Acoustic Lily Pads: Innovation at the Speed of Deterrence

Team 6, SHIELD 2024

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Executive Summary

Guam is susceptible to 360-degree attacks. This territory is a strategic U.S. military power projection platform located in the Western Pacific Ocean. The island's geographical location facilitates rapid joint deployment and logistical re-supply capabilities. Guam's advanced Integrated Air and Missile Defense System (IAMDS) architecture is key to maintaining a credible deterrence and preserving the integrity of a free and open Indo-Pacific region.

This research examines the feasibility for augmenting island defense and employing a passive detection network against low-flying altitude threats. Low-flying altitude threats fall into a category of targets whose altitude is defined for this paper as surface up to 100 meters and subsonic speeds. Threats such as cruise missiles and one-way suicide drones are the focus. The combination of these weapons is being observed in the Russian invasion of Ukraine with high success. More troubling, the employment of drone swarms provides a cost-affordable exchange option while posing a high risk to complex IAMDS.

This paper utilized Ukraine's Sky Fortress as a case study. Sky Fortress developed, tested, and fielded a disruptive, passive, and acoustic-sensing technology in under a year. Costing only $300 per unit, these sensors can identify, classify, track, and provide intercept points while functioning as a mesh network. This network now covers 80 percent of Ukraine and provides an impressive detection rate of 99.6 percent against Shahed-variant drones and cruise missiles. Mobile fire groups equipped with only .50 caliber machine guns are now able to intercept cruise missiles.

This research has determined that Acoustic Lily Pads provide a low-cost defense solution for allies and partners along the first island chain and augments Guam Defense Architecture. This technology has a vast application across the joint force as well. Maritime acoustic,

autonomous persistent sensors can be deployed in a massive mesh. Together, this mesh provides air defense awareness to cover the vast areas within the Indo-Pacific region and function as maritime trip lines around critical maritime infrastructure. The fastest approach to fielding in a timely manner is through the Urgent Capability Acquisition Pathway, which drives a statutory requirement to field in two years.

Background

Problem

The U.S. Indo-Pacific Command is a geographic combatant command, assigned to a four-star Navy Admiral, with an area of responsibility (AOR) covering the land, air, and sea operations across a massive area that includes all the Pacific Ocean, from waters off the American continents through much of the Indian Ocean. The Indo-Pacific Strategy of the United States describes integrated deterrence being at the cornerstone for U.S. efforts to bolster regional security (White House, 2022). The U.S. strategy focuses on fielding innovative capabilities to maintain technological advantages and collaborating closely with Allies to build advanced self-defense capabilities. Within the region are the home territories of the two most militarily threatening countries of China (PRC) and North Korea, each rapidly modernizing and advancing their military capabilities. The PRC is aggressively pressuring Taiwan and countries in the East and South China Seas away from the established rules-based order that currently benefits many nations toward a PRC-centric one. North Korea launched more than 30 missiles in 2023, all in violation of the United Nations Security Council resolutions.

U.S. Indo-Pacific Command pursues four activities to meet its mission to “implement a combat credible deterrence strategy capable of denying our adversaries sustained air and sea dominance by focusing on posturing the Joint Force to win before fighting while being ready to fight and win, if required" (USINDOPACOM, 2024). It is recognized that PRC's large number of short-range ballistic missiles (SRBMs) can decimate U.S. and partner nation bases within the first island chain that includes the Northern Philippines, Taiwan, and Japan and makes more difficult any military operations designed to counter PRC aggression within the East and South China Seas, the Sea of Japan, and across the Taiwan Strait. The second island chain includes the islands of Palau and the Western-most U.S. Territories of Guam and the Northern Marianas and has enough distance from PRC, approximately 1,865 mi (3,000 km), to be out of range of the SRBMs, while still being close enough to those locations to support any military response. Figure 1-1 updated in 2021 is likely an underestimation of the numbers of Indo-Pacific Command regional threats from China (Missile Threat, 2018).

All the locations within the first and second island chains suffer from being far removed from the primary U.S. bases and supply hubs in North America and Hawaii. Sustainment of a credible and capable force presence across the vast distances of the Pacific Ocean to these forward operating locations require persistent and complicated logistics that are made even more difficult during crisis when re-supply could be contested. Typical ship transit time are 7 days from Hawaii and 14 days from the West Coast. The maritime environment surrounding Guam complicates defense implementation. The water around Guam provides extreme variation in depth. The immediate coastal waters remain relatively shallow but are associated with extreme depth transitions of 32,000 feet with the Mariana Trench. The island of Guam is relatively small with dimensions of 30 miles long and approximately 9 miles wide.

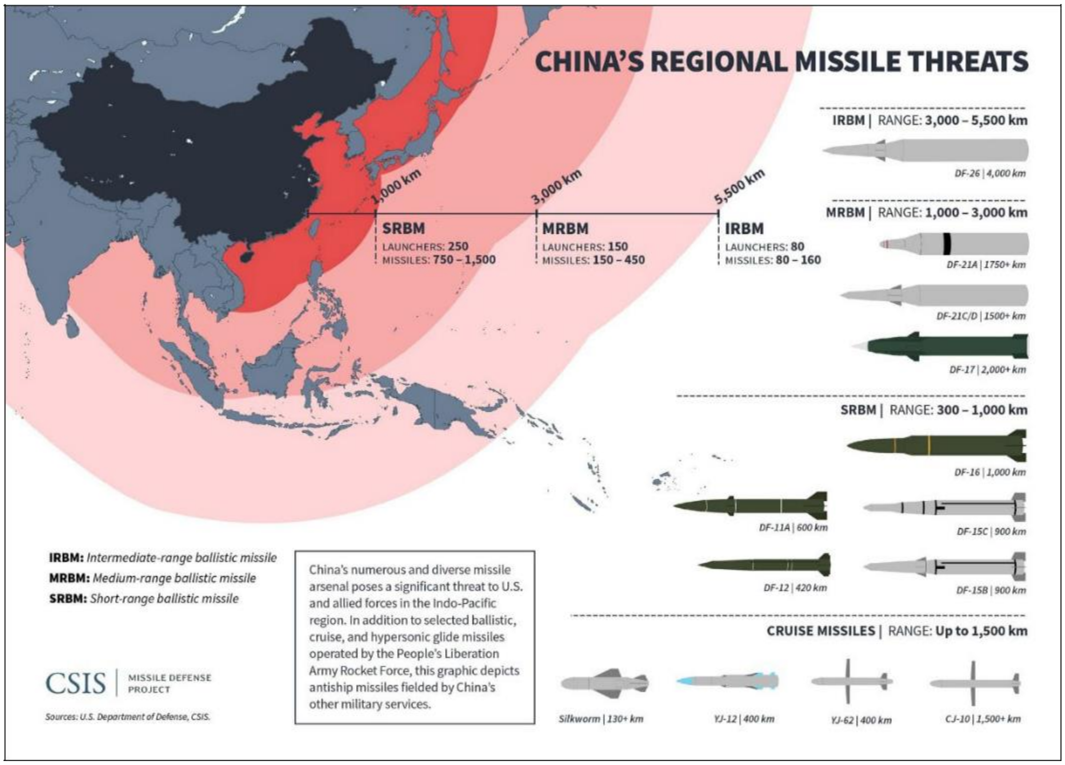

Figure 1-1. Chinese regional ballistic missile and cruise missile ranges (Missile Threat, 2018)

Ukraine Solution/Case Study

<u>Russian Strike Campaign</u>

Russia initiated its February 2022 invasion of Ukraine with complex electronic attacks, followed by a large strike package of Kalibr cruise and Iskander ballistic missiles (Bowsher, 2023). Hundreds of sorties complimented the attack, striking Russian-identified High Value Targets (HVT). Included in the HVT list was Command and Control (C2) sites, radars, and air-defense sites (Zabrodskyi et al., 2022). The combination of these targets comprised Ukraine's integrated air and missile defense systems (IAMDS) architecture. Initial reports indicated a high success rate in destroying Ukraine's air defenses, which facilitated Russian air superiority (Trofimov et al., 2022). Despite a numerical advantage, combined with a surprise attack, these reports proved to be incorrect.

Russia's initial strike campaign did not meet its full objectives and failed to establish air superiority. The failure was largely attributed to ineffective execution of suppression of enemy air defenses (SEAD). Resulting in engagement of 75 percent stationary IAMDS with only 10 percent of mobile air defense systems engaged in the first 48 hours (Zabrodskyi et al., 2022). As a result, Ukraine's IAMDS were left largely intact, but decentralized. However, the mobile air defense systems were able to implement heavy losses to fixed- and rotary-wing aircraft through use of mobile sites (Wetzel, 2022).

