support tools employ a service-oriented architecture with existing computing hardware and communication links comprising sensor data from multiple platforms to provide rapid confidence in the decision processes between sensors and weapons.

An initial USW-DSS build was delivered in late 2009. And Advanced Capability Build 2 (ACB-2) was developed in 2013-3014 that was rolled out from 2014-2019. A new software build is currently in development in 2019-2020 that aims to enhance collaborative ASW tools, Electronic Master Tactical Plot, and expand net-centric data nodes.

System and Technology Development

Sensor Technologies

Passive and active sonar sensors supplemented by magnetic sensors are likely to remain the most important sensors for undersea warfare at least within Horizon 1 and possibly well beyond this. Many non-acoustic sensing approaches are challenging to exploit due to practical limitations on the sensor technology or its employment in operational environments or the high processing power required to achieve a viable capability (e.g., the need for large amounts of processing and sophisticated target or environment models to detect very small changes in the background noise environment caused by the presence of a quiet submarine or undersea vehicle).

Acoustic sensors have relied on many different technologies over the past 100 or more years. Piezo-electric based sensors have been the standard for much of this time and these have continued to evolve through the introduction of new advanced materials, manufacturing processes, and sensor designs or concepts. These sensors convert received pressure fluctuations in three-dimensions into electrical signals that can be processed to detect broadband signals within a frequency band or narrow band structured signals via a range of non-coherent or coherent processing techniques. Each acoustic sensor can be designed to provide omni-directional or directional responses, and these are typically incorporated into multi-sensor arrays of varying shapes and sizes that can provide further spatial directionality using array beamforming techniques that reduce the background noise to improve the detection of incoming signals and provide better estimates of the angles of arrival of these signals.

More recent advances in sensor technologies include the use of single-crystal piezo-electric materials and a range of fibre-optic (or hybrid) sensor technologies that provide smaller, more efficient and more robust sensor designs. Most of these sensors already provide sensitivity and sensor performance that are below the lowest (sea state zero) ambient noise levels within the ocean environment so further increases in sensitivity are not necessarily a driver for further development.

Further improvements in sensor directionality can be achieved through the use of small groups of sensors such as triplets or quad-elements that are being introduced into towed array designs to overcome left-right ambiguity and provide increased background noise and reverberation suppression, particularly for surface ship towed active sonar arrays. Larger groups of sensors are also being incorporated into more complex sensor array structures for new volumetric or conformal array designs, particularly for submarine bow or flank arrays. These produce large amounts of sensor data so increased processing power and automated processing are key enablers for realising these types of arrays.

In some applications, further improvements in sensor directionality can be achieved through the use of small groups of sensors such as the triplets or quad-elements that are used in some towed array designs such surface ship active sonar towed array receiver modules to resolve left-right ambiguity and provide increased background noise and reverberation suppression. Larger groups of sensors are being incorporated into more complex sensor array structures for new volumetric or conformal array designs, particularly for submarine bow or flank arrays, to provide increased angular resolution and detection performance. These arrays produce large amounts of sensor data so increased processing power and automated processing are key enablers for realising these types of sensor systems.

Acoustic vector sensors that provide three-axis sensor measurements of incoming pressure waves (or acoustic particle velocity) in addition to pressure fluctuations are also increasingly being introduced as individual sensors or in horizontal or vertical line arrays that being used for deployable surveillance systems. By exploiting the extra signal information received by arrays of vector sensors it is possible to significantly improve estimates of the direction of arrival for received sound signals and further suppress unwanted background noise with simpler array structures than would otherwise be possible. These vector sensors are quite large by comparison with standard piezo-electric sensors but are only just starting to reduce to practical sizes with the introduction of single-crystal piezo-electric sensor components.

Acoustic source development is largely focused on new materials for high-power active transducers and transducer element or source array designs that are more compact and efficient in both transfer response and power usage. Drivers for the development of new source technologies include operation at lower frequencies, over wider frequency bands, and to support more complex signal transmissions with reduced signal distortion. Flexible signal generation and power amplification are also important in the design of these sources.

Other system characteristics such as improved electronics or optics, telemetry, power generation and distribution, and simpler construction for more robust and easier deployment are also important for the design of acoustic sensors and sources.

New magnetic field sensors are continuing to evolve with introduction of new magneto-strictive materials and fibre-optic (or hybrid) sensor technologies. Traditional magnetometers can detect the ferromagnetic hull of a submarine at ranges up to several hundred metres. The introduction of new, more sensitive approaches such as Superconducting Quantum Interference Devices (SQUIDs) offer the potential for longer detection ranges, but these are currently limited by practical challenges including sensitivity to background noise and the need for super-cooling, which may be difficult to overcome in undersea surveillance applications. Magnetic sensors are increasingly being combined with acoustic sensor arrays for more robust detection in shallow water environments. Electric field sensors for the localised detection of surface or undersea platforms and vehicles continue to be developed for some niche applications but the performance of these sensors is often limited by background noise issues.

The detection of submarines from above-water using non-acoustic sensors has been around for almost as long as sonar. Technology development for tactical platform sensors such as magnetic anomaly detection, radar periscope detection and other imaging approaches that exploit features on the ocean surface which originate from submarines operating on or near the surface is expected to continue into the future.[30]

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[30] Scourzic, Daniel, Op.cit

However, much of this development is being driven by increased processing capabilities that better exploits and automates the processing of huge volumes of raw sensor data, rather than improvements to the sensor technologies themselves.

Electro-optic sensors that can exploit different wavelengths of light including the ultra-violet, visible band, near infra-red and infra-red are driving the development and increasing use of multi-spectral and hyperspectral imaging methods. These sensors can combine information from different parts of the electromagnetic spectrum to detect subtle changes in the environment or objects within the environment that may be difficult to see in individual frequency bands. There is some potential for the application of these sensors for the detection of submarines or undersea vehicles operating on or near the sea surface, but it is not yet clear whether these approaches will be useful in other circumstances.

Other non-acoustic sensor options such as light detection and ranging (LIDAR) using blue-green lasers, anti-neutrino detection and satellite based wake detection are generally considered to be worthy of further exploration. LIDAR sensors using red lasers have been used for several decades to measure shallow water bathymetry and to detect sea mines down to depths of 50 metres.[31] The introduction of new blue-green laser technologies that can provide increased detection capabilities down to 100 metres or more are currently being explored and will allow these systems to be used in a wider range of undersea surveillance applications. Anti-neutrino detection has so far been impractical due to the size and nature of the sensors required to detect these particles and is challenging to due to high background noise from solar neutrinos. Wake based detection is largely conducted by visual or electro-optical imaging methods as described above.

Laser-based photo-acoustic sensors that can detect acoustic vibrations on the surface of the water through laser interferometry are also being explored but these are still relatively immature. This approach has been demonstrated in laboratory and benign environments but suffers from many practical challenges in more realistic open ocean environments particularly in higher sea states and wind conditions.

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[31] Ibid

The use of above-water sensing approaches at significant altitude, or even from space, where the sensor field of view can be steered over wide areas of ocean are of increasing interest.[32] This is due to the introduction of longer endurance medium-high altitude un-crewed aerial vehicles and the proliferation of new satellite technologies, such as low earth observation satellites and micro-satellites, that are rapidly emerging for a wide range of sensing and communication applications. The challenges of realising many of these systems are the high sensor resolutions and wide angular coverage which produces large amounts of data that needs to be processed with automatic detection and classification to make them viable in practice.

Many of these sensing methods are also only useful for detecting submarines and undersea vehicles when they are operating at or near the surface so are generally not applicable to many important scenarios or environments.

Figure 13 - Low earth observation satellite

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[32] Marouchos, Andreas, Op.cit

Signal Processing and Computing Technologies

Signal processing developments over the past few decades have shifted from dedicated custom computing hardware to software-based applications running on standard commercial-off-the-shelf (COTS) computing hardware. The increasing use of common processing systems that use modular software and hardware architectures to enable faster system processing development, integration and testing allows the same general processing hardware to be leveraged across many different Navy sensor processing development and upgrade programs. This has also accelerated the use of new computer processing features, architectures and methodologies that can be more easily leveraged from commercial research and development.

Some important research areas relevant to sensor processing for undersea surveillance systems include adaptive signal processing, signal estimation and analysis, automated detection and classification, target localisation and track estimation, and sensor control and optimisation. These processing techniques have been applied to a wide variety of new sensor arrays with larger numbers of sensors, cooperative processing between multiple passive and/or active sensors, integrated processing across widely distributed sensor networks, and the fusion of sensor information from multiple diverse sensor types.

Some important sensor processing challenges relevant to undersea surveillance have included:

- Advanced signal processing to support new sensor arrays including vector sensor, volumetric, and conformal arrays to provide increased sensitivity, bandwidth or directionality.
- New sensor signal processing to better exploit new sensor arrays with increased cooperative, integrated and networked sensor processing and fusion.
- Improved passive sonar processing to reduce the impact of high ambient noise and shipping noise in shallow water environments.
- Improved active sonar processing to reduce the impact of clutter, false alarms and reverberation in shallow water environments.

- Advanced active sonar waveform design for improved detection and classification performance particularly in complex shallow water environments, including waveforms with improved Doppler sensitivity to better detect slower speed targets and structured sequences of complex waveforms to provide improved target detection and classification.
- New sensor information processing for improved detection, classification, localisation and tracking with multiple complementary sensor modes or diverse sensor types, including distributed localisation and tracking using sensor networks. The fusion of different signal types and better models of the ocean environment have the potential to distinguish target signals or anomalies with much greater discrimination.
- Automated detection, classification, localisation and tracking that leverages advances in machine learning and artificial intelligence. Automated classification of quiet submarine targets by passive and active sonar sensor systems is one of the most challenging problems for undersea surveillance.
- Improved sensor processing, scheduling and control for optimal system performance through exploitation of detailed environment and threat models.
- Increased operator efficiency (or workload reduction) through automated sensor signal, detection and classification processing.
- Improved command and control support. New collaborative multi-sensor optimisation tools for operator or command decision aids and mission planning.

Advances in new computer and processing technologies are important enablers for new sensor processing algorithms and their implementation in operational sensor systems. Quantum computing, edge processing, data storage and retrieval, artificial intelligence and machine learning, and big data processing are all likely to fundamentally change the way sensor signal processing, analysis and estimation will be envisioned and applied in the future in ways that are difficult to predict.

For remote undersea surveillance systems, as in any distributed autonomous sensing network, a core issue is the volume of sensor data, it’s location in the network, and the viability and cost of data transport. It is likely that some ‘leaf’ sensor nodes on the network will have limited ability to communicate back to a central processing node, so much of the processing will need to be done at the edge of the network. For other sensor nodes, limited power and space for advanced processing capacity may require the transfer of large amounts of sensor data for centralised processing and analysis. In the extreme case, an autonomous sensor may only have bandwidth to communicate when it discovers a high value detection. How can users of this network have trust in what they receive when current sonar requires significant analysis and interpretation by a human operator; when automatic detection and classification has not yet reached sufficient maturity or reliability; and where limited communications bandwidth may preclude providing sufficient analysis evidence to support independent verification by a human operator to underpin command decisions.

Edge processing, which is the ability to process data away from a central hub or headquarters, and cloud computing, which refers to a distributed computing architecture where computing and analytical power is dispersed across a wide range of servers and locations, both have significant relevance to command and control for a wide variety of military applications. As these approaches become more sophisticated and integrated into military platforms and systems, there will be increasing amounts of information available to inform decision making during planning and execution of operational activities.