Ukraine Radar Gap Vulnerability

In the weeks following the initial attack, Ukraine was able to implement an impressive air defense campaign through reestablishment of its IAMDS, denying Russian air superiority. The defense architecture forced Russian aircraft to fly at low altitudes, exposing them to man-portable air defense systems (MANPADS). Suffering heavy losses, the Russian air force was unable to successfully penetrate Ukraine's airspace. The Russian air force was forced into a close air support role or delivering fires from inside Russian airspace (Zabrodskyi et al., 2022). With Ukraine's airspace contested, Russia adapted to battlefield conditions and changed tactics by increasing employment of various drones and ballistic, hypersonic, and cruise missiles. Through these new tactics, Russia identified radar gaps and challenges faced by Ukraine in defeating low-flying altitude threats such as cruise missiles and drones (Sky Fortress, 2024). Cruise missile interceptions average approximately 50 percent due to radar gaps (Zabrodskyi et al., 2022).

Primary drivers of the gaps included terrain, placement of systems, and sophistication of Russian cruise missiles. "The Russians routinely adapted flight routes for every mission and such missiles were observed to make up to 80 changes of course on their way to a target. It is not economical for any state to maintain coverage across the requisite frontage to be able to defend all targets at sufficient density of air defenses to guarantee defense against these systems" (Zabrodskyi et al., 2022).

Introduction of Shahed Drone

Complicating the vulnerability of the radar gap, the first use of Shahed drones began in October 2022 (Grise & Evans, 2023). The introduction of this weapon system facilitated a dynamic shift in the long-term strategy in the fight for Ukraine's sovereignty. The employment of these drones provides a cost-affordable exchange ratio and capability to overwhelm air defense systems. The Shahed drones provide flexibility for a sustained offensive capability due to low production costs, which is estimated at $20,000 per unit (Knights & Almeida, 2022). Ground-based interceptors, however, can exceed a cost of $4 million (Missile Defense Advocacy Alliance, 2024).

Shahed Drone Capabilities

The Shahed-136 is designated as a one-way loitering munition employing suicide attacks. The drone claims a 2,500 km range and features payload delivery options up to 40 kg. Weighing approximately 400 lbs., it can reach speeds in excess of 100 mph with its four-cylinder engine (Army Technology, 2023).

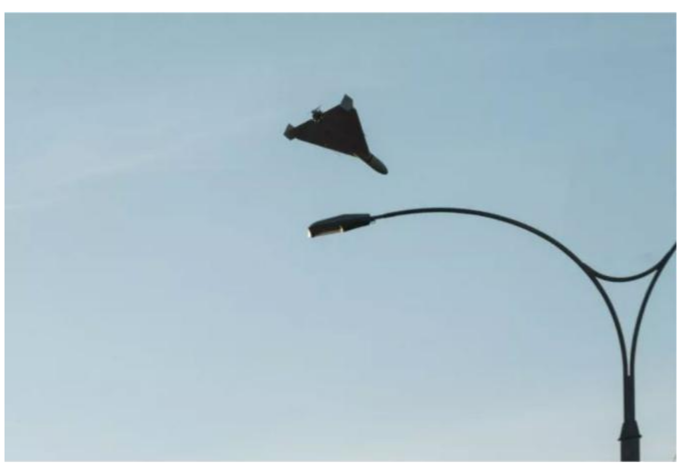

Figure 1-2. Iranian Shaheed-136 Drone on Approach for Kyiv Assault October 17, 2022.

Since invading Ukraine, Russia has increasingly executed its strike campaign through combined attacks using missile and drone strikes. As of February 2024, Ukraine reported that more than 8,000 missiles and 4,630 drones were launched against them (Dysa, 2024). These tactics aim to exploit, overwhelm, and fix Ukraine's IAMDS and exhaust interceptor stockpiles for follow-on attacks.

Future Outlook

Russia's current estimated Shahed production capability stands at 400-500 units per month. Leaked documents provided indication that Russia is working toward a capability to mass-produce these one-way drones (Bennett & Ilyushina, 2023). Satellite imagery taken just three months after the leaked documents revealed construction of Shahed production facilities located in Alabuga Special Economic Zone in Yelebuga, Russia (Albright et al., 2023).

Sky Fortress

A beacon of hope came in the form of a voluntary citizen effort called Sky Fortress. Sky Fortress consists of a patriotic group of scientists, engineers, and businesspeople who came together with the unified goal of developing and deploying a solution in response to the powerful Russian invasion Sky Fortress designed and implemented an integrated acoustic-sensing disruptive technology to defeat low-flying altitude threats. When Sky Fortress created this system, they deemed it a "poor man's solution" to fill the identified gaps. To date, this system has proven highly effective, with detection rates for cruise missiles and Shahed drones sitting at 99.6 percent (Sky Fortress, 2024). Video evidence has shown interception of cruise missiles with a modified .50 caliber machine gun. The technology continues to advance and is now catching the attention of U.S. military leaders, with demonstrations to the U.S. and NATO militaries set to occur in 2024 in Europe (Trevithick, 2024).

Sky Fortress Problem

During an interview with Sky Fortress developers, they explained that the acoustic-sensing technology evolved mainly because of the identified radar gap that the Russians were consistently exploiting. Even if targets were successfully tracked, they were destroyed using disproportionally expensive air defense missiles (Sky Fortress, 2024).

Solution: Acoustic-sensing Technology

To counter these low-flying, subsonic threats, Sky Fortress developed a passive first-generation acoustic-sensing network leveraging cell phones. These sensors used a self-developed proprietary acoustic-detection algorithm that could be continuously trained using embedded machine learning at the edge. These devices are easily deployable and are able to be spread across the battlefield to provide real-time threat pictures.

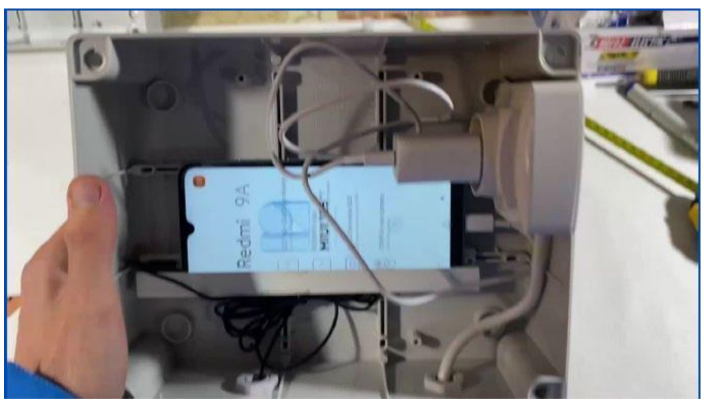

Figure 1-3. First generation acoustic sensing device

At the time of our last interview, Sky Fortress was manufacturing and deploying a second-generation acoustic-sensing technology. Improvements consist of greater microphone sensitivity, enhanced environmental resilience, and replacing cell phones with microcomputers based on the Linux operating system. These units now cover 80 percent of Ukraine proving a real-time threat picture for low-altitude threats (Sky Fortress, 2024).

Acoustic Network Data Fusion

The acoustic network consists of passive acoustic sensors, various network communications capabilities, and a cloud server. Once a threat is detected, the passive acoustic sensor conducts edge-computing analysis capturing threat device sound signatures, coordinates, target type, and speed. Within 30 seconds of detection, the sensor sends a signal either through the short-range radio-linked mesh network or to the cloud-based general situational awareness system via a Global System for Mobile Communications (GSM) connection.

The cloud-based server collects target detections from multiple alerts, confirms the target type and speed, and then calculates the target's trajectory data. It also uses a neural network as a filter to eliminate false positives using a machine learning algorithm. The trajectory data is sent through an application programming interfaces (API) as exportable data to the Ukraine Airforce's Viraj system, C2 elements, mobile fire groups (MFG), and ground commanders (Sky Fortress, 2024). The cloud-based architecture separates the sensing network from directing the C2 elements, allowing local commanders to maintain sole direction of their MFGs and humans to still order any effects on targets.

Mobile Fire Groups and High-fidelity Cueing

MFGs are small units equipped with various weapons ranging from Browning M2, ZU-23 variants, Igla, and stinger launchers. These units are integrated into the passive acoustic-sensing network and provide an inexpensive means for interception using modified commercial-off-the-shelf (COTS) components. Sky Fortress enhanced MFG thermal sights and mounting equipment with COTS components. Tablets and goggles were also integrated into the firing platform using SkyLock aiming solution software. SkyLock receives course interception data provided via API from the cloud server. Once the MFG is in position, SkyLock provides precision ballistic aiming solutions, which are viewed through the gunner's goggles or tablet.

Through these upgrades, 90 percent of Shaheds are destroyed by kinetic weapons in MFGs area of operations with zero friendly fire incidents (Sky Fortress, 2024). This exchange creates a sustainable cost-to-kill ratio when comparing inexpensive ballistic rounds to a $20,000 Shahed unit. Sky Fortress advertises a 50-times kill rate improvement for an MFG-equipped with Stinger/thermal/SkyLock upgrades with repeatable cruise missile detection at 5 km. MFGs also have video evidence of cruise missile intercepts utilizing machine guns while equipped with the upgraded platforms (Sky Fortress, 2024). Estimates of the Russian cruise missiles are around $5-20 million each (Malyasov, 2024), while a single .50 caliber bullet can cost around $15. It should be noted that multiple bursts are required for successful intercept.