Distributed networks and edge sensors are able to provide more dynamic management of bandwidth as the cloud is able to reconfigure itself in terms of storage and transmission. Micro edge processors can be activated on demand, meaning that they are not consuming bandwidth when not in use. This in turn allows for time-sensitive information from the battlespace to be transmitted with low latency to those who require it. The private sector is leading the way in this space. If the ADF wishes to take full advantage of these advances, particularly in cloud computing, it needs to find more effective methods of leveraging these innovations.

While cloud-based technologies may provide great opportunities for information management and the integration of networks, further research is required to understand what ‘gateways’ and protocols are required for military integration.

Distributed sensor processing is an emerging technology where many, smaller sensors are distributed as an array across a large area and create a very wide sonar aperture. The sensors ‘talk to each other’ and use their collective computational power to process the huge amounts of data collected, all while keeping inter-node communication minimized to save energy. This is still a challenging problem due to the physics of the ocean and some of the limitations of sensing and communication in the undersea environment. The processing power of quantum computing might be able to solve the problem of classification, distinguishing between different contacts and working out ranges. Acacia Systems is currently investigating this technology.[33]

Figure 14 - Gadi Supercomputer

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[33] Blake, Commander Steven, Interview with Ash Colmer, 25 Apr 21

(Future) Sensor System Drivers

In addition to new sensor and processing technologies, there are many sensor system design drivers and new concepts that are evolving the way these sensors systems are employed and operated in the undersea environment. These vary between different sensor types and applications but there are some design features that are common across many systems, including:

- New sensor technologies to develop smaller sensors to allow easier packaging and deployment;
- New active acoustic source technologies to increase surveillance coverage and contact rates;
- Advanced energy systems to increase sensor endurance;
- In-sensor DCL processing to reduce communication bandwidth requirements for reporting;
- Common processing architectures and techniques;
- Standard packaging and deployment concepts (e.g., from sonobuoy canisters, shipping containers, etc.);
- Automatic deployment, operation and maintenance of sensor arrays including methods for minimising array deformation or calibrating sensor locations to prevent degradation of sensor performance;
- Improvements in space, weight and power, and cooling (SWAP-C) to reduce system size and increase system endurance;
- Advanced communications for reliable and secure data transfer;
- Networked underwater and above-water communication to exchange sensor and tactical data (e.g., using acoustic communications or fixed cables to shore, communication repeater nodes, surface buoys or surface platforms);
- Adaptive sensor management and algorithms to optimise the use of environment and intelligence mission data; and
- Undersea warfare decision aids and tools to assist tactical operators and commanders to optimally employ, operate, and respond to undersea threats.

Some design drivers for deployable surveillance sensors that are relevant to remote undersea surveillance include:

- Affordable, scalable and effective performance;
- Proactive deployment and operation with good reliability and survivability;
- Increased robustness and adaptability for faster deployment in a wider range of ocean environments and by more diverse means; and
- Persistent, wide-area coverage in diverse ocean environments using distributed sensor networks that are integrated with crewed and/or autonomous platforms and other available information sources.

Integrated ISR

Theatre Undersea Warfare, all sensor data and information extracted from each of the tactical platforms and undersea surveillance systems outlined in this section needs to be combined to generate a single Common Operating Picture (COP) for a given region of interest. The generation of this COP is provided by a centralised Command and Control organisation that further processes the sensor data and information, and fuses it with analysis, intelligence, environmental and other relevant information to contextualise, interpret and understand the COP.

A decision support system, such as the USW-DSS described earlier, provides the tools for command to develop this COP, distribute to fleet tactical platforms, and to conduct mission planning with real-time feedback to inform command decisions. In its most ambitious form, the USW-DSS is attempting to implement a near real-time, distributed warfare network that enables command to develop and refine mission planning. This then connects to each tactical platform and sensor node within the network and enables low-latency, integrated intelligence, surveillance, reconnaissance and response options. In effect, connecting all relevant platforms and sensors for the joint localisation, targeting and potentially engagement of an undersea threat in a coordinated way.

For remote undersea surveillance systems, the unique challenges posed by underwater acoustic propagation, automated processing, reporting via potentially complex communication channels, and time to analyse, interpret and respond to undersea threats all impose significant latencies that need to be properly accounted for in order to achieve the effective coordination of surveillance and tactical nodes and optimise their tasking and contributions to achieve the desired mission outcomes.

RUS & autonomy

Autonomy - freedom from external control or influence; independence.

The RAN’s RAS-AI Strategy 2040 defines ‘RAS’ (Robotics and Autonomous Systems) as a term used by academic, scientific and technology communities to describe the physical (robotic) and cognitive (autonomous) aspects of a system (or platform). Defence uses this term for systems that perform a function on their own by being either physically remote from a human operator, performing cognitive functions on behalf of a human operator or, (increasingly) both.[34]
In the undersea domain, autonomy spans everything from data processing, maintenance, sensing, and system sub-components, through to the conduct of undersea operations themselves.

Figure 15 - Sea Hunter USV

Autonomous systems remove the restriction of requiring the sensor to be attached to or near a manned platform. The more autonomy that can be incorporated into RUS systems, the more benefit that will be achieved. Autonomous underwater vehicles allow for the opportunity to deploy sensors, particularly acoustic sensors, in places where it would otherwise be hard to deploy them and where they can greatly enhance situational awareness through object identification, understanding and tracking.[35]

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[34] Royal Australian Navy, RAS AI Strategy 2040, p8.
[35] Duncan, Alec, Interview with Ash Colmer, 11 Feb 21

In particular, it could enable the smart placement of sensors far below where a submarine can operate either to exploit the deep sound channel for very long-range acoustic detection and underwater communications, or to exploit the reliable acoustic path for upward looking acoustic detection or communication with platforms or systems operating on or near the surface.

Advances in autonomy are all about decision making, that is decisions made entirely by the unmanned platform without human intervention. These may be decisions for devices to follow or investigate a potential target; or decisions regarding what, how much and how to communicate priority information. There are opportunities for large numbers of autonomous devices to 'self-organise' as they cooperatively conduct their mission. They may need to rearrange their formation to take advantage of transmission pathways, undersea terrain, or to compensate for the loss of a node within the network.[36]

There is no doubt that autonomy is the future of Ocean Observation. However, the significant challenges imposed by the undersea domain have led to delays in realising the benefits of these systems compared to the air and land domains. This is largely due to the harsh operational constraints of the undersea environment, where sensing and communications are more challenging, navigation cannot rely solely on GPS, and where pressure, salinity and biofouling are the great enemy of nearly all man-made systems.

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[36] Manzie, Chris, Interview with Ash Colmer, 1 Mar 21

For autonomous capabilities to be of any value to RUS, and here we mean the ability to carry out military missions successfully, there are four key considerations - mobility, persistence, scale and effectiveness. These should be considered in addition to the vehicle SWAP-C requirements to support sensor and payload systems for undersea surveillance.

- **Mobility** – The ability to go where you need to go.
- **Persistence** – The ability to maintain a presence in very harsh conditions for extended periods.
- **Scale** – The ability to build and maintain a presence that does so more cost effectively and over a far wider expanse than a vast fleet of submarines, surface ships and maritime aircraft could achieve.
- **Effectiveness** – The ability to detect and classify a required target set and input that detection into the C2 system to enable timely decision making.[37]

It is relatively easy to create an autonomous system. It is much more difficult to create one that is capable of undertaking complex missions independently with an ability to adapt and respond to changing circumstances that might impact its operation, security or survivability without human intervention. Engineering reliability and redundancy issues need to be dealt with – for example if one pump fails, what is the design for options for a second pump to replace it, and then for the decision to return back to base or to a safe location for recovery and repair?

These considerations are significant, especially given that a strong driver for the introduction of these systems is the requirement to conduct missions of much longer duration and in remote locations or environments that are unreachable or unsafe for the manned platforms that they are supposedly replacing. They will require very sophisticated on-board architectures that enable the complex management required to control and operate the system as a whole and all of its component sub-systems.

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[37] Marouchos, Andrea, Op.cit. However, the authors have added ‘effectiveness’ as a fourth consideration

To make such a platform safe you need a diverse collection of sensors for operation, navigation, communication and specific mission payloads that are integrated into a central decision-making system that may, at any time, be presented with multiple dilemmas. For example, ‘safety decision making’ may override ‘mission decision making’ to avoid a collision with another object.

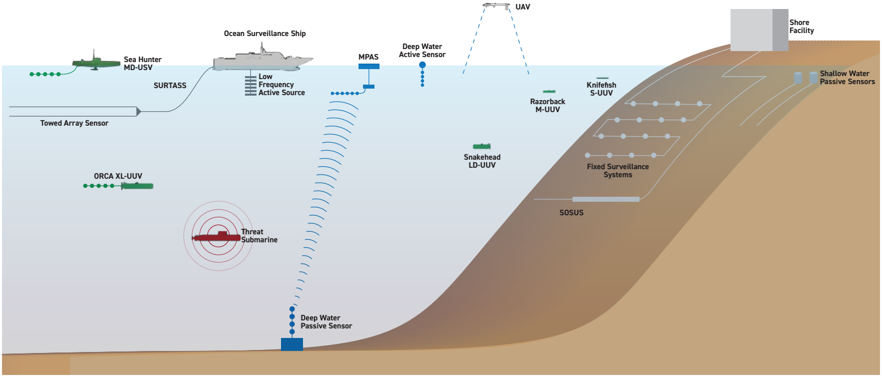

Figure 16 – Potential RUS System of Systems

Un-crewed Undersea Vehicles

Technology may overtake the need for manned submarines in the future, but for the foreseeable future, they are the most potent strike capability in the ocean, and they remain difficult to detect. However, there will be an increased demand for undersea characterisation and an ‘arms race to process and send data’, and to increase decision support for the undersea domain.

Part of this ‘arms race’ is the requirement to grow autonomous capability and to understand how various types of platforms act independently, or as part of a network, to provide the most cost effective and robust decision support. This cost effectiveness should not be considered within just a narrow RUS perspective, but as part of enabling the full spectrum of undersea warfare which include both detection and response options. As discussed above, it must be assessed in terms of SWAP-C requirement as well as its ‘mobility, persistence, scale and effectiveness’ and its potential growth path that, in the distant future, may lead to a lesser role for manned submarines.

To allow discussion about what the most suitable capabilities, or mix of capabilities might be, we have adapted the United States' taxonomy presented to Congress in 2016 to describe and categorise Un-crewed Undersea Vehicles (UUVs). While also sometimes referred to as Autonomous Undersea Vehicles (AUVs) their levels of autonomy will vary from none, or virtually none (e.g., remotely operated vehicles); to full autonomy.[38] UUVs are platforms that:

- Conduct operations below the sea surface;
- Are un-crewed and do not have a 'human-in-the-loop' as part of their mission decision making ability; and
- Possess propulsion capability in order to complete their mission.

UUVs are grouped into three broad classes:

- Self-propelled;
- Environmentally powered; and
- Other systems.

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[38] United States Navy, CNO Report to Congress: Autonomous Undersea Vehicle Requirement for 2025, 18 Feb 16, pp5-6

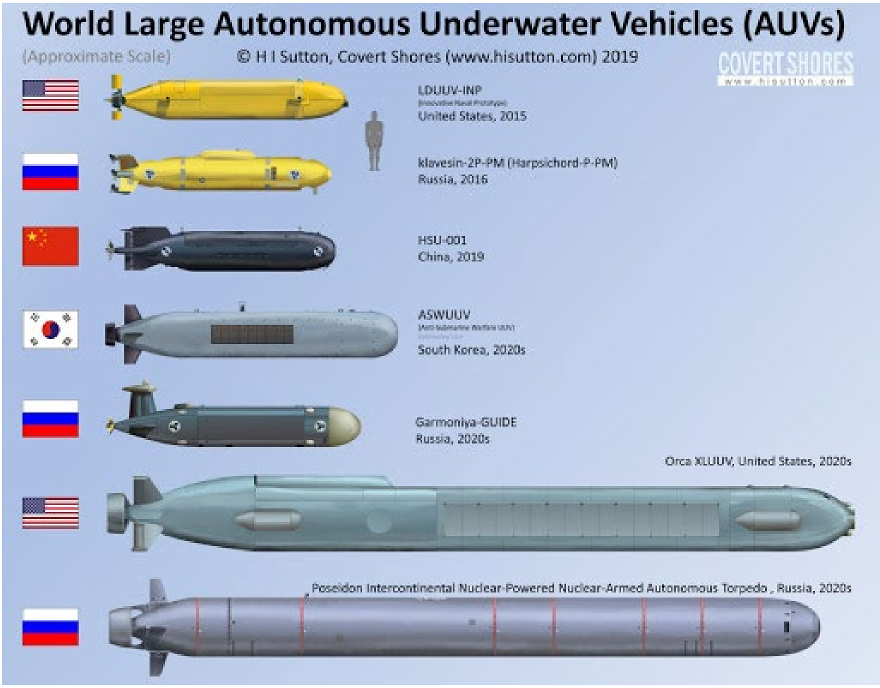

Figure 17 - Current and Future UUVs in the Indo-Pacific

Self-Propelled UUV Classes

There are four UUV size classes: extra-large, large, medium, and small. All but the largest are deployed from a host platform.

- **Extra Large UUVs (XLUUV)** – have diameters larger than 84 inches (2.1336 metres) and are shore or ship launched with appropriate handling facilities such as cranes, well-decks etc. They are in principle capable of ‘pier-to-pier’ operations. Their holds are large enough to store and deploy smaller UUVs and sensors.
- **Large UUVs (LUUV)** – have diameters between 21 and 84 inches (53.34 centimetres and 2.1336 metres) and are currently deployed by USN submarines. They may also be launched from shore or surface ship and require appropriate handling equipment to support stowage, launch and recovery from seaborne host platform. Like the XLUUV, they may also be used to deploy smaller UUVs and sensors.

- **Medium UUVs (MUUV)** – have diameters between 10 and 21 inches (25.4 and 53.34 centimetres) and are also launched from submarines (depending on the class, usually via standard torpedo tubes), surface ships, USVs and from shore. They can be recovered back on board a manned surface ship using standard handling equipment.
- **Small UUVs (SUUV)** – have diameters between 3 and 10 inches (7.62 and 25.4 centimetres). They may be man portable and may be deployed from a variety of platforms including larger UUVs and USVs.

Environmentally-powered UUVs

Some argue that we should invest in more underwater glider capability, while others argue that they offer limited RUS capability. Underwater gliders are relatively inexpensive, have long endurance and are both very efficient in terms of energy and are also very quiet. They may be used for some forms of undersea surveillance, but are more suited to the collection of environmental data to support submarine and undersea operations. Collection of that data, and the denial of that data to an adversary will continue to be an important source of friction.[39]

The main issue with gliders is their limitations on payload. Even larger gliders have very limited payload capacity. SWAP-C constraints and hydrodynamic characteristics limit the types of sensors that they can carry. However, they may have potential to provide support to, or collaborate with, other autonomous platforms or sensors such as providing other functions like communications nodes.

Gliders may be categorised as either ‘buoyancy’ or ‘wave’ gliders.

- **Buoyancy Gliders** - Instead of propellers or thrusters gliders use ‘variable-buoyancy propulsion’. They seemingly ‘fly’ through the ocean by changing buoyancy to alternately sink or rise to the surface. They use wings to create lift, and a rudder to steer them slowly through a pre-programmed route. At a certain depth, the glider switches to positive buoyancy to climb back up and forward, and the cycle is then repeated. This method of propulsion limits speed and some that are augmented with a propellor may be capable of speeds up

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[39] Battle, David, Interview with Ash Colmer, 26 Feb 21

to one or two knots for short periods. Power is generally conserved for sensor payloads and communications. Their endurance though, can be measured in months. They are capable of operating in depths up to 2,000 metres and can be deployed from surface platforms or from the shore.[40]

- **Wave Gliders** – Wave gliders consist of a surf board like float attached to a semi-stiff umbilical attached to a glider fitted with 'winglets' several metres below the surface. Wave motion is converted to thrust by the winglets (which may be augmented by a 'propulsor') to reach speeds up to two knots. The float will carry batteries which may be recharged by solar cells). They are both ship and shore launched and have endurance measured in months.

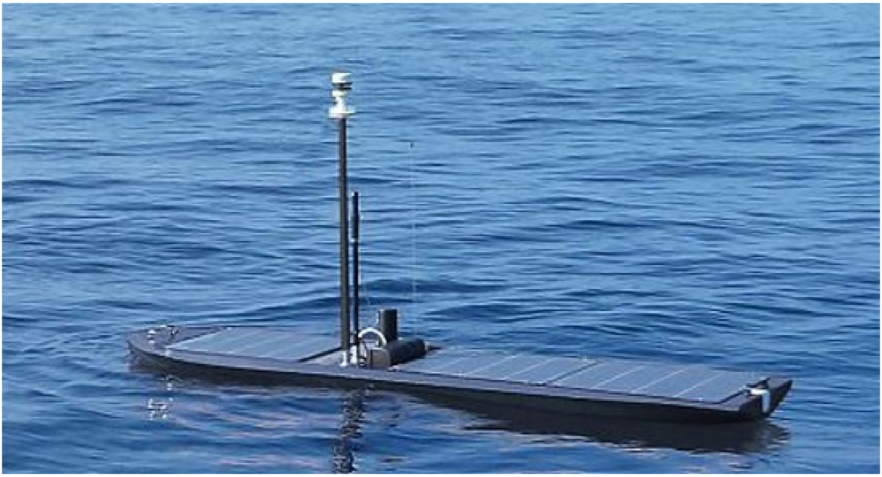

Figure 18 - Wave Glider at Sea

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[40] Lundquist, Ned, 'Subsea Defense: Navy Deepens Commitment to Underwater Vehicles' in Marine Link https://www.marinelink.com/news/subsea-defense-navy-deepens-commitment-485303, accessed 26 Mar 21

Reliability and Trust

The key issue for autonomous systems, no matter where they are employed, is trust. If they are reliable, then those who seek to employ them will trust them. To achieve this, they must exhibit the right behaviour at the right time, even with unforeseen situations, and be able to 'persist' with the mission despite adverse environmental or operational effects. If something goes wrong will an autonomous RUS platform or sensor adapt to another process to allow it to keep continuing with its mission?[41] The level of reliability and its implementation across the platform and all relevant subsystems will also depend on the overall cost, complexity and the disposable versus reusable nature of the system. Failure of key components may make it impossible for the platform to return home for repairs and it might be too expensive to be disposable thereby requiring logistics and support arrangements to enable them.

The autonomy of UUVs will remain constrained, however, by imperfect situational awareness. For example, while a UUV may have the computer algorithms and control systems to avoid safety hazards or security threats, it may not be able to understand with certainty where hazards and threats are and what they are doing. In the face of uncertain data, a human operator can make choices and be accountable for the results. Commanders may not want to place the same responsibility in the hands of a UUV control system—or its programmer.[42]

The US Navy's 2016 Report to Congress clearly explains the extent of these constraints. Achieving intelligent levels of comprehension of "purpose" within UUVs in the undersea warfare during Horizon 1…

> '…will be difficult given the inherent C2 challenges. Autonomous systems with organic decision making capability (and not just a narrow range of pre-programmed responses to potential changes in operational conditions) will take time and dedicated effort to develop and reliably demonstrate. Complete autonomy may not develop linearly without incremental experience and learning informing subsequent steps. Lacking sufficient sensors, the power it takes to run these sensors and onboard information processing hinders an organic capability to interpret unexpected conditions outside those for which an autonomous system is designed.

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[41] Frankish, Glenn. Interview with Ash Colmer, 22 Feb 21
[42] Clark, Bryan, Op.cit p4

> To mitigate this shortfall, a…(UUV)… will rely on external communications and a manned command center or node with the incumbent operational risks and potential delays that these external communications entail.'[43]

Furthermore, the Report states that UUVs will be restricted to performing specific tasks such as bathymetric collections, bottom surveys, and mine warfare related tasks.

> UUV tasks will improve overall Undersea Warfare (USW) performance and capability; extend the reach of the host's organic visual, acoustic, and electronic sensors to detect targets outside its current range of influence; and, as UUV endurance and tasking experience grows, increasingly facilitate the simultaneous execution of multiple missions by host platforms, eventually including multi-mission autonomy from UUVs.[44]

Communications and Processing

If research and development can overcome all of the wicked challenges thrown up by both the undersea environment and a contested battlespace, then increased processing power, artificial intelligence and machine learning may ultimately enable UUVs to act more autonomously in a growing number of scenarios. They may be increasingly capable of making informed decisions and sharing information with other such platforms or back to a 'mother ship' without operator intervention.

There are many options for how this information may be communicated. Via satellite, line-of-sight communications, relayed via aerial vehicles, or any combination of these well may be plausible if we can work out how to do it securely. The next step would be to work out how to conduct the signal processing on board and feed tracks and other information back to an operator whilst keeping the data rates low and reducing the chance of detection.[45]

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[43] United States Navy, CNO Report to Congress: Autonomous Undersea Vehicle Requirement for 2025, 18 Feb 16, p7
[44] Loc.cit
[45] Cain, Tim, Interview with Ash Colmer, 12 Feb 21

However, the additional constraints that may apply to UUVs regarding self-protection, security or other operating constraints will impact the realisation or development timeframes for them. How long it takes to develop the capability required at affordable cost to achieve these benefits remains to be seen.

First and foremost, the communication problem underpins all of the other problems that need to be tackled. Incorporating more efficient electrical and electronic systems and higher density power supplies are challenges that will be solved over time. Smaller batteries and more effective energy harvesting techniques will emerge.[46] This may result in a preponderance of smaller, cheaper and possibly disposable sensor fleets. However, the additional challenge to this concept, is that sensor capabilities do not scale well underwater with the best long-range sensors being physically much larger and with significant SWAP-C requirements that may not be compatible with the smaller, cheaper and disposable logic in this argument.

Understanding the balance between size, cost and surveillance capacity per system and total number of systems required to provide wide area coverage and persistence is not well understood at the moment (and will likely vary considerably across different ocean environments and operational scenarios). This is without the added layer of survivability and reliability in remote and potentially contested environments.

Power and Endurance

The power onboard a UUV is critical for it to achieve its mission. Power is fundamental for it to generate the mobility and persistence required for it to get to where it needs to go in effective time, stay there or follow a potential target at matching speed. Power is fundamental to the operation of its onboard sensors, systems and propulsion and is fundamental to the SWAP-C considerations for the design of all autonomous systems.

New power and control technologies are improving the endurance and reliability of UUVs. This may ultimately see them able to operate un-refuelled for months within the next decade.

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[46] Manzie, Chris, Op.cit

This could depend on how payloads for sensors, processing, counter-measures etc. evolve which might grow faster than advances in power and control technologies as well.