Figure 1-4. Mobile fire groups with SkyLock upgraded platforms

Mobile Fire Team Effectors Description

The M2A1 is a .50 caliber heavy machine gun that can be used as a semi-portable weapon. The gun is belt-fed and fires .50 BMG (12.7x99 mm NATO) rounds at a rate of 450-600 rpm with a maximum range of 7,400 meters (General Dynamics, 2012). The original M2 has demonstrated anti-aircraft capabilities throughout history (Edwards, 2022).

The ZU-23-2 is towed 23mm twin barrel light anti-aircraft gun developed in the 1950s by the Soviet Union (Axe, 2024). It is currently operated by Ukraine. It fires 23x152mm shells at a rate of 2,000 rpm but must be fired in short bursts to allow the barrels to cool (Axe, 2024). The ZU-23-2 has effective range of 2.5 km (Axe, 2024). The gun is fed with two 50-round belts (Axe, 2024).

The FIM-92 Stinger is an American short-range man-portable air defense system (MANPADS) designed for air defense employment for light infantry. It uses an infrared guidance system to lock onto low-altitude aerial targets. The launcher fires one missile at a time and is operated by a single user with an effective range of 4.8 km (Missile Defense Advocacy Alliance, 2022).

The 9K38 Igla is a Soviet-made MANPADS currently used in Ukraine (Cook, 2023). Firing one 72mm missile at a time while operated by a single user, it has an operational range of 5.2 km and uses sensors to lock onto a target (WeaponSystems.net, 2024).

Sky Fortress Acquisition Novelty

The acquisition novelty for the disruptive acoustic-sensing technology is enhanced by numerous attractive attributes. The technology is proven in an operational environment and is self-assessed at a technology readiness level (TRL) 9. Since mid-2022, the production line has been operational and produced over 10,000 acoustic sensing units. Another appealing attribute is the unit cost of one detector, which is $300 using COTS components. To develop and cover 65 percent of the Ukraine landmass, Sky Fortress spent around $3 million. The price point combined with the effectiveness of this technology creates an attractive option for U.S. defense industrial base, provided the cost can be kept low (Sky Fortress, 2024).

Detection Rate

Ukraine’s passive acoustic network consistently demonstrates a 99.6 % detection rate for cruise missiles and Shahed drones. Since mid-2022, the network has tracked over 2,600 cruise missiles and more than 2,200 Shahed drones. Currently, 60 percent of Shahed detections come from the passive acoustic network.

During an interview with Sky Fortress, they reported that Russia took concerted efforts to change the noise signatures and employment altitude in the Shahed drones. This effort resulted in a temporary detection rate reduction to 95.5 % until software was updated. Additionally, employing the Shaheds at a higher altitude resulted in detection and engagement of more complex western systems (Sky Fortress, 2024).

Timeline of Development

The developmental timeline of the acoustic disruptive technology is nothing short of incredible. Russia’s invasion in February 2022 served as the catalyst for Sky Fortress. Critical radar coverage gaps were identified shortly thereafter. In May of 2022, software, hardware, and user interface concepts were developed. Just eight months after the invasion, Sky Fortress was granted permission from a Ukrainian Colonel to test the system. The acoustic network was first employed in an operational setting in October of 2022. By the of December 2022, over 8,000 sensors covered 65 percent of Ukraine (Sky Fortress, 2024).

Future Sky Fortress Efforts

The innovation and dedication to freedom of Sky Fortress shows no signs of slowing down. In the next six months, the group is scheduled for new weapon systems employment. All weapon systems will be integrated in the passive acoustic network. These new systems include drone swarms consisting of 16 small quadcopters that create a 100 m x 100 m grid. The quadcopters carry a payload of 1 kg and provide a hit-to-kill capability along a flight trajectory for various threats. They are expected to cost around $5,000 per unit. Automatic static robotic turret systems capable of tracking and engaging targets moving up to 250 m/s are also scheduled to deploy. Versions of these robotic turrets come integrated with a low-cost, supersonic anti-aircraft missile expected to cost around $7,000. These missiles are self-guided with a laser target illumination module (Sky Fortress, 2024).

Figure 1-5. Future Sky Fortress weapon systems

U.S. Acoustic Programs

By far, most acoustic sensing research and development in the DOD has been centered on acoustic sensing for submarine applications. Outside of this field, significant amounts of basic and applied research on atmospheric acoustic sensing has explored atmospheric conditions to identify vectors toward sound sources and attenuation in different environments like forests and seas (Collier, 2005; Collier et al., 2017; Collier & Wilson, 2003, 2004). The DOD therefore has a very strong history for using acoustic signatures to understand the nuances of sound in physical domains.

One significant impact of acoustic sensing on DOD operations has been its use in mortar launch detection in Iraq where the unattended transient acoustic MASINT Systems (UTAMS) were able to detect a mortar launch before impact providing warning to likely targets (Tenney et al., 2004). This system is applicable for small arms and rocket launches as well as impacts from any of these weapons (Naz & Marty, 2006). An extension of the MASINT was used for UAS tracking experimentation (Benyamin & Goldman, 2014). In these studies, both the direction and altitude were analyzed from single tetrahedral arrays, but it was observed that single nodes are insufficient for assured locating and altitude tracking. A mesh architecture like Sky Fortress is required.

Figure 1-6. Tetrahedral Microphone Array in Iraq (Tenney et al., 2004)

The simple employment of using easily available COTS components for acoustic sensing has generated tens of thousands of reports in the Defense Technical Information Center's database. Many completed programs are not suitable for this audience, but atmospheric acoustic sensing has been, and continues to be, a vital arena for ISR in operational theaters against legacy and emerging threats. The DOD should be able to leverage a large portion of its previous experience and research investment into atmospheric acoustic sensing to easily and rapidly create a disruptive solution like Sky Fortress if needed.

Process for Rapid Development

Required Rapid Development Environment

In the late 1950s, "Kelly" Johnson, the lead of Skunk Works, began design work on a CIA urgent operational need (UON) to provide a high speed, low observable intelligence gathering platform. By 1960, Kelly Johnson had a prototype for testing, followed by a maiden flight in 1964 (Mickeviciute, 2023). Twenty years after the invention of the jet engine, the DOD military industrial complex had created a jet achieving Mach 5+ airspeeds, virtually invisible to radar and missile systems of the time. Though our industrial base still produces state of the art weapon systems, it does so far slower than historical examples, at increasingly higher costs, and more importantly, slower than near-peer rivals, who benefit from command-driven economies. The Skunk Works ethos has been lost.

It could be argued that the Ukrainian acoustic sensor acquisition program, timeline, and proven operational success demonstrates a Skunk Works ethos more succinctly, unincumbered by the bureaucracy that comes with an unwieldy and archaic acquisitions ecosystem. Though tragic, the Ukrainian model benefits from being unconstrained and defined by conflict. It is easy to dismiss the comparison between these two environments, but the Ukrainian model, which can provide low-cost, mass-produced capability, easily operated by a large pool of users, better defines the environment where the U.S. DOD professes to reside. The distinction between what the U.S. DOD design and acquisition acumen was historically and what the Ukrainian system is currently resides in the perceived lack of a U.S. existential threat. Bureaucracy and bravado die in the crucible of conflict. A major reason the DOD was so innovatively adept during WWII, the Cold War, and even the Global War on Terror was due to the existence, whether real or perceived, of that ever-present threat. It exists in the Ukraine. If we put down our collective Tik

Tok apps and heed President Xi, this threat exists in Asia's cauldron (Kaplan, 2015). Though the rhetoric is resounding, there is no urgency in today's DOD processes.

An Urgent Operational Need (UON, JUON for joint-related projects) is defined by CJCSI 5123.011 as "capability requirements that impact ongoing or anticipated contingency operations. If left unfulfilled, UONs can result in critical mission failure or even loss of life." (Joint Staff, 2021). In the very language is the essence of Skunk Works and the SR-71 and U-2 programs; this is the urgency that this paper intends to highlight. Further, due to grave necessity, the UON process is to conceive (with assistance from industry), develop, test, and field within two years. Granted, programs that propose to create entirely new technologies will most likely take longer to complete and deliver. However, there are a host of capabilities residing within current DOD programs and industry that can be harnessed, vetted, and either killed or fielded within stated and desired UON timelines.

The foundation of this project is the understanding that the U.S. cannot wait for conflict to erupt before it revamps its capability development and fielding processes. A mindset shift must take place now to foster a Ukrainian/Skunk Works style environment. That environment is defined (though not all encompassed) by:

1. **Distinction Between Operational Need and Requirement**. The DOD can collectively agree that the standing requirement to deter, and if needed, defeat an adversary already exists. However, when the time arrives to put funding toward capability development, an additional "requirement" is mandated within a specific acquisition silo. The umbrella requirement of "deterrence and/or victory in conflict" should suffice to commence development. If a capability is being fostered toward that end, no further requirement

document should be needed. Allow the test enterprise and warfighter to determine its relevance in the combat arena.

2. **Incentivize *Yes* and Embrace Failure**. The foundation of bureaucracy is *NO*. Each time a reason to say no occurs, the adversary benefits. DOD employees that do not have the power to grant approval cannot be allowed or incentivized to say no. The desired process should reward individuals, directorates, programs, and Commands that grant funding to initiate development and testing. Punitive measures should be implemented that punish zero risk prioritization. Space X's last two launches resulted in explosion, culminating in billions of dollars of costs; the type of event that would have similar DOD programs shuttered. The glaring difference is that the Space X work force considered the perceived "failures" as successes is that they provided much needed data for future development and launch. The DOD cannot incentivize a 100% success rate, particularly by feigning concern of cost, as the antithetical second order effect is a zero-risk organization. A return to incentivizing and the rewarding the generative mindsets of the "Kelly Johnsons" in organizations is a necessity.

3. **Combined Test Milestones Default**. There are undoubtedly instances that mandate a methodical, long-term test vetting process in cutting edge technology development, particularly when the human is at risk. However, as the DOD and industry development worlds draw closer together, many times the vetting process is already complete or needs a rapid government "top off" validation. The Ukrainians did not have the luxury of a drawn-out developmental test, followed in succession by operational test milestones (many times evaluating identical criteria). They rapidly and vividly proved that conception to combined test/fielding can successfully run concurrently. The examples in

DOD are legion of combined test rapidly fielding capability that adhere to the UON desired two-year timeline.[1] The DOD's Operational Testing and Evaluation (OT&E) processes will benefit from a combined test-default mindset, while mandating strict criteria for concurrent Operational Testing and Operational Evaluation elements prior to fielding. Again, the zero-risk system is wedded to long-term OT&E.

4. **Dedicated Funding Streams**. Whether funneled through Combatant Commands or entities within Services, such as Army Futures, funding streams must be created that allow innovative institutions the ability to rapidly put funding to conception, with the understanding it may result in a no fielding recommendation. Funding would reside at a higher level, but the capability requirement would be conceived at the tactical level, in a "bottom up" approach. This process already resides in the DOD ecosystem, in the form of the National Guard and Reserve Equipment Account (NGREA)[2] (Under Sectretary of Defense (Comptroller), 2023). Because the funding must be 80% allocated within the first year and spent within three years of approval, it incentivizes rapid acquisition, testing, and fielding or divestiture. In addition, the annual Congressional oversight disincentivizes fraud and/or waste. Though the funding stream is not intended for large weapon system acquisition such as a Next Generation Air Dominance (NGAD) fighter or Joint Light Tactical Vehicle (JLTV), as the current NGREA stream is relatively low by DOD budget definitions (approx. $200 million to $400 million per year to be allotted

[1] See HMIT discussion.

[2] In 1981, Congress created a separate equipment appropriation for the Reserve Components (RC) from the President's Budget submission entitled the Dedicated Procurement Program (DPP) which is now known as NGREA. The Congress intended NGREA to supplement the Services' budget requests to provide for investments in RC equipment which do not meet the prioritization threshold for inclusion in the President Budget submission. The Congress typically appropriates funding in lump-sum amounts to be used for aircraft and miscellaneous equipment.

across all Guard and Reserve components), with higher and higher awarded budgets, the process can be replicated and expanded to scale[3] (Thales, 2023).

If indeed the DOD resolves to be a "medium risk" entity, it must endeavor to assume risk in all it does, knowing that conflict with a near peer will be catastrophic. Zero risk is not an option, and processes, individuals, and organizations within the DOD that subscribe to a zero-risk ethos must be removed (White House, 2022). The recommended policy changes begin to address in the near term until the correct culture is codified.

Attributes of Sky Fortress for Rapid Acquisition

At the outset of the 2022 Russian invasion, Ukraine's air and missile defense architecture required augmentation and expansion to be effective against modern missile threats and defend greater area. The roughly 250 S-300 long-range surface-to-air systems, typical of the defensive capability at the start of the war, were designed in the 1960s to shoot down missiles and aircraft of that era (Foltynova, 2022). The threats to Ukraine include many modern low-flying missile

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[3] The GENTEX Helmet Mounted Integrated Targeting (HMIT) system, which enhances situational awareness and targeting capabilities for pilots, was adopted for both the A-10 Thunderbolt and the F-16 Block 30/32 Viper aircraft.

Selection and Award (2010):

In September 2010, the GENTEX Corporation and Raytheon were awarded the HMIT program. The program aimed to enhance targeting accuracy and mission performance for these aircraft.

Initial Phases and Integration (2010-2011): The HMIT program commenced immediately after the award. Initial phases focused on integrating the Scorpion HMCS into the existing aircraft systems. This phase involved adapting the helmet-mounted system to seamlessly interact with the aircraft avionics and sensors.

Operational Testing and Evaluation (IOT&E) (2011-2012):

Following integration, the system underwent rigorous operational testing and evaluation. Pilots tested the Scorpion HMCS in various scenarios, assessing its performance, accuracy, and ease of use.

Production Phases (2012-2013):

After successful IOT&E, production phases began. A total of 574 Scorpion systems were anticipated to be supplied over the life of the program. The program's total potential value was estimated at approximately $45-50 million. The entire system resolved to approximately $150k per copy, a large decrease from the Air Force's chosen Joint Helmet Mounted Cueing System (JHMCS) at $450k per system.

and lethal one-way attack drones that present detection and engagement challenges. Two years into the conflict, Ukrainian President Zelenskyy still prioritizes air defense system and missiles over all else in his request for aid.

From the outset of the war through October 2022, Ukraine created, demonstrated, and scaled an innovative network of air defenses sensors to detect the acoustic signatures of overhead missiles and drones. The speed at which they were able to create and field a functioning acoustic sensor for missile defense is remarkable when compared to the ten-plus-year timeframe more typical of new radar development (Randolph, 2018). While war was the impetus and provided the urgency, the conflict created a unique environment where funding deliberations loosened, skilled workers turned their attention to aid the war effort, and risk tolerances adjusted to allow less traditional solutions.

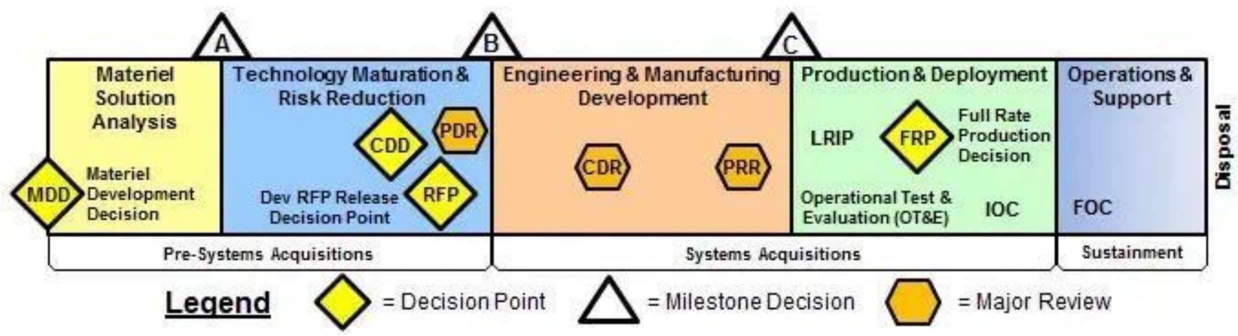

Figure 2-1. Major Capability Acquisition Stages (Manning, 2017)

While less formal than the U.S. Defense Acquisition Process, both components of Ukraine's Sky Fortress defense system (acoustic sensor network and SkyLock) began with an identified operational need and then mirrored the five phases of the U.S. acquisition process, which include: (1) Materiel Solution Analysis, (2) Technology Maturation & Risk Reduction, (3) Engineering & Manufacturing Development, (4) Production & Deployment, and (5) Operations & Support (DOD Instruction 5000.85, 2020). The Ukrainian acoustic sensor network began with recognition of the existing capability gap in the Soviet-era air defense radars. Russian attacks with low flying missiles and Shahed-136 drones were difficult to detect using the legacy radars that existed at the start of the war. The missiles fly low, at altitudes of 50 – 100 m off the ground, which greatly limits the detection range of the radar to about 50 km and compresses response times. For a subsonic missile travelling at approximately 0.5 – 0.7 Mach (617 – 864 km/h), the missile defender has 3.5 - 5 minutes to detect, track, ID, and engage the missile under optimal circumstances. Even more challenging for missile defense systems are the small radar cross sections of the Shahed-136. Several design characteristics of the Shaheed-136 make it difficult for even modern radars to detect these threats due to their delta wing geometry, radar absorbing materials (e.g., carbon fiber), radar absorbing structures (honeycomb), and slower speeds (Rubin, 2023). Leading SkyLock’s development was recognition of the imbalance between the number of missiles in Russia’s arsenal and the available missile interceptors in Ukraine’s arsenal. As of February 2024, Ukraine reported that more than 8,000 missiles and 4,630 drones were launched against them (Dysa, 2024). Any effective defense against such an arsenal requires the use of cheap and easy to produce effectors to intercept such quantities. The need for an improved and scalable air and missile sensing network and an inexpensive effective method to stop Russian attacks were well understood early in the conflict. Solution development began in the research and development (R&D) community without formal requirements validation, or more importantly, without time spent seeking validation from the acquisition community.