Advances in battery technology, or other kinds of power generation may provide the breakthroughs needed for UUV endurance. However, there may be some alternatives. As discussed above some gliders have solar panels attached to assist with power generation and other autonomous systems move to and from the surface to either acquire solar energy or to create ‘variable-buoyancy propulsion’. If the surface is denied, then other forms of undersea energy creation may need to be examined. While the ‘burning of seaweed’ or other undersea organisms (demonstrated by continued research into microbial fuel-cell batteries) may be considered as a technically plausible way of generating power, how this might be done by a UUV conducting specific RUS missions, firmly sits in Horizon 3 discussions.

On the other hand, the development and deployment of ‘support UUVs’ such as XLUUVs or ‘docking stations’ fitted with on-board recharging capabilities, may enable a fleet of UUV in the same manner that a ‘tanker’ supports a fleet on the surface.

Navigation

One of the biggest issues in the undersea domain is navigation. UUVs must be capable of navigating to and from their area of operation, safely avoiding obstacles and detection, and, if necessary, following an object of interest. There is no ‘Undersea GPS’. Geographic features used for localisation above ground are not as accessible underneath the sea. Away from shallow waters, visibility is low, and all looks the same from the sea floor to just below the surface. We need to understand how we can work collaboratively across fleets of undersea devices and vehicles to solve this localisation problem without pushing elements to the surface. The answers to this problem may lie with a combination of selective communication and edge computing and autonomous systems themselves that may be able to make reasonable decisions regarding where they are and what they should be doing and then communicating back to the command and control node.[47]

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[47] Manzie, Chris, Op.cit.

Networks of navigation beacons to provide differential localisation may solve this problem, but the scalability and extent of such a network would be very cost prohibitive across wide areas of ocean.

Survivability and Security

We must always remember that the RUS problem is a warfighting problem. Therefore, any RUS solution must not only be capable of enhancing decision support within the undersea domain, but be able to do so despite an adversary's best efforts to confuse it, interdict it, or destroy it. Consideration as to 'where' it is deployed to, when it is active or passive, adversary threat capabilities - counter-surveillance, cyber and/or kinetic-, in-built counter-measures and deception, as well as the relative 'pay-off 'opportunities will tax our future capability developers. The detection and destruction of a three million dollar MUUV whose surveillance activities led to the destruction of a nuclear submarine would appear to be a high pay off investment. The 'scooping up' of the same MUUV in a fishing net and the exposure of its on-board technology and classified mission systems may present an equally high pay off for an adversary. Large numbers of small, cheaper, and less capable SUUVs, may present less of a risk than a small fleet of highly capable, expensive XLUUVs and/or LUUVs.

While most of the discussion seems to be about the detection of submarines, detection of those systems that seek to detect submarines is an equally important aspect of undersea warfare. An adversary will be equally aware of the need for counter-surveillance. They will be seeking our RUS systems and this game of 'cat and mouse' will continue until one side can 'see' everything under the ocean's surface. This is unlikely to occur until beyond the third horizon, or ever. So, our operational concepts will be an important contributing factor to the survivability of our RUS systems.

Does Size Matter?

The solution to the RUS problem cannot be an ‘all seeing, transparent ocean’. This ‘utopian’ solution would require a complete network of fixed, deployable and mobile remote surveillance systems integrated persistently and almost perfectly with the full spectrum of national and allied undersea warfare capabilities and unpinned by a vast of vast fixed undersea communications infrastructure. What we actually seek is the most cost effective solution to provide us with the best possible RUS solution as soon as possible, and for as long as possible. Investing in the full spectrum of UUVs may be cost prohibitive. We need to understand what the best future mix of these capabilities needs to be to meet our future contingencies.

The key development within the US is the adoption of families of autonomous systems of all the different sizes that are being developed to support differing mission sets. These are being designed from the outset with commonality and modularity in mind to ensure the sharing/leveraging of developments in autonomy, control, communication, sensors, hardware, system/sub-system components etc across the families of systems across all domains.

For Australia, we need to understand what our mission sets need to be and potentially ‘cherry-pick’ the most suitable categories. Or we can simply narrow the problem down to two approaches. One using large networks of relatively cheap less capable devices spanning large amounts of ocean versus a few, much larger, devices employing much more capable sensors at strategic locations that exploit the environment. They might be ‘looking up’ from deep on the sea bed, exploiting their wide aperture. They might be deployed where they may be able to achieve very long range communication by exploiting the different channels within the ocean’s acoustic environment.[48]

In comparison to small, relatively inexpensive UUVs, large UUVs have increased endurance, speed, and an ability to carry an increased sensor payload which may be attached to the vehicle and oriented where they can be most useful.[49] Smaller platforms are relatively cheap and easier to handle, but they are limited in what they can do – limited endurance and speed, carry smaller sensor payloads which

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[48] Gleed, Matthew, Interview with Ash Colmer, 23 Feb 21

[49] Colby, Simon, Interview with Ash Colmer, 19 Feb 21

are in turn limited to where they can be placed on the vehicle without hindering its mobility. Large UUVs, in turn may also deploy and recover smaller autonomous vehicles and act as a hub, or 'mothership' for a networked 'constellation' of undersea sensors.[50]

Currently, the US and the UK, and one can assume the Russians, Chinese and other countries too, are experimenting with these larger UUVs. By going bigger, you unlock so much more potential capability. Larger UUVs are generally more expensive[51] and harder to deploy and maintain, but they potentially offer an exponential increase in capability and open up a whole new range of missions that cannot be done with smaller vehicles. There is still a long way to go to realise the higher end potential for larger UUVs and, as with nearly all undersea surveillance dilemmas, there are risks. In the end, the user must see the value in this investment.

Figure 19 - Orca XLUUV

XLUUV – At the moment the US Navy, along with Boeing, is developing the Orca Extra Large Unmanned Underwater Vehicle (XLUUV). Based on Boeing's Echo Voyager prototype UUV, the 15.5m-long submersible could (with appropriate levels of development time and effort) be used for mine countermeasures, anti-submarine warfare, anti-surface warfare, electronic warfare and strike missions.[52]

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[50] Loc.cit

[51] Sammut, Karl, 'Pricing would indicate that cost does not increase linearly with volume. The majority of the cost is in the electronics, making the XLUUV much cheaper per unit volume than a SUUV.'

[52] Cain, Tim, Op.cit.

Importantly, XLUUVs are too large to be launched and recovered by other platforms so will present some unique challenges.

Some believe that we should be jointly investing in ‘Orca’ now. Michael Shoebridge from ASPI recently argued that investment in ‘Orca’ now will bring the most undersea combat power most quickly to Australia’s military. He argues that the opportunity is there for Defence to take advantage of favourable market conditions now and establish a close partnership with the US Navy and US and Australian industrial partners to develop and field Orca. It should collaboratively experiment with a range of different payloads, working in unison with the Collins-class fleet and extend undersea capabilities to create new undersea challenges for our adversaries.[53]

Furthermore, if we adopt this approach, he argues that the RAN will develop broad experience in the operation of large un-crewed undersea platforms in the lead up to the introduction of the Attack-class submarines. He envisages them working most effectively ‘…as part of a manned–un-crewed undersea team, less closely tethered but a bit like the rapidly developed ‘loyal wingman’ un-crewed aerial vehicle that the Royal Australian Air Force is developing and testing with Boeing Australia.’ [54]

While this all sounds reasonable, Australia needs to consider the relative benefit that an Orca-like capability will bring in the coming years. If we discover that Orca is limited to non-time critical data collection missions, we may be better served by investing in smaller, cheaper systems that can be launched from a submarine or other seaborne platforms.

And on the tail of the UK announcing its own XLUUV joint development – Manta – the USN recently better articulated the challenges and simple missions that it is trying to achieve with Orca over the next decade. RUS will necessarily pose a much greater challenge for autonomous platforms and payloads and is probably at least 2-3 decades away.

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[53] Shoebridge, Michael. ‘Australia Should Do More Than Wait for the Attack-Class Submarines to Arrive’, The Strategist (Australian Strategic Policy Institute), 9 Mar 21

[54] Shoebridge, Michael. Loc.cit

Larger, more complex, more expensive systems usually require a big business to take on the risk and have the breadth of technical skills and understanding needed to integrate the whole capability. It's not clear where the breakpoint is, though, as it's a combination of complexity and size.

The Current Situation

If we are talking about mine counter measures and hydrography, then there is potential to do much more with un-crewed and autonomous vehicles. Such vehicles offer the potential to thoroughly map the terrain accurately employing a range of sensors, such as synthetic aperture sonar and camera, consequently accumulating significant quantities of raw data (terra bytes). Because the information is not as time critical, and communication bandwidths are too constrained to permit uploading while submerged, the data must be stored on board until the vehicle is retrieved. In the future, these vehicles may have the capacity for on board processing and target recognition. They may also have an ability to communicate, or set off some kind of alarm alerting the operator, or another autonomous vehicle, that they have found a potential target or a pre-programmed item of interest that requires further investigation. 'As computers get smaller and algorithms more capable, we will be seeing this kind of capability – reliable enough to be sent on a real mission – within the next ten years.[55] However, RUS poses much more complex challenges, and it is not yet clear how important a contribution autonomous vehicles will be able to play in the short-medium term.

The key issue for un-crewed autonomous platforms in the future is adoption. Adoption implies a confidence within the user community in their capabilities, and a willingness to invest in them.[56]

Operators will need to progressively 'let go' of some of the human-in-the-loop interaction and learn to trust these systems and develop new operational concepts and procedures.[57] However, there are other legal and regulatory constraints that may stand in the way of autonomy within the maritime domain. Concept and capability developers will need to keep this in mind and work closely with the Australian Maritime Safety Authority (AMSA), Defence Legal

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[55] Colby, Simon, Op.cit

[56] Colby, Simon, Op.cit.

[57] Scourzic, Daniel, Op.cit

and other stakeholders to ensure that future capabilities are compliant and to understand where legal matters must evolve to address previously unforeseen circumstances.

To meet all of these and other emerging challenges it is important that Defence develops the necessary engagement and support mechanisms that enable collaboration across industry, academia and other key stakeholders. If we do this in an open and frank forum, one where the important questions might be discussed without fear or favour, then we might get the topology right. There are many lessons to be leveraged/learnt from autonomy from the resources sector (remote underwater vehicles, autonomous trains and trucks), Very Large Scale Arrays (e.g., Square Kilometre Array) in Radio Astronomy, and other existing surveillance systems.[58] So what is that Australia requires? How do we adapt these non-military lessons into effective RUS? 'Is it a vast array of many thousands over a large area at low cost with less capability and limited processing; or is it fewer bigger devices with more capability and endurance, but not necessarily at the right place at the right time?' [59]

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[58] Hale, Gary, Op.cit
[59] Gleed, Matthew, Op.cit

ORCA XLUUV

(‘Orca XLUUV’ Orca XLUUV, United States of America (naval-technology.com) sourced 25 Mar 21)

Orca is an autonomous extra-large unmanned undersea vehicle (XLUUV) being manufactured by Boeing to meet the growing demand for undersea operational awareness and payload delivery. The US Navy will use the XLUUV for potential capabilities such as mine countermeasures, anti-surface warfare (ASuW), anti-submarine warfare (ASW), electronic warfare (EW) and strike missions.

The long-range underwater vehicle is being developed to perform critical missions with reliability. It is expected to provide the ability to launch, recover, operate and establish communications with the vehicle from a home base away from the area of operation without the need for navy personnel.

The underwater vehicles are expected to be delivered by June 2022 under a programme to address a Joint Emergent Operational Need (JEON).

The US Navy selected Boeing and Lockheed Martin for the first phase of the XLUUV programme with the companies securing design contracts in September 2017. The programme aims to create an unmanned system that can operate independently at sea for months. The design contract awarded to Lockheed Martin was worth $43.17m, while the one awarded to Boeing was approximately $42,27m.

The US Navy intends to procure a total of nine vehicles under the programme. Boeing won a $43m contract in the second phase of the competition to build, test and deliver four XLUUVs and related support elements in February 2019. A contract modification worth $46.7m was awarded to the company in March 2019 for the production of an additional prototype vehicle, bringing the total contract value to $274m.

Boeing partnered with Huntington Ingalls Industries (HII) to design and develop new unmanned undersea vehicles for the US Navy’s XLUUV programme in June 2017.

Boeing’s winning design for the Orca programme is based on its Echo Voyager fully autonomous XLUUV, which was introduced in March 2016.

The company tested various configurations of Echo Voyager and improved the performance of the platform. The vehicle underwent the first sea trial in 2017, while the second test was conducted in 2019.

Echo Voyager has an overall length of 26m, including the length of added payload carriage. It is 2.6m-wide and weighs 50t in air.

The submersible can carry out operations for months as it is fitted with a hybrid rechargeable power system and a large modular payload bay. It is designed to operate ‘pier-to-pier’, much like a manned submarine, without the requirement of support ships.

Orca will feature a modular design with an open architecture and potential for reconfiguration. It will provide guidance and control, autonomy, navigation and manoeuvring capabilities. The XLUUV will be integrated with interfaces to allow for future upgrades to accommodate the latest technology and meet evolving threats. It will be able to travel to an area of operation, loiter there, communicate, deploy payloads and return to its home base.

An Active buoyancy control system aboard will mainly provide capabilities, including autonomous buoyancy control, seafloor mooring and forward and aft trim control.

challenges & opportunities

The purpose of Section 4 is to provide both the ‘so what’ for the future RUS problem and to list some of the more ‘out there’ potential technologies/concepts that may be worth further thought. How we combine these concepts and technologies and how we might organise ourselves to field them may provide the actual disruption to the RUS problem.

A Notion of Disruption?

> Many are happy to fund and talk about disruptive technologies, but much less keen to disrupt anything else that is being done now to adapt to new challenges. [60]

There are plenty of opinions regarding where Australia’s RUS R&D investment should be targeted, however, as in all endeavours to predict the future, the focus cannot be too narrow. We cannot aim to illuminate the ocean within the next 20-30 years, and, even if we could, how could we monitor it? Decisions will require some ‘hedging’ and contingency. The decisions must be made within the context of the undersea environment and the constraints of the undersea battlespace; and within the full spectrum of undersea warfare from seabed to space, from humans to AI and the cyber/information domains. They must fit more broadly within a national defence strategy.

While, of course, the detail of such consideration is not within the scope of this Insights Paper, some facts are available through open sources that allow us to make some reasonable assumptions. Firstly, we know that in the oceans and sea lanes that directly or indirectly affect Australia’s well-being, crewed submarines are proliferating. It is likely that the current and the next generation of submarines may operate for another 50 years or so. Secondly, at present and probably into the foreseeable future, we won’t know how to address all of the threats posed by these submarines through conventional means or extensions that rely solely on automation and autonomy. Thirdly, people remain the best capability for solving warfighting, logistics and maintenance problems (or the combination of dilemmas posed by all three).

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[60] Noble, Roger Major General, Interview with Ash Colmer, 24 Sep 20

How do we gradually take away this trust from people and transfer it to machines? Would we seriously entrust an autonomous platform to control torpedoes, mines, missiles and more importantly strategic nuclear capabilities? At the same time, there are some missions such as those composed of simpler tasks that are not time critical and can be reliably achieved using complex but lower-level decision making methodologies, where an autonomous system is expected to be able to perform well.

With that in mind we need to balance what is likely with what is probable. Later in this Section we will look at some novel technologies and concepts that, with some major breakthroughs in science and affordability, could potentially provide the revolutionary gamechanger for RUS. The reality remains, however, that while they remain difficult to detect, and that science grapples with all the SWaP-C variables of UUVs, submarines will remain the most potent capability under the ocean. To that end, and although maybe a little dated in 2021, in its 2016 report to Congress, the US Navy stated that it is unlikely that any adversary would 'make the ocean transparent' nor dramatically increase the threat to their submarines in the next one to two decades.

We have noted that sensors continue to become smaller and more capable with an increasing ability to share more information using enhanced communication protocols and edge processing. As discussed earlier, sensor design and approach for RUS is different to that for land, air or space domains given the dynamics of undersea sensing and communication. So, the questions are, firstly, how to best apply these advances to the undersea environment, and secondly, what 'different' developments will be required? Some argue that these advances offer the opportunity for their potential users to change their operating procedures to properly accommodate their use. 'For instance, we need to convince Navy that trying to hunt submarines with surface vessels is like trying to hunt foxes with chickens. Aircraft and dispersion are your friends'. [61]

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[61] Davies, Andrew, Interview with Ash Colmer, 23 Feb 21

Gary Hale from Curtin University suggests that there are four potential disruptors for which future research could focus on:

- Deciding the sensing approach - what is it that we actually need to detect in the future? Displacement, sound, motion or something else that is yet to be introduced to the undersea domain?
- The physics or wave elements necessary for detection in the undersea environment (undersea equivalent of RF).
- What the design of the actual ‘on-board’ processing, including use of Machine Learning (ML) and Artificial Intelligence (AI), to achieve the lowest ‘noise floor’ for detection might look like in future undersea sensors.[62]
- Deciding where do humans best fit within these systems to allow optimal and timely decision making.

There are many who believe that future success lies in the fusion of ‘everything’ from the tactical to the strategic. That there should be a layered approach that includes terrestrial-, space-, and seabed-based sensors, those mounted on ships or submarines, and everything in between, in order to gain the tactical picture quickly. Fundamentally, to enable this future, quickly acquired tactical picture, we must know what it is that our future sensors are looking for. What are the indicators that need to be acquired? Could they be radio signals, water displacement, chemical traces, sonar, penetration of thermal layers, or a combination of all? How will artificial intelligence and machine learning enhance these processes, and where in this system are the unique traits of the human best placed?

The future will require more diverse, complementary and distributed sensors, with a greater ability to detect and interpret a greater range of indicators in the environment. Simply put, there are a number of options, or combinations of options, for enabling these enhancements. How do we best assemble and test these options? Who has responsibility for what and how do we share knowledge and lessons that maximise these enhancements? Through DSTG leadership, could we develop a specialised ‘learning loop’ that incorporates all of the RUS stakeholders, and contributes to a continual evolution of our sensor array and detection capabilities?[63]

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[62] Hale, Gary, Op.cit

[63] Ibid.

Response/Counter-Surveillance, Degraded Networks and Denied Access

Importantly, the future undersea surveillance capability must be developed with the response options in mind. While it is one thing to deploy an array of sensors and integrate them into an effective network capable of detecting the necessary threats, it is another to be able to do something about them. What would that response be? One would expect that whatever the response might be the sensor network would need to be part of the solution. Whether it is designating a target, guiding a weapon or seeking the countermeasures deployed to intercept it. What about targets that are detected outside of the range of traditional weapons systems.[64]

While we are obviously constrained by the unclassified nature of this forum, we must assume that our potential adversaries are most likely investigating and developing similar concepts and technologies in the same, if not faster, trajectory to us. In particular, submarines are becoming less observable as they continue to reduce their signature. We will need to develop new methods and enhanced capabilities to counter this trend. Additionally, long range UUVs with effective surveillance or even offensive capabilities, that are able to potentially traverse the seabed at very deep depths, or remain dormant for a period of time, present a challenge for future capability planners.[65]

Increasingly we are developing new ways to minimise detection. Platforms may make use of the background noise within the ocean to ‘camouflage’ their signature. Due to the detection challenge ahead, they may employ ‘biomimicry’ active sonars that seek to disguise a platform’s transmissions with that of naturally occurring phenomena such as a whale to reduce the danger of counter-detection.[66] However, many of the techniques used throughout recent history will remain effective such as using a mix of underwater communications exploiting low power and low probability of detection technologies. We will need higher frequency ‘intercept sensors’ that scan the spectrum for threat indicators to improve our capacity to detect such reduced signature platforms and communication systems.

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[64] Blake, Commander Stephen, Op.cit.
[65] Ibid
[66] Cain, Tim, Op.cit

Sensor and communication threats such as jamming, denial of space, GPS and SATCOM present other challenges, especially given the vagaries of undersea communication. How does the future RUS system continue to do what we want it to do during such situations? If SATCOM becomes the solution to moving large packages of data from, to, and among deployed undersea sensors, what are the capability options? Do we use alternative frequencies or alternative wave forms, or both, to mitigate these challenges?

zSpectral diversity and adaptability will be important in the future however there are a number of design challenges (e.g., physical design of sources that can operate over wide frequency bands) and environmental constraints such as the vastly different transmission ranges, data bandwidth and rates at different frequencies and for different signal types (phase coherence is much more challenging underwater). Time latency is also much more problematic as the speed of sound at 1500 m/s is quite a bit slower than that for electromagnetic waves at 300 million m/s and this is compounded when larger amounts of data need to be reliably transmitted.

So, just as we seek advantage from surveillance sensor systems and un-crewed or autonomous systems, we should expect that our adversaries will be seeking to confound them. Today, above ground, there are a range of UAV countermeasures that are being developed. These include anything from simply dropping nets on the UAV's, GPS spoofing to confuse their navigation systems, laser targeting them or using electronic measures to 'fry' the on-board communication and sensors that they are carrying. Maybe future submarines will themselves carry a swarm (or swarms) of 'counter-UUV' UUVs, mobile countermeasures or smaller weapons that once launched, hunt down and destroy or disrupt an encroaching swarm. Platforms may need to have a layer of shielding around them, whether it is a net or a form of disablement mechanism. Maybe UUVs can be developed that can interdict such a swarm and jam or confuse its communications, sensors or command and control systems.[67]

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[67] Manzie, Chris, Op.cit

The Wicked Surface Dependency Problem

Potentially, communications, data processing and C2 problems for a future sensor network may be solved by a system that combines autonomous surface or aerial platforms with those working below the surface. Many of the challenges facing RUS could be solved if you could 'simply' connect a cable back to a friendly shore or had robust connectivity to the surface. Such connectivity could potentially solve the power generation problem as well. For example, a surface platform may use active sonar with onboard processing, while those underwater would be passive receivers and use their knowledge of the environment to optimally collect data. Edge processing will allow these platforms to work out where they need to be to optimise their signal to noise ratio. Breakthroughs in machine learning and computer sizes, processing speeds and power requirements drive these advances.

But what happens in a contested environment? What happens when there is no access to the surface, or that access has been removed? A system that is dependent on what lies above the surface clearly cannot operate in such a scenario. How does C2 work in such a situation? How would a sensor pass on information to a decision maker or an effector in a denied environment, under water and potentially over a large area? A system capable of operating in such an environment would require the following high level specifications:

- Secure communications between sensors, effectors and decision makers over a large area, and potentially at great depths.
- A suite of sensors that effectively cover the area with the necessary communication to enable collaboration.
- The processing power to identify and classify the threats.
- Something that controls the system and makes decisions – whether this be human or not.
- The system may be either fixed, mobile or deployable (and recoverable?).
- Capable of operating in extremes of weather, high noise environments, and with the potential for high levels of congestion.[68]

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[68] Blake, Commander Stephen, Op.cit.