In the U.S., new defense programs begin with a formal definition and validation of requirements by leaders in the defense acquisition community, that result in a Materiel Development Decision (MDD) (see Figure 2-1) or similar formal acceptance. When the requirement is approved, the program is already on one of three relevant paths in the Adaptive Acquisition Framework, each of which has its own process for obtaining requirement approval.

The deliberate process for systems more than two years out requires several supporting documents, resulting in an Initial Capabilities Document (ICD). This path typically takes 9 – 18 months or longer to move through the requirements definition and validation process and allows for 97 days for staffing alone. The fastest path for urgent capability acquisition is initiated by a need statement from the warfighter. An acquisition lead is then appointed to create an acquisition strategy. This process is largely limited to vetting known acquisition activities that can be fielded and tested within two years and has minimal visibility within the U.S. defense R&D cadre, which is part of the larger R&D community that made Sky Fortress so successful (Defense Acquisition University, 2024; Joint Requirements Oversight Council, 2021). Middle Tier Acquisition (MTA) is designed to meet emergent military needs and quickly field prototypes of capabilities already at higher levels of maturity. MTA, like the other two processes, have requirements to start the development activities that include plans for security, risks reduction, test strategies, and a transition plan (2019). Navigating any of these paths requires experienced professionals with significant understanding of the budget, programming, contracting, and acquisition processes, which locks out anyone outside the active military or defense civilian acquisition cadre. The deliberate delays and entrance criteria of the acquisition processes preceding requirement validation and isolation from the R&D community make it unlikely that the Sky Fortress program would have succeeded through any of the three defense acquisition processes.

Private industry provides an option for rapid progression to align developers, requirements, and funding through their independent research and development processes. Or, as in Ukraine’s case, donations from private citizens and businesses provided the $3 million in initial funding for a technically savvy team to develop a solution outside of the traditional defense enterprise. Ukraine’s Sky Fortress team specifically names the fact that the effort began with non-governmental dollars outside the defense acquisition process as a key reason why they were able to go fast and introduce such novel solutions.

For urgent operational needs prioritized by a Combatant Commander, the U.S. DOD must be able to replicate the rapid development, utilizing solutions from the defense R&D enterprise without the delays introduced by requirements validation and programming processes. DOD has a standing cadre of creative and innovative R&D professionals employed in the DOD Service laboratories: Army Research Laboratory (ARL), Air Force Research Laboratory (AFRL), and Naval Research Laboratory (NRL). Most DOD research is funded through reimbursable funds from DOD program offices and the intelligence community using processes separate from the acquisition processes that often require a technical proposal in response to a call from a program manager. As recently opined by the first Defense Innovation Unit director, it is absurd that the U.S. has no method in place linking the R&D community successes to the acquisition process (Brown, 2024). Perhaps even more so is that answers to the most pressing and needed capability gaps are filled without the deliberate input from the thousands of scientists and researchers readily available to the DOD. Like the ability of Sky Fortress to quickly pull from the R&D community to close a capability gap, the U.S. DOD must normalize a pathway to leverage their existing cadre of motivated and technical R&D staff with set-aside funding to provide innovative solutions to the most pressing problems.

Recommendation 1: Formalize R&D community engagement for every Joint Emergent/Urgent Operational Need (JEON/JUON) submitted by tasking at least one Service Laboratory (ARL, AFRL, or NRL) to provide recommended options within a month's time and provide sufficient funding $400k/lab to support that R&D recommendation report.

Recommendation 2: Fund at least one R&D solution, selected by the JEON/JUON submitting organization, to produce a minimally viable product and have the assigned PM support the R&D effort through minimally viable product development. This funding should be in parallel to any accepted solution from the acquisition community.

During the materiel solution analysis phase of Sky Fortress, one solution was to obtain modern air defense systems from like-minded foreign partners and allies. Several modern defensive systems were delivered to Ukraine from advanced Western militaries (e.g., IRIS-T, NASAMS, and PATRIOT systems). These sophisticated systems include at least three large vehicles, one of which carries an active radar. The radar and thermal signatures of these systems make them vulnerable to being targeted by Russia. Coupled with the high system cost, extensive personnel training requirements, scarcity of replacements, and low interceptor availability, these modern systems provide the greatest value defending critical assets against the most damaging, threatening Russian attacks. The Sky Fortress technical team realized that solutions for much more numerous subsonic cruise missiles and Shahed drones must consider only options that were readily available, relatively inexpensive compared to Western systems, and still effective for both detecting and defeating the air and missile threats to large areas of Ukraine. The team also recognized the challenges of detecting and tracking the low-flying trajectories of modern missiles and small radar footprints of drones using traditional radars. These understandings led them to consider a passive missile tracking technology that had not been used since the invention of radar by the Naval Research Laboratory before World War II (DeGering, 2018). Acoustic sensors offer a passive solution that is inexpensive to build with widely available components. Sound is good for detecting airborne targets because any object flying at speed will produce sound, and the engine itself produces signatures that allow for object typing, or identification of the threat, which makes even the hard targets for radars that are radio quiet and thermally cool, detectable by the sound they emit (Sky Fortress, 2024). During this phase, Sky Fortress deliberately chose to take an atypical approach and build a distributed network of sensors instead of single, long-range and powerful sensors common in air defense systems. The networked approach offers several logistical benefits that fit the intended operational environment, including the ability to power each sensor with a battery, short-range detection capability providing accurate position information and line-of-sight communications, and an ability to scale the coverage area with inexpensive, attributable units. The initial design used cell phones that had the ability to provide mobile communications and connections to the internet. During the initial deployment, the Sky Fortress team relied on readily available commercial-off-the-self components, which enabled the rapid procurement, assembly, and deployment of a large amount of hardware. Concurrent with hardware build and fielding was the development of the sophisticated software package that allowed for targeting of the threats using the .50 caliber machine guns that comprise the SkyLock component. For Ukraine, the transition out of the materiel solution analysis phase was marked by the successful demonstration of the first operational demonstration around Kyiv. This demonstration required a Ukrainian Colonel to have interest and accept the risk for allowing the installation of these systems without any formal performance or safety evaluations.

Recommendation 3: Validate requirements more quickly by matching R&D outputs and industry products to the operational needs provided by the warfighter, and move the activities currently done in the pre-decisional, pre-MDD, and pre-ADM phases to after requirement validation and initial funding (e.g., the materiel analysis phase).

By the time the Ukrainian government invested in Sky Fortress in December 2023, the team was already running concurrently the last four phases of a U.S. acquisition: Technical Maturation and Risk Reduction, Engineering and Manufacturing, Production and Deployment, and Operation and Support. Two key enablers of the concurrent development and speed of the program are a) the internet connection to each of the individual hardware components, allowing for frequent updates to the software on the individual sensor package and increased performance of the distributed network of sensors while additional hardware is being assembled, and b) the partnership with major network operators of the electric grid and cellular networks, leveraging an existing workforce to service the thousands of sensors in the acoustic network. While the network was expanding, updates were being distributed, and hardware received upgrades, Sky Fortress became more effective at destroying Russian air and missile threats. Ukraine continues to expand the acoustic network, with their next objective of using buoy versions of the acoustic sensors, shown in Figure 2-2, to provide the early warning of threats transiting the Black Sea, which requires refinement of the communication network to longer-range radio relays and satellite communications (likely via Starlink).

Recommendation 4: Prioritize the fielding of the capability by creating a system that plans for upgrades, software/firmware updates, and capability enhancements while positioned in the intended operating environment.

Figure 2-2. Black Sea Deployment of Ukrainian Bouy with Acoustic Sensor

Proposed Acoustic Lily Pads

Translating the successes of Sky Fortress into the U.S. Indo-Pacific theater inherently requires the Ukrainian land-based solution be 1) sea-worthy and 2) at a much larger scale. There are increased technical challenges associated with the transfer to a wider maritime environment, but they can either be overcome or already have solutions through previous research. Through the JUON process, a full-scale generation-1 mesh can be implemented within two years, with upgrades six months following.

Presented here is a concept for a meshed network of autonomous untethered maritime acoustic sensing nodes called Acoustic Lily Pads. The Acoustic Lily Pads can perform the same acoustic sensing, identification and tracking operations as Sky Fortress, but they are integrated into the U.S. Indo-Pacific Command missile and air defense structure, specifically providing situational awareness of subsonic cruise missiles and low-cost UAVs.

Technical Description

Each Acoustic Lily Pad can be thought of as a single sensing platform in communication with each other sending information to relevant networks. The nodes are simple for construction in that they consist of a microphone, processing chip, power, communication capability, and environmental protection. All components are easily sourced domestically, requiring no technical breakthroughs for the development process, which increases the rate of implementation and keeps costs low for scaling. Work performed by the U.S. Naval Academy has estimated that similarly designed floating buoys could cost around $500 each (Laun & Pittman, 2018). The Sky Fortress system was able to maximize domestic supply chains and only needed to extend locally into Western Europe when the domestic supply of components was insufficient, resulting in a cost per node of approximately $300. Risks associated with global supply chain reliance for the Acoustic Lily Pads are therefore minimized.

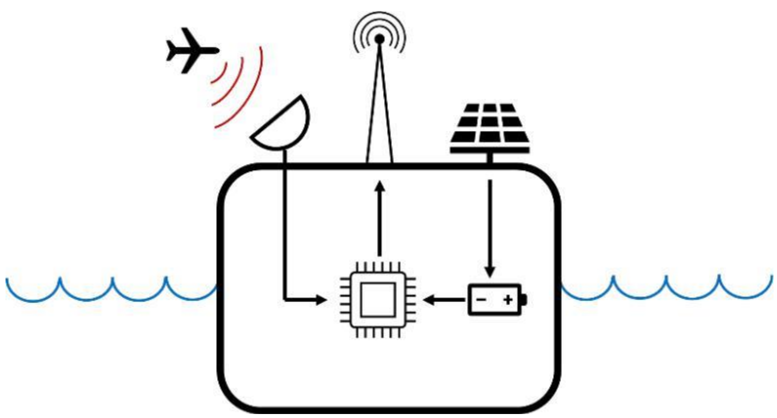

Figure 3-1. Schematic diagram of the Acoustic Lily Pad components, microphone, processor, communications, renewable power harvesting, and battery.

According to our interview with the developers of Sky Fortress, the largest, most expensive and technically challenging component of each acoustic node was the environmental protection container. This challenge will be even more pressing in a maritime environment where salt-induced corrosion will be a defining factor for the operational lifetime of individual nodes.

All components should be hardened to the marine environment and encased in a floating container with pass-through ports resilient to seawater intrusion. Designs currently in use by NOAA's "Global Drifter Program" would be suitable for these purposes (U.S. Department of Commerce; van Sebille et al., 2021). It is acknowledged that the Western Pacific Ocean regularly sees extreme storm systems. Survival of the nodes in these weather events is not expected, though weather monitoring drifter buoys are often employed to gather weather data from such storms (Lagrangian Drifter Laboratory, 2021). The low-cost nature of the Acoustic Lily Pads enables replacement without straining sustainment budgets if they are lost.

Floating Platform

The Acoustic Lily Pad is a small floating platform without any anchoring cables due to the deep-water environments of the Western Pacific Ocean. One key decision is therefore required at the outset of design is whether the system will have any station-keeping capabilities. With station-keeping, the network can be more certain in the location of each node giving more predictable and persistent coverage. However, the additional power and added components will make each Acoustic Lily Pad larger, more costly, and create more opportunities for failure. Drogues can be used to maintain some stability in the current and are used on most of the Global Drifter designs. Some research has shown that using ocean currents can provide predictive control over the routes of floating platforms though most path planning models are built for underwater autonomous systems (Yoo & Kim, 2016). A network without station keeping can also overcome persistence challenges by distributing more nodes into an operational area increasing redundancy.

Microphones/Hydrophones

Direct translation of Sky Fortress to Acoustic Lily Pad would employ a microphone for sensing threats. This design is the simplest and most likely quickest path to scale. One identified challenge is the noise produced by surface waves and splashes on the unit, which will impart a non-negligible background signal.

The use of hydrophones to detect aircraft has been studied in the past with some intriguing results (Urick, 1972). Because sound travels approximately 5 times faster in water than air there can be greater range of detection. Secondly, placing a hydrophone at sufficient depth (>100 ft) can eliminate the noise from surface waves to create a clearer signal. Finally, reflections from the ocean bottom can even be employed by the deeper hydrophones where the reflection off the ocean bottom at 14,000 ft has a much cleaner signal compared with direct sensing. Given the mature nature of both microphones and hydrophones, it is neither burdensome in cost nor technically unreasonable to have both employed on the Acoustic Lily Pads. The potential capabilities of employing various sensors can be explored experimentally to give Acoustic Lily Pads greater range and fidelity, but if rapid acquisition is needed, surface-mounted microphones should be used in initial production. Rapid in-field experimentation should also be employed to modify later generations of Acoustic Lily Pads within six months of initial launch and periodically improve the capabilities of the units. This rapid experimentation or “tinkering” was professed as the best route for development in an interview by our team with NavalX (Newborn & Jensen, 2024).

Power

The sensing and communication components of the Sky Fortress nodes have been analyzed to pull 1-10 W average power. The power requirements of the Acoustic Lily Pad should be similar without station-keeping. Transmission communication will cause spikes in power demand, which will be handled with onboard rechargeable batteries. To recharge the batteries a sky-facing photovoltaic panel on the surface of the Acoustic Lily Pad can enable longer duration without battery swapping. Each solar panel would need to be only 600 – 6,000 cm^2 (assuming 10% efficiency), approximately the size of a sheet of printer paper, to provide virtually indefinite power.

Data Fusion

Each node has the capability to sense, process, and identify threats in its environment. Once the data is analyzed, the node must transmit this data and continuous tracking data to the cloud for triangulation and filtering. Sky Fortress uses both cellular networking and inter-node radio transmission for transferring the data to cloud servers. Commanders can call the server with an API to obtain the current threat picture. The design is such that there are no automatic deployment of effectors through Sky Fortress, enabling the commanders on the ground to build their responses any way they wish. Acoustic Lily Pads should be similar with the only exception that cellular networks are absent far from shore. Satellite linkage is a suitable alternative, which is available through satellite constellations (Space Development Agency, 2022) like Starshield (Schogol, 2023) or Iridium (Iridium Communications Inc.). The node-to-node radio frequency mesh is also a backup option if satellites are unavailable and will need an online connection for server access either through ground communications or through a more centralized transmitter.

Recently, DARPA’s Ocean of Things (Ocean of Things, 2024) program published results from Persistent Environmental Awareness Reporting and Location (PEARL) drifters. The PEARL drifters are almost exactly what are being proposing with Acoustic Lily Pads. They were renewably powered individual platforms with atmospheric and subsurface acoustic sensing capabilities, which communicate via data packets to the Iridium constellation. Without any steering capability, the experiments showed that ocean currents can be used to disperse the array over the course of a week from a central drop point from a ship to an average node spacing of 2 km required of the Acoustic Lily Pads for full acoustic coverage of an area of interest. For the sensing purposes of Acoustic Lily Pads, the PEARL drifters would require upgrades for edge processing capabilities specific to identified missile threats and the additional capability to pass communications from drifter to drifter instead of satellite-only communication. Corrosion and bioaccumulation were reported on PEARL drifters but should not be an issue if Acoustic Lily Pads are deployed with ≤ 10 days before an anticipated attack (Cocker et al., 2022).

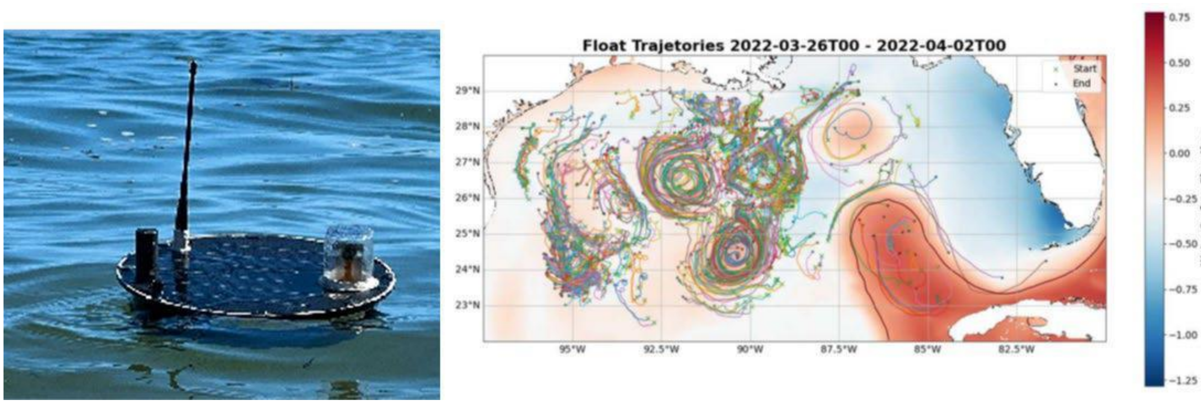

Figure 3-2. PEARL drifter program for floating sensor arrays (Cocker et al., 2022).

<u>Shooter Orientation</u>

The fidelity of any acoustic tracking mesh network is dependent on the number of nodes and their effective range. A single node will be able to provide a threat ID and a vector initially. With some processing while tracking, it may also give direction of travel, but many nodes are necessary to give verifiable location data and altitude. Acoustic sensing has an effective range of up to 2 km without interference from ocean surface noise (Sky Fortress, 2024). Ideally, more Acoustic Lily Pads than the minimum would be used to provide redundant and more accurate coverage. Table 3-1 directly translates the Ukrainian coverage to the western Pacific regions, and the total estimated number of units with materials cost needed to blanket each region with the fidelity of Sky Fortress.