To add to this problem, networking in a military sense has yet to really deliver on the promises made. Networks tend to be built and constrained by security parameters and other regulatory, physical or other connectivity requirements, rather than imagining what is needed and what is actually possible in an unconstrained sense, while building security into the service, rather than on top of it. There may be many opportunities, in a network sense, that we are missing because of ad hoc development stovepipes. There would be advantage in a stock take of current and emerging undersea sensors, networks and communications, and an analysis of the opportunities and economies that might be achieved. [69]

Some suggest that advances in signal and data processing will probably see a change towards ‘inference’ rather than direct identification of targets. Networks of devices may be able to ‘come together’ and achieve a consensus about what it is that they are seeing. Each device may pick up on different aspects of an object whether it be by different sensors, or whether it is through the combination of the different locations from which they’re picking up the signal thereby achieving consensus through a networked decision-making process.

For example, Devices A and B think that the object is a submarine with 80% probability. Devices C, D and E think that it is a submarine with 60% probability and Device F thinks that it is a whale with 20% probability. The network then makes a decision based on this information which may or may not result in a response.[70] Technological and environmental issues apart, the key for the delivery of such a successful network will be the level of trust that the warfighter develops based on its reliability and consistency.

The military will need to develop new techniques, tactics and procedures for the use of autonomous underwater systems. It is most likely that we will see these changes firstly in the conduct of underwater mine warfare. The first systems that will emerge to replace traditional mine hunters will be delivered soon. Navies will have to ‘let go’ of some of the human-in-the-loop interaction and learn to trust these ‘off-board’ or ‘stand-off’ systems and develop new operational concepts and procedures.

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[69] Hale, Gary, Op.cit.
[70] Manzie, Chris, Op.cit

They will need to develop trust in order to take advantage of this evolving technology. For example, a crewed 'minehunter' platform needed to enter a minefield to execute its mission. An autonomous mine hunting platform allows the humans to stay outside of the minefield while the information is sent to the decision maker. There will need to be a learning curve to understand the opportunities provided, accept the technology and build the necessary trust.[71] So, while the introduction of such localised mission systems presents many challenges for those conducting underwater mine warfare, RUS is even more complex and challenging with far greater requirements on component systems and technologies.

A Simple Matter of Defining the Problem

As stated above, there is much research and development taking place that is relevant to the undersea domain. For RUS there are many prospective solutions ready to solve a set of problems that are difficult to define. There is not one solution that solves all RUS problems. We cannot 'boil the ocean'. How do we prioritise what we can afford and scale it to meet the projected threat? Whilst we may build moderately capable sensor packs that are easy to deploy and relatively robust, we cannot, however, change the laws of physics underwater, and that is the same for us as it is for our potential adversaries. The actual 'arms race' is largely defined by increased signals processing capacity. [72]

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[71] Scourzic, Daniel, Op.cit

[72] Frankish, Glenn, Op.cit

However, it also includes the optimisation of sensor/system placement, knowledge that exploits the environment, understanding of the threat, and processing that extracts the right information, analyses it and allows the effective decision making in a timely manner.

Some argue that we need to think about the future of warfare more radically. That maybe we are in a similar position to the protagonists of World War One, who despite the lessons of the American Civil War and the Russo-Japanese War, sent their armies in to refight the Napoleonic Wars with catastrophic results. Andrew Davies from ASPI argues that when we consider how we might best use evolving technologies, Defence needs to contextualise where it is headed in terms of broader historical trends. The history of warfare can be described as a steady increase in the dispersion of troops and platforms. Despite this, Navies still insist on massing platforms together, even in an age of hypersonic anti-ship missiles and increasingly deadly A2/AD technologies. Andrew assesses that:

> ‘…the age of the surface combatant really ended in 1945, but people forgot to tell Navies. Some may point to the supposed success of surface combatants in the Falklands in 1982, however the reality is that a poorly organised Air Force with a handful of Exocet missiles were able to cause major issues for the Royal Navy. Additionally, in this vein it is worth noting that the submarine that sank the Belgrano did so with a Second World War-era torpedo. Navy should follow these historical trends when thinking about surveillance technologies just the same as combat platforms. Small, numerous, dispersed, and integrated platforms are the only viable future in this domain.’ [73]

If we accept ‘the small approach’, then a key challenge will be determining exactly how small the platforms can be and still remain effective and affordable to deploy in sufficient numbers. Such a trade-off can be radically different for different system and technology options with different threats operating in different environments.

Australia is essentially a ‘maritime nation’ with a large technical talent base for undersea capability spread thinly throughout small to medium business entities. So, to design real and enduring engineering solutions, Defence needs to define a

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[73] Davies, Andrew, Op.cit

real, focussed challenge for undersea surveillance, attract the major players and allow it to grow. If for example, the challenge might be to monitor every ship in one of Australia's major sea-lanes. Or it could be, how do we build a system to protect the top ten highest priority ports, that shares common components and is supported by a sustainable industrial base? To these scenarios we might add how Defence's undersea surveillance capability might support the protection of oil and gas infrastructure, natural resources and border security etc. Without the defined problem, it is difficult for industry to channel its effort. Compared to the US there is little investment in undersea technology, and it will be challenging to reach a scale that could make Australian industry viable. To do so many hope that the STaR Shot program can assist with this and help set the conditions for a forum through which the short-term challenges may be addressed.[74]

The challenge will be getting the right combination of large prime(s) to manage the complexity of the whole system and niche sovereign contributions from a broad industry base for specific system/technology components. There needs to be more surety for home grown success to make its way to the front line without Defence defaulting to cashed up primes that provide lesser solutions. There may be opportunities for DSTG assist here by guiding innovation and the maturing of relevant technology to ensure that Australia does not miss out on the best opportunities available.[75] There may be direct research, cooperative development, prototyping and testing or different partnership options to help achieve these ends. This will be the challenge of the Star Shots and the broader Defence Innovation programs to get this balance right and, in particular, to look for opportunities for RUS that may have synergies in other domains or within other sectors of society.

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[74] Frankish, Glenn, Op.cit
[75] Marouchos, Andreas, Op.cit

Possible Versus Probable

Some argue that the next generation of submarines may be built more like a 'mother ship', with docking stations, large areas and components that allow them to deploy and recover UUVs, sensors and seabed arrays, and that the one that follows may be the last generation of crewed submarines.[76] Others say that this is unlikely as we are too far away from solving the technical development and integration problems necessary to achieve this, and much too risk averse to allow the level of trust required to enable them full autonomy.

More probable are advances in communications that allow networks of sensors to be deployed to the seabed. These sensors may be deployed themselves by autonomous vehicles which in turn could act as the hub or node for the collection activity. At the completion of the mission, the autonomous vehicle collects the sensors (or just the sensor data if they are disposable) and either returns to its base or continue on to conduct another mission. Cost challenges, power source challenges, communications and communications security are all opportunities for further research, along with the challenges presented by the vastness and extreme depths of Australia's EEZ oceans.[77] While all the component pieces appear viable and possible – maybe – within laboratory settings, some argue that moving to this next iteration of RUS has even greater challenges and research opportunities that may not be solved in the next few decades.

As sensors and processing improve, UUVs will progressively gain more autonomy in operating safely and securely while accomplishing their missions. In the meantime, the U.S. Navy will attempt to shift some operations to uncrewed systems for which the consequences of an incorrect decision are limited to damage and loss of the vehicle, rather than loss of life or unplanned military escalation. These missions could include deploying payloads such as sensors or inactive mines, conducting surveillance or surveys, or launching UAVs for electronic warfare. For missions where a human decision-maker is needed, unmanned systems can operate in concert with submarines or use radio communications to regularly "check-in" with commanders.[78]

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[76] Cain, Tim, Op.cit
[77] Ibid
[78] Clark, Bryan, Op.cit, p4

Evolving Concepts for Undersea Autonomous Systems

Heterogeneous Systems

One of the greatest opportunities for RUS lies in the development of what is described as ‘heterogeneous networks’. Each domain – air, land, sea surface and undersea – has its own physical strengths and weaknesses. If we are able to take advantage of this fact and build networks that include devices, from each domain, we may be able to effectively communicate from seabed to space. “Heterogeneity” is a big buzzword in autonomous systems at the moment and some say that ‘heterogeneous swarms’ may present opportunities for the future. Such a swarm would be capable of sensing and situational awareness through multiple media across a range of environmental conditions.

It would be self-organising, adapt and overcome ‘agent drop out’, and capable of scalable algorithmic development through cross-domain challenges.[79]

The benefits of heterogeneous networks may be exponential. However, consideration of both operational and environmental constraints indicates that meaningful application for RUS sits firmly within the third horizon for the moment. An effective system capable of deployment within the next 10-20 years would provide a serious advantage.

Swarming

RAN’s RAS-AI Strategy 2040 predicts that we will see ‘emergent swarming behaviour’ in the near term

A submarine may place itself at the centre of a swarm, acting as both a communications hub and a C2 node. A The ‘swarm’ of UUVs branch out in different directions extending its sensor reach. The difficulty is that they need some sort of mechanism to communicate this information without illuminating the whereabouts of the submarine.

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[79] Manzie, Chris. Op.cit

Also, the sensor (and potentially the UUV) need to be able to keep pace with the submarine, or at least maintain its depth.[80]

Docking Stations

A docking station is a form of un-crewed autonomous vehicle capable of re-charging the batteries of other UUVs, collecting and processing their data and acting as either a communications and/or control node for a network of undersea platforms. The docking station may have the capability to interpret the data (using AI, ML and advanced processing) and may transmit that information to another C2 node. This may mean that the docking station itself would need to expose itself by moving to a position from which it can communicate, or raising an antenna to the surface.[81]

The use of docking stations within a military UUV concept present many operational questions that need to be addressed in order to provide a viable capability. These include:

- How permanent it is?
- Is it fixed or moving?
- Is it possible to have a standardised docking interface to accommodate different vehicles?
- Is there more than one docking station? If so, are they networked?
- How far would a vehicle need to transit to get to the nearest docking station (and the associated time delay/lag in transferring data or reporting information as well as increased numbers of vehicles/sensors required to keep some on station at all times),?
- How would a vehicle navigate to the docking station reliably (what scheduling if there are more than one station servicing multiple vehicles simultaneously).
- How does the docking station provide navigation, data transfer/exchange, recharging, and reporting back to command or updated mission data?
- How much pre-processing and fusion of the raw collected mission data can be done on board the docking station so as to minimise communications back to a C2 node?

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[80] Duncan, Alec, Op.cit

[81] Sammut, Karl, Interview with Ash Colmer, 17 Feb 21

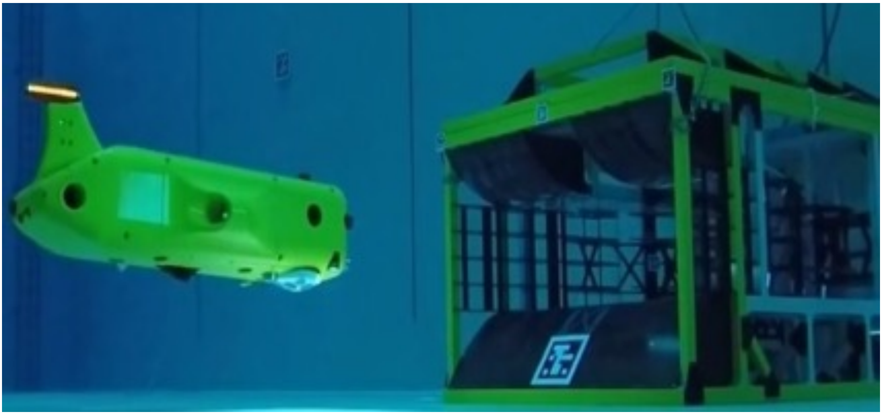

Figure 20 - Prototype Testing for a UUV Docking Station

Constellations

There is discussion regarding what a future undersea ‘community’ of self-supporting and interconnected sensors and vehicles might look like. We could look at the undersea domain in a similar way to how we look at space where we might develop a ‘constellation’ of sensors arrayed in layers. The further way from the earth’s surface we find the larger more capable satellites and, as we get closer, we find smaller but more, less capable satellites. We could ‘flip’ that view over and look at undersea as a ‘slice’ of the earth’s atmosphere, where we find small numbers of the larger more capable sensors on the sea bed, with a range of sensors, decreasing in size and capability, but increasing in number until we reach the ocean’s surface. Such a topology would allow for an ability to rapidly, but progressively change the network architecture if the threat changes, providing the network with ‘flexible edges’.[82]

Such a constellation would see smaller, cheaper, less capable sensors queuing less mobile automated sensors to conduct further, more in-depth investigation of possible finds. UUVs, equipped with even more capable sensors can then be sent to confirm high value findings and further investigate them. This would only be possible with a large number of distributed sensors/UUVs and assumes that larger more capable systems have the mobility and endurance to get to where they need to be to provide surveillance information when it is needed (this is no

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[82] Gleed, Matthew, Op.cit

different than arguments for crewed platforms). Assuming once again that we cannot provide coverage of the entire ocean, knowing where to place such a constellation, and deploying it with sufficient time and potentially stealth, in order for it to be of use remains the fundamental question for this approach.

Many undersea surveillance programs are trying to solve part of the problem, but maturing each program and integrating it into real operational capability, is far more challenging and takes longer than most wish to acknowledge. For example, the US Navy's shallow water surveillance systems such as the Advanced Deployable System (ADS), Seaweb, and the Persistent Littoral Undersea Sensor Network (PLUSNet) are good examples of systems and concepts that have focused on particular technology challenges and have matured over many years (up to 2-3 decades) without becoming fully operational systems.

The Undersea Constellation (UC) is a NAVSEA program to develop scalable networks of complementary or cooperative sensors, vehicles, communication networks, navigation beacons, energy recharging and data transfer nodes that leverage technical advances in underwater communications, unmanned systems, sensors and power distribution networks to provide greatly improved communication connectivity between US undersea forces and other US force elements to support enhanced theatre operations; enhanced intelligence and surveillance capabilities; greater connectivity for maritime interdiction, anti-surface warfare and anti-submarine warfare; enhanced support for special operations and mine warfare; and better integration of strategic forces. An initial Request for Information (RFI) was issued by the Naval Undersea Warfare Center (NUWC) Newport in February 2020. This is a longer-term program that may become increasingly relevant to future undersea surveillance systems.

Figure 21 - 'An Ocean of Things' (Source DARPA Website)

An 'Ocean of Things'

At the other end of the 'size matters' argument lies the 'very many – very small' approach, best articulated by the John Waterston led DARPA program 'The Ocean of Things.' It consists of thousands of floating sensors that aim to obtain "an unprecedentedly fine-grained understanding of what is happening in vast ocean environments." It is modelled on, Argo, an international program that collects information from inside the ocean using a fleet of robotic instruments that drift with the ocean currents and move up and down between the surface and a mid-water level. Each instrument (float) spends almost all its life below the surface profiling the water columns measuring temperature and salinity. DARPA is looking at ways in which sensors with military application may be integrated into such a concept.[83]

Emergent Behaviour

Emergent behaviour is described as the behaviour of a system as a whole. It does not depend on its individual parts, but how these individual parts collaborate to achieve its goals. Research is focussing on how this occurs in nature. How do ants find food sources and organise a whole nest's population to retrieve that food source? How do birds fly in formation? How is the leader of the formation automatically replaced if it is removed? How do lions and wolves hunt so successfully in packs without seemingly communicating?

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[83] Gleed, Matthew, Op.cit

How can we learn from these emergent behaviours and adapt them into an undersea surveillance capability?

Researchers are looking into several methods by which emergent behaviours can be adapted in to RUS systems. Stephanie Blouin, from Defence R&D Canada, is examining how a distributed network of both fixed and mobile sensors behaves '…like an intelligent collective entity to locate a target of interest.' There is no single C2 node, but the system as a whole conducts the analysis and makes a decision.[84] The system 'adapts' to the changing circumstances and 'collaborates' between its nodes. The key element for this system is of course a very sophisticated communication system.

Figure 22 - How do seagulls signal to each other when they discover a food source?

An alternative approach considers how a swarm of relatively cheap, small autonomous vehicles may detect an object of interest and then behave in such a way that demonstrates to the system, where that object is and queues more sophisticated assets to investigate or take other action that may be necessary. Defining how this system could possibly operate, both above and below the surface, and within all of the SWaP-C parameters, would represent a game changer of enormous consequences that we will not likely see until the third horizon.

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[84] Blouin, Stephanie, 'Adaptive Multi-Sensor Biometrics for Unsupervised Submarine Hunt (AMBUSH): Early Results' https://apps.dtic.mil/dtic/tr/fulltext/u2/1004159.pdf, Accessed 23 April 2021

Bio-Inspired Design

In a similar vein, the US Navy is looking at how marine mammal behaviour may provide unique solutions within the undersea domain. Understanding how they navigate, dive, sleep, and find their food or sense their environment may provide clues to how technology might be adapted to find and understand things undersea. For example, they are endeavouring to discover the unique qualities of seal whiskers and how they react to differences in water flow. The whiskers have bumps across their surface that allow them to 'glide' through water without the interruption of unwanted vibrations. Understanding what the cancellation of these vibrations allows the seal to detect may be a way off, however 'bio-inspired design' that they have learnt has been adapted into assisting evolving UUVs to minimise drag and move more efficiently through the water.[85]

Figure 23 - How do seals use their whiskers to find food and sense danger underwater?

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[85] Sutherland-Pietrzak, Sally, Interview with Ash Colmer, 26 Mar 21

Ants, Seagulls and Remote Undersea Surveillance

Dr Simon Colby, from BAE Systems in the UK is sponsoring research into understanding how biologically inspired swarm algorithms may enable emergent behaviours from constellations. For example, why do foraging ants all go off to the same place, or seagulls converge on a school of fish in the ocean? What he is seeking is how these algorithms might translate into a surveillance technique where swarms of simple autonomous vehicles can behave in a similar way without reference to the mother ship. If we understand and are able to apply the analogy to a swarm of autonomous vehicles, it may minimise the need for the large and expensive systems and platforms that we currently use. For example, if they are looking for submarines, then they may be searching for wake turbulence or other behavioural indicators. If a vehicle reacts in a certain manner when it may have come across a pre-programmed indicator for a submarine, sea mine or other object of interest, then this behaviour queues other vehicles to 'swarm' into the location to conduct further interrogation of the object to allow its classification for decision makers.

What is inspiring Dr Colby is the possibility that this biologically inspired concept might do away with the need for the autonomous vehicles to communicate acoustically with a C2 system to tell it what it is doing and what it has found. Each autonomous vehicle is programmed to find something specific and to make a substantial and measurable change to their behaviour when it finds one. He is thinking of the system where the seagulls just do 'seagull things' completely autonomously (for example one seagull finds a chip on the beach and within a minute the original seagull has been joined by a large number of friends).

In a systems sense we programme the autonomous vehicle and let it go. When it finds something of interest it changes its behaviour. The C2 watches the autonomous vehicle using non-cooperative means – perhaps tracks them on radar, or perhaps just watches the area of operations. When the behaviour change is triggered in each autonomous vehicle the C2 recognises the behaviour in its surveillance picture – perhaps via an algorithm. Perhaps the individual autonomous vehicles are too small to be detected unless they cluster together.

To make it a bit more real, Dr Colby suggests that we might start with the development of a small UAV with a simple and cheap sensor that can detect floating mines in the water column. We programme it to fly over an area of interest, then dive into the water near to a mine it has detected. It is equipped with a sea anchor and radar reflector which deploys when it is within a certain range of the mine. We take them off to an area we want to sanitise and launch 200 of them. We programme them with an area of interest/area to clear before we launch. The C2 node then just waits for them to all hit the water - either because the battery is dead, or they have found something - then launches a larger UAS over the top to seek the radar reflectors. We would probably find clusters of reflectors around suspicious objects which then allows us to concentrate localisation activities. (Clustering and voting would help to mitigate false alarms, although there's a balance around losing hard to see targets as always).

This could be done whilst the small UAVs were in flight to be a bit more like the seagull behaviour – detecting the dive. There are many issues to solve here, among them SWaP-C considerations, sensor performance, and environmental issues as we'd be unlikely to be able to get them all back post mission. The key element of this concept is that we take out the need for communications and complex processing on the UAV and probably also do away with potential security issues. This concept may of course, be applied to many situations across all domains. 'I don't know if this would end up being a cost-effective system compared to other options, but it'd be fun to do the work to find out! And if you are looking for disruptive ideas then this might fit the bill.'

Dr Colby believes that there is a broad conceptual pattern around using simple things that work in bulk to make it easier to detect things that are otherwise hard to detect. As we approach the limits of technology and physics with existing approaches, we should look for radically different ways to do things.[86]

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[86] Colby, Simon, Op.cit

Other Technologies and Concepts

While the STaR Shot program seeks to uncover new technologies for future research, for the moment ‘we need to remember that sound propagates better than anything else under water, so acoustics must remain at the top of the list for consideration. Submarines continue to become less noisy, so that it is really a case of adjusting the problem variables. Most would agree that the days of SOSUS have gone and that it is now very difficult to detect and then track a submarine using such technology. Submarines are now more likely to be revealed through their active sonar or through operational indiscretions. There may be no continual track data or radiated signature. Submarines might instead reveal themselves through ‘transients’ and those things that are simply unavoidable when operating such a ship.

What we might be picking up through sonar is a batch of data that computers might be able to help us with to compile and associate with an object such as a submarine.[87]

Other sensor technologies, such as lasers, LiDAR, magnetic, electric and chemical may present greater opportunities for undersea surveillance. To do so effectively they need to become more compact, consume less power and increasingly have on-board processing abilities enabling them to exploit the parts of the undersea environment where they could successfully detect a submarine or other targets of interest. New battery technologies and new energy sources will be made available leading to either more compact systems, greater endurance and faster speeds.[88] We will continue to see advances in what are being referred to as ‘intelligent sensors’. These are sensors that are much more aware, can take readings or make detections that can be ‘sanity checked’. These ‘unattended’ sensors can be ‘tamper proof’ or tamper ‘resistant’ and provide ‘chain of custody’ memory data. They can interact with other sensors, calibrate themselves and conduct maintenance on themselves. Additionally, the validity of the information collected, and the survivability and persistence of the activity may be mitigated by the number of sensors deployed.[89]

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[87] Battle, David, Op.cit
[88] Scourzic, Daniel, Op.cit
[89] Marouchos, Andreas, Op.cit

Another area that might be a potential game changer is in decision support. The utopian dream would be the fusing of all of environment modelling, intelligence for mission planning and the optimised mix of sensors enabled by the networking and tools to allow near real-time decision support. Adding artificial intelligence and big data processing to supplement operator/commander decisions and adapt these as the mission plays out will be a big leap forward.

Some other, technologies and concepts that may benefit from more research and development are listed below. This list does not attempt to be comprehensive, nor can it be given the open source nature of this paper, but it serves to demonstrate the breadth of possibilities that may influence the future of RUS.