Table 3-1. Metrics for Translation to U.S. INDO-Pacific Command

Region	Ukraine	E China Sea	S China Sea	Philippine Sea	Guam 360˚ 200-mi radius
Area	233,000 mi^2	300,000 mi^2	1,400,000 mi^2	2,200,000 mi^2	125,663 mi^2
Number of sensors	15,000 (est.)	19,313	90,128	141,630	8,089
Total Est. Cost	$4.5 million	$5.8 million	$27 million	$42.5 million	$2.4 million

Figure 3-3 shows that the scale of the Indo-Pacific theater would require vastly more units than currently employed in the ground-based solution of Sky Fortress by at least an order of magnitude.

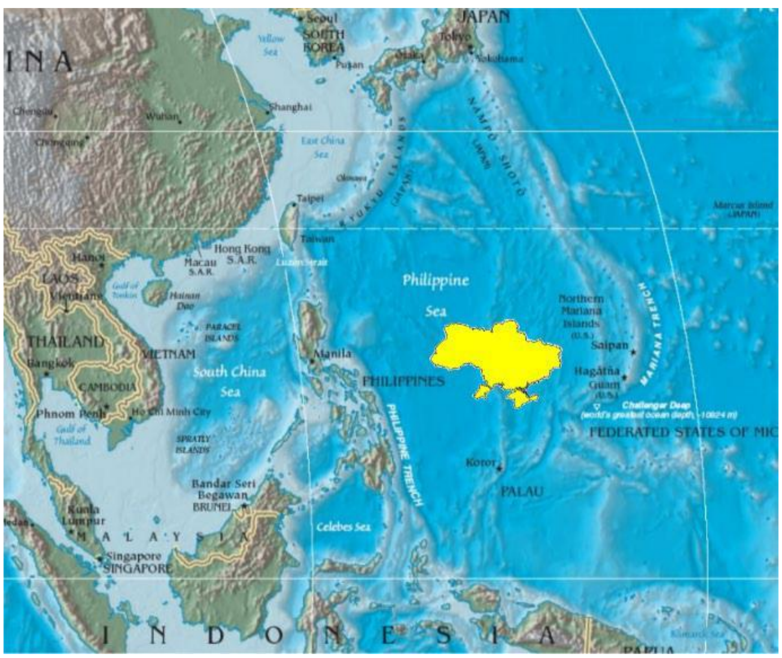

Figure 3-3. Map of the Western Pacific Ocean with Ukraine for Scale

Use Cases

Forward Fixed Base Island Defense

Challenge: Fixed military installations in the Pacific are particularly vulnerable to sophisticated attacks. These bases require large startup costs and are permanently installed at well-established locations. Any attacks on these bases can benefit from long-term target reconnaissance and detailed operational planning that optimizes for success. Additionally, these U.S. and allied bases in the Pacific are on islands far from U.S. support, making the complex logistics supporting forward fixed bases even more complicated during conflict. American military bases, even when located in the proximity of large cities, are still islands of U.S. control in host nations that are subject to the details of the basing agreement with the host nation. Introducing relocatable and dynamic sensing architectures into fixed-base defense capabilities introduces operational flexibility and mitigates the effectiveness of the preplanned attack.

Operational enhancements: Options for Acoustic Lily Pads allow for them to be deployed as necessary based on the threat assessment and risk tolerance of the base commander. Table 3-1 is an estimate of the numbers (8,000 +) and cost ($2.4 million) of a fully populated network of Acoustic Lily Pads equally spaced on a grid with a 2 km separation from each other. As the tensions escalate, the theater area air defense commander would order the deployment of the Lily Pad sensor grid to detect and track any air and missile threat within a 200 km radius of the island, like Guam. Integration of the sensor network into established missile defense command and control systems like the Navy's Aegis system and the Army's Integrated Fire Control Network would add warning time, expand the operator's decision space, and provide real-time updates to threat maneuvers that support and intercept decisions. One option to have each individual sensor platform be self-propelled and autonomous would support the sensors being launched from shore in addition to being dropped by boat or plane in position. The addition of either autonomous surface vessels with smart interceptors or fast boat fire units, like the mobile fire teams of SkyLock will add another layer of defense against the low-flying cruise missiles and drones. Short-term deployments keep the maintenance and operating costs down and minimize the environmental and local area impacts. Deployments of the Acoustic Lily Pad sensor network reveal defensive posture preparations that complicate enemy planning and possibly deter additional aggression.

U.S. Indo-Pacific Command Application (Island Base Defense)	
Advantages	Risk/Challenges
• **Maritime application avoids many of the schedule delays associated with land-use impact studies** • **Mobile platforms can dynamically adjust to sensor gaps in land-based architecture (either due to maintenance or attrition)** • **Sensor coverage expanded to beyond the radar horizon for earlier detection of threats**	• Maritime application could meet with pushback given the current complex and land-based defenses in Guam • Slow to move sensor network • Maritime environment drives maintenances cost for long-term deployments

<u>Expeditionary Support</u>

Challenge: Operating in contested locations. Since the mid-1990s, China pursued an anti-access/area denial (A2/AD) strategy mostly within the immediate vicinity of the Chinese mainland and extended out past the first island chain into the Western Pacific. A2/AD seeks to add enough risk to foreign troops maneuvering in the protected area that they would instead choose to avoid entering those locations all together, especially with easy-to-target or hard-to-replace national assets like aircraft carriers and large expeditionary units. These assets distributed within the A2/AD zones will be targeted with precision strike missiles and must be able to operate in this environment actively or passively.

Operational enhancement: Acoustic Lily Pads will be deployed by ship, plane, or autonomously guided into position from the nearest friendly land base days or hours before the primary operations begin. The sensor network connected either through line-of-sight communication pathways or through airborne or satellite relays provides early, and perhaps the only, warning of approaching air and missile threats. The hundreds if not thousands of sensors will provide a hard-to-counter and easy-repair forward sensor capable of scaling to cover massive areas of ocean between the first and second island chains and around the Western and Southern Pacific islands. After each mission, the network can be recovered manually, programmed to return automatically to base, or self-detonated. The sensor network can again support missile tracking and will cue and orient available missile defeat capabilities to add engagement space and defense system effectiveness. The Taiwan Strait and South China Sea share many similar operational attributes relevant to the current conflict around the Red Sea. The Red Sea can therefore be used as experimentation grounds for Acoustic Lily Pads.

Allies and Partners

Challenge: Access is even more limited so close to the Chinese and Russian coastlines due to the high quantity of short-range munitions, not to mention the large quantity of commercial ship traffic in the area. Large missile defense radars are expensive to install and easily targetable by the large inventory of short-range missile and drones from China. Any permanent maritime sensing solution within the first island chain would be difficult to maintain, likely to disrupt private shipping operations, and susceptible to adversary inference. Without a missile warning and tracking solution, U.S. and allied forces would be much more vulnerable to strikes against them. Additionally, many allied partners in the Western Pacific and around the South China Sea are significantly smaller than China and are at a substantial disadvantage in capacity to counter an extended period of aggression with regional support.

Operational enhancement: Acoustic Lily Pads will strengthen the defenses of U.S. allies and partners and of U.S. forces at bases in Japan or Korea within the first island chain. The components of the Lily Pads are readily available and non-proprietary commercial products, which makes them assessable for allies and partners to assemble and deploy themselves. Ideally, a composite picture of U.S. and allied missile warnings should want to be common and shared among partners. Deploying the agile, autonomous effectors with deep magazines will have the greatest impact in this use case by adding a new defensive layer with significant capacity improvements to counter the expected raids of inexpensive and plentiful low-end threats that portend the more calamitous but less numerous strategic threats anticipated in subsequent raids, reducing overall risk to these units from air and missile threats.

Key Challenges / Risks

Technical

- Sound from surface waves clouds microphones.
- Communications in a denied environment will need to maintain connectivity.
- Deployment into the large area of interest could take significant time.

- No requirement.
- Current acquisition process delays restrict rapid acquisition.
- Limited testing opportunities during peace time.

Integration

- Foreign partner cooperation for use of their territorial waters.

Policy

- Ocean Pollution Laws, Treaties, and Regulations – also has the advantage of being off land sites, thus avoiding environmental impact studies and contentious NIMBY discussions. The United States is a signatory to several annexes of the International Convention for the Prevention of Pollution by Ships – MARPOL. Annex 5 of the convention deals specifically with garbage and was further strengthened in U.S. laws by the Act to Prevent Pollution from Ships. These laws prohibit, among other things, the discharge into the ocean of plastics and synthetic materials.
- Interference in fishing and commercial shipping.
- Operating area overall, perhaps unintentional with EEZ of foreign nations.
- Resistance from established industry that feel their business model is threatened.

Conclusion

Acoustic Lily Pads provide a scalable and cost-effective option to augment complex and expensive IAMDs. Whether the mission is protecting small units or strategic islands, such as Guam, there is no argument against the capability. These assets offer a combat-proven and mature technology that is reliable, producible, and maintainable. The technology has created strategic advantages against pacing competitors such as Russia. Acoustic Lily Pads provide diverse application across the joint force while seamlessly aligning with National Strategic Documents. The 2022 Missile Defense Review states “The United States Requires responsive, persistent, resilient, and cost-effective joint IAMD sensor capabilities to detect, characterize, track, and engage current and emerging advanced air and missile threats” (Department of

Defense, 2022). It is not practical to wait until war breaks out. The leaders of all services owe its servicemembers access to this innovative technology at the speed of deterrence.