Advances in Piezo Ceramics

Advances in single crystalline piezo ceramics present significant performance enhancement for acoustic sensors. Limitations in supply is affecting Australia's ability to benefit from this technology. The piezo is the smart part of the acoustic sensor. It is the thing that transforms an acoustic pressure signal in the water to an electrical signal. Piezoceramic components are used in sonar technology and hydroacoustic systems, for measuring and position-finding tasks especially in maritime applications. Polycrystalline piezo ceramics (PZT) have been the most common ceramics used in acoustic sensors for some time. The 'next generation' is known as single crystalline piezo ceramics. Currently, due to its specialised manufacturing process, its availability is limited by supply. The majority of the material is consumed by the healthcare sector for use in ultrasound technology. Singapore, China and other countries are manufacturing it, but Australia doesn't have a reliable supply source. Thales is aiming to manufacture them commercially in Australia in the coming years. [90]

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[90] Cain, Tim, Op.cit

Non-Acoustic Sensing

Most agree that acoustic sensors will remain the most effective undersea sensor, however there are certain ‘novel, non-acoustic sensor’ capabilities that may gain more prominence for some surveillance applications in the future. While these capabilities cannot be discussed in too much detail in this paper, they include electro-magnetic, chemical, and seismic technologies. Distributed acoustic sensing using cross fibre optic cabling is becoming a reality, utilising fibre optic cabling already laid as part of existing communication networks. We can also use such infrastructure to integrate with other sensor arrays to provide the communications link back to a decision node. We can monitor the health, integrity and performance of deployed assets using sensors to monitor sensors.[91]

Chemical sensing is not widely discussed in a military undersea surveillance capacity although it was a method used to detect diesel-engine submarines from aircraft. The problem with a chemical sensor, assuming that you are looking for something coming out of a submarine as it goes past, is that whatever it is that you are sensing would have to be present in the wake of the submarine. Additionally, there may be a considerable amount of time taken between when the submarine transits and when the turbulence, or whatever it is that spreads the substance, enables the sensor to make a detection. All that could be deduced therefore, is that something that emitted whatever the chemical element that was detected, had ‘gone past, at some distance, and at some time.’[92]

SPAD

A potential game changing alternative technology is SPAD – Single Photon Avalanche Diode. Using the realm of hyperspectral technologies SPAD seeks single photons from under the water that might belong to a submarine, or may be ‘bounce’ photons off a submarine. These sensors may be able to operate from space. They may be passive or active and would effectively allow a user to see through water. However, wide area surveillance implies the collection and analysis of enormous data sets, multiplied in this case by the potential need to deploy multiple SPADs. The amount of data collected from these, and potentially other sensors deployed in support, would requires massive computer processing capacity. The classification of a detected submarine, along with the determination

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[91] Gleed, Matthew, Op.cit
[92] Duncan, Alec, Op.cit

of its location and trajectory would be a ‘big data problem’. This technological concept is considered by most to be ‘right on the edge’ of reality and time will tell whether it presents a real game changer for undersea surveillance.[93]

Figure 24 - Dr Dennis Delic collaborated with BAE Systems to demonstrate his SPAD sensor’s ability to detect and track aerial targets. Source: DSTG Website

SQUID Device

A superconducting quantum interference device (SQUID) may be developed, in an undersea sense, to seek out objects of interest through sensing the perturbation created by that object as it pushes through gravity. While currently only at the laboratory stage, SQUID is a mechanism that can measure extremely weak signals, such as subtle changes in the human body’s electromagnetic energy field. Using a device called a Josephson junction, a SQUID can detect a change of energy as much as 100 billion times weaker than the electromagnetic energy that moves a compass needle.[94]

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[93] Blake, Commander Stephen, Op.cit

[94] Cain, Tim, Op.cit

Neutrinos

The development of an ability to deploy sensors capable of detecting neutrinos emitted from nuclear reactors would be a game changer for future anti-submarine warfare. Neutrinos are a neutral subatomic particle with a mass close to zero and ‘half-integral spin’, which rarely reacts with normal matter. Three kinds of neutrinos are known, associated with the electron, muon, and tau particle. Nuclear reactors produce neutrinos. Neutrinos permeate most matter and are incredibly difficult to detect. Current neutrino detectors are large and lack the fidelity required for target detection and identification. The sun emits neutrinos for which the sensor would need to specifically ignore as part of its detection process. Further, each of the three types or neutrino ‘oscillates’ its identification between the three so it is difficult to identify which is which and therefore, the neutrino’s origin.

Most believe that the enormous technical and physical challenges that need to be overcome make the pursuit of this opportunity cost prohibitive, however the development of an effective and deployable neutrino sensor would be a game changer in the detection of nuclear submarines.[95]

A Future Vision That Defence, Industry and Academia Can Grow Towards…Together

For a country of our size, there is a decent industrial base that supports undersea surveillance. Thales, L3 Harris Oceania and Sonartech Atlas, all have footprints in Australia, both on the east and west coast. We are well served by highly competent underwater surveillance experts such as Ron Allum who led the team that took Deepsea Challenger to the bottom of the Mariana Trench (12,000 m deep). We have companies developing sensors, signal processing, underwater acoustic communications systems and composite materials.[96]

Some argue that Australia has a bit of work to do to be where it should be regarding RUS and that we should be more self-sufficient. They say that we cannot believe or hope that other countries will provide us with the cutting-edge technologies and algorithms required to achieve the capability advantages to

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[95] Duncan, Alec, Op.cit

[96] Cain, Tim, Op.cit

succeed and win in the undersea environment. We have seen a reduction in local manufacturing and training in this domain. We have had difficulty in retaining talent in autonomy as they are recruited by the US. Industry argues that Australia needs to build a clearer vision for what it intends to do in the undersea domain. A vision that can be shared with the primes who are then able to make strategic capability investment decisions that lock them in to sharing these goals. They are then in a position to make the investment in both people and local industry that will allow Australia to build the industrial base necessary for advantage.[97]

There are many other users of the undersea environment who are presented with similar challenges as the military, such as oil and gas, marine science, and the blue economy. These sectors are developing systems that operate in the undersea domain which may have utility for Defence. That said, though, Australia's undersea surveillance capability must be developed with the military threat and response options in mind. What RUS is looking for presents far differing characteristics and challenges to what others are seeking to do under the sea.

Technical Skills Base

To that end we need to improve the attractiveness of careers in RUS for science, technology, engineering and mathematics students. There are only a few universities working with the technological concepts needed to further RUS capabilities. Graduates prefer to engage in careers involving space, aerospace and medical technologies, where there is more money and where the pathways are more obvious. Those that remain in the undersea domain are also more likely to be 'head hunted' by the oil and gas sector or by other companies or academia overseas. DSTG must figure out ways to attract and retain people in this area. This may be by way of offering to do the more technical projects rather than just managing them.[98] While the Defence Strategic Update and Force Structure Plan both stated the importance of RUS, there is a feeling that its overall priority may not allow Australia to develop the technologies required for advantage.

There is a legitimate concern in both industry and academia as to where the next generation of ocean acoustic physicists and engineers come from?

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[97] Manzie, Chris, Op.cit

[98] Sammut, Karl, Op.cit

If Australia is serious about seeking an advantage in undersea surveillance, then a long term capability strategy is required to ensure the attraction and maintenance of a suitable body of these people.[99] This is a critical shortfall and there is a risk of losing the expertise that we already have. Some suggest that Defence must invest in making ocean science and ocean acoustics a worthwhile career option now. This could be further helped by providing DSTG with its own ocean-going capability which could be shared and integrated with industry.

A Clearer Vision for RUS

A clearer vision for Australia's needs in the undersea domain is required. This should be shared with primes to make strategic capability investment decisions in both people and local industry that allow us to build the industrial base and retain the talent necessary for advantage.[100] There is a general feeling among industry and academia that there are so many aspects to both the capability and technology requirements for undersea surveillance, that Defence is perceived to be trying to 'boil the ocean'. They ask that Defence define a real, focussed challenge for undersea surveillance, and allow it to grow. They generally agree that Australia has the skills and technology required to successfully develop RUS capability, but that Government needs to confirm its willingness to capitalise on this existing expertise in a similar manner as it has done for the cyber and space environments. They also seek pay-offs beyond RUS, where advances in robotics may provide industry with opportunities to be more automated and where greater surveillance capabilities may provide major benefits to undersea conservation.[101]

To that end, Defence needs to be more coordinated in how it works in this area. Industry, both primes and small to-medium entities, need to be brought into the fold and be part of the discussion. The development of trust and how sensitive concepts and technologies are managed within the discussion will be critical to its success.

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[99] Duncan, Alec, Op.cit

[100] Manzie, Chris, Op.cit

[101] Sammut, Karl, Op.cit

Australia already has significant sovereign capability in undersea surveillance, remote operations and automation; however, it is in pockets.[102] DSTG has an opportunity to play a leading role in aligning and coordinating capability and effort between industry and academia and in forcing collaboration with other countries as well.

Maybe we should start by endeavouring to understand what capability we already have, maybe through an audit? Then have it analysed to understand what may be possible, in terms of partnerships, collaboration and capability opportunities.[103]

Many argue that we need to share our knowledge, create international scholarships and exchanges that encourage a broader understanding of RUS technologies. The US, UK and France are obvious partners for this sharing, but Singapore, South Korea and Japan also have a lot to offer.[104] Like all capability sharing between sovereign nations, balancing cooperation and protection is a fine art.

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[102] Hale Gary, Op.cit

[103] Hale, Gary, Op.cit

[104] Sammut, Karl, Op.cit

Conclusion

The emergence of new technology heralds a new era in undersea competition that will require a reconsideration of how military forces conduct undersea warfare.[105] Australia will require a more sophisticated end-to-end sensing system that can feed from the strategic to the tactical and back again to enable decision making faster than a competitor. This system cannot hope to scan Australia's undersea area of interest, but must be flexible, deployable and networked to allow warfighters to plan and make decisions that seek advantage against that competitor. The warfighters may decide to deter, discredit, isolate, confuse or even destroy that competitor and require RUS capability that integrates with the systems that deliver these responses.

How these technologies and concepts emerge and are successfully deployed is the real 'arms race' in which we find ourselves. Decisions to invest in autonomy need to be weighed up in terms of realistic fulfillment, cost and legality. They also need to be weighed against the relative ability of a future aggressor successfully achieving such autonomy, or in producing new capabilities that negate any of our advances.

What we do know is that Australia has relatively advanced pockets of RUS knowledge and capability. It has a considerable Ally and many close friends in which it may share R&D risk and knowledge. Along with necessary reconsideration of operational concepts, it is potentially well placed to compete in this arms race.

Perhaps the technology for real for disruption for remote undersea surveillance is already with us. It lies in our ability to leverage combinations of existing and emerging technologies, capabilities and stakeholders to produce an exponential capability improvement.

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[105] Clark, Bryan, Op.cit., p 7

Appendix - List of Interviewees

Name	Organisation
Dr David Battle	Mission Systems
CMDR Stephen Blake	Royal Australian Navy
Dr Tim Bubner	DSTG
Dr Simon Colby	BAE, UK
Tim Cain	Thales
Dr Andrew Davies	Australian Strategic Policy Institute
Glenn Frankish	Leidos, Australia
Matthew Gleed	BAE, UK
Dr Damien Guihen	Autonomous Maritime Systems Laboratory, University of Tasmania
Gary Hale	Curtin University
Professor Chris Manzie	University of Melbourne
Andreas Marouchos	CSIRO
Dr Karl Sammut	Flinders University & DSTG
Daniel Scourzic	ECA Group, France
Phillip Stephenson	DSTG
Sally Sutherland-Pietrzak	Naval Sea Systems (NAVSEA), US
Michael Vaccaro	US Office of Naval Research

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