References

Albright, D., Burkhard, S., & The Good ISIS team. (2023). *Visible Progress at Russia's Shahed Drone Production Site Satellite Imagery Update and Call for Action*. https://isis-online.org/isis-reports/detail/visible-progress-at-russias-shahed-drone-production-site

Army Technology. (2023). *Shahed-136 Kamikaze UAV, Iran*. Army Technology. Retrieved 3/20/2024 from https://www.army-technology.com/projects/shahed-136-kamikaze-uav-iran/?cf-view

Axe, D. (2024). Ukraine Has A New Air-Defense Vehicle: An Old M-113 APC Armed With An Equally Old ZU-23-2 Auto-Cannon. *Forbes*. https://www.forbes.com/sites/davidaxe/2024/01/06/ukraine-has-a-new-air-defense-vehicle-an-old-m-113-apc-armed-with-an-equally-old-zu-23-2-auto-cannon/?sh=6954a07d4cf6

Bennett, D., & Ilyushina, M. (2023, August 17, 2023). Inside the Russian Effort to Build 6,000 Attack Drones with Iran's Help. *The Washington Post*. https://www.washingtonpost.com/investigations/2023/08/17/russia-iran-drone-shahed-alabuga/

U.S. Army. (2014). *Acoustic Detection and Tracking of a Class I UAS with a Small Tetrahedral Microphone Array*. (ARL TR-7086). U.S. Army Research Laboratory

Bowsher, H. (2023). Air Denial Lessons from Ukraine. *149*(9), 1447. Retrieved 3/20/2024, from https://www.usni.org/magazines/proceedings/2023/september/air-denial-lessons-ukraine

Brown, M. (2024). The Big Disconnect: Defense R&D And Warfighter Capabilities. *Forbes*. https://www.forbes.com/sites/mikebrown/2024/03/26/the-big-disconnect-defense-rd-and-warfighter-capabilities/?sh=6995df736de4

Cocker, E., Bert, J. A., Torres, F., Shreve, M., Kalb, J., Lee, J., Poimboeuf, M., Fautley, P., Adams, S., Lee, J., Lu, J. P., Chua, C., Chang, N., Neltner, S., & Gray, M. (2022). Low-Cost, Intelligent Drifter Fleet for Large-Scale, Distributed Ocean Observation. *2022 Oceans Hampton Roads*. https://doi.org/10.1109/Oceans47191.2022.9977209

Collier, S. L. (2005). Fisher information for a complex Gaussian random variable: Beamforming applications for wave propagation in a random medium. *Ieee Transactions on Signal Processing*, *53*(11), 4236-4248. https://doi.org/10.1109/Tsp.2005.857046

Collier, S. L., Solomon, L. I., Erikson, M. M., Ligon, D. A., Denis, M. F., Noble, J. M., Alberts, W. C. K., Sim, L. K., Reiff, C. G., & James, D. D. (2017). Atmospheric Effects on Acoustic Vector Sensing. Military Sensing Symposia Specialty (MSS) Group on

Battlespace Acoustic, Seismic, Magnetic, and Electric-Field Sensing and Signatures (BAMS), Springfield, VA.

Collier, S. L., & Wilson, D. K. (2003). Performance bounds for passive sensor arrays operating in a turbulent medium: Plane-wave analysis. *Journal of the Acoustical Society of America*, *113*(5), 2704-2718. https://doi.org/10.1121/1.1554691

Collier, S. L., & Wilson, D. K. (2004). Performance bounds for passive sensor arrays operating in a turbulent medium: Spherical-wave analysis. *Journal of the Acoustical Society of America*, *116*(2), 987-1001. https://doi.org/10.1121/1.1760111

Cook, E. (2023, May 23, 2023). Ukraine Shoots Down Russian Mi-24 Helicopter Using Igla MANPADS. *Newsweek*. https://www.newsweek.com/ukraine-shoot-down-russia-mi24-attack-helicopter-igla-manpads-1801999

Defense Acquisition University. (2024). *JCIDS Staffing and Validation*. Retrieved 3/21/2024 from https://www.dau.edu/acquipedia-article/document-staffing-and-validation

DeGering, R. (2018). *The Invention of Radar*. A. U. Press. http://www.jstor.com/stable/resrep19549.8

Department of Defense. (2022). *2022 National Defense Strategy of the United States of America*.

Office of the Under Secretary of Defense for Acquisition and Sustainment. (2019). *DOD Instruction 5000.80 Operation of the Middle Tier of Acquisition (MTA)*. Retrieved from https://www.esd.whs.mil/DD/

Office of the Under Secretary of Defense for Acquisition and Sustainment. (2020). *DOD Instruction 5000.85 Major Capability Acquisition*. Retrieved from www.esd.whs.mil/DD/

Dysa, Y. (2024). Ukraine appeals for air defence aid, citing hundreds of missile attacks in March. Retrieved 3/21/2024, from https://www.reuters.com/world/europe/ukraine-appeals-air-defence-aid-citing-hundreds-missile-attacks-march-2024-03-19/

Edwards, E. (2022). Why the M2 Browning .50 Caliber is the Most Lethal Heavy Machine Gun in History. https://www.warhistoryonline.com/guns/m2-browning-50-caliber.html

Foltynova, K. (2022). Protecting The Skies: How Does Ukraine Defend Against Russian Missiles? Retrieved 3/20/2024, from https://www.rferl.org/a/ukraine-missile-defense-weapons-charts-russia/32192132.html

General Dynamics. (2012). M2HB .50 Caliber (12.7mm) Heavy Machine Gun Reliable, Accurate, Effective. In General Dynamics (Ed.). St. Petersburg, FL: General Dynamics,.

Grise, M., & Evans, A. T. (2023). *The Drivers of and Outlook for Russian-Iranian Cooperation* (Expert Insights on a Timely Policy, Issue. https://www.rand.org/pubs/perspectives/PEA2829-1.html

Iridium Communications Inc. *U.S. Government: Defense, Intelligence, & National Security*. Iridium. Retrieved 3/19/2024 from https://www.iridium.com/markets/defense-intelligence-national-security/

Department of Defense. (2021). *Manual for the Operation of the Joint Capabilities Integration and Development System*. Defense Acquisition University

D. o. Defense. (2021). *Charter of the Joint Requirements OVersight Council and Implementation of the Joint Capabilities Integration and Development System*.

Kaplan, R. D. (2015). *Asia's Cauldron: The South China Sea and the End of a Stable Pacific*. Random House Publishing Group.

Knights, M., & Almeida, A. (2022). What Iran’s Drones in Ukraine Mean for the Future of War. https://www.washingtoninstitute.org/policy-analysis/what-irans-drones-ukraine-mean-future-war

Lagrangian Drifter Laboratory. (2021). *Global Drifter Program Wave Drifters Measure the 2020–2021 Hurricane Seasons* https://gdp.ucsd.edu/ldl/global-drifter-program-wave-drifters-measures-the-2020-2021-hurricane-seasons/

Laun, L. T. A., & Pittman, E. N. S. E. (2018). Development of a Small, Low-Cost, Networked Buoy for Persistent Ocean Monitoring and Data Acquisition. *Oceans 2018 Mts/Ieee Charleston*. <Go to ISI>://WOS:000461320200036

Malyasov, D. (2024). Ukrainian soldier shot down Russian missile with machine gun. *Defence Blog*. Retrieved 3/25/2024, from https://defence-blog.com/ukrainian-soldier-shot-down-russian-missile-with-machine-gun/

Manning, B. (2017, 2/15/2022). *Acquisition Process Overview*. AcqNotes. https://acqnotes.com/acquisitions/acquisition-process-overview

Mickeviciute, R. (2023). The SR-71 Blackbird: unveiling the fastest plane ever built. *AeroTime Hub*. https://www.aerotime.aero/articles/the-sr-71-blackbird-a-look-at-the-fastest-plane-ever-built

Missile Defense Advocacy Alliance. (2022). *FIM-92 Stinger*. Retrieved 3/27/2024 from https://missiledefenseadvocacy.org/defense-systems/fim-92-stinger/

Missile Defense Advocacy Alliance. (2024). *Missile Interceptors by Cost*. Retrieved 3/20/2024 from https://missiledefenseadvocacy.org/missile-defense-systems-2/missile-defense-systems/missile-interceptors-by-cost/

Missile Threat, C. f. S. a. I. S. (2018, April 12, 2021). *Missiles of China*. Center for Strategic and International Studies. Retrieved 3/25/2024 from https://missilethreat.csis.org/country/china/

Naz, P., & Marty, C. (2006). Sound detection and localization of small arms, mortars and artillery guns - art. no. 62310Y. *Proceedings of SPIE - The International Society for Optical Engineering*, *6231*. https://doi.org/10.1117/12.672936

Newborn, D., & Jensen, G. (2024, 1/23/2024). *Interview with NavalX* [Interview]. MS Teams;

Ocean of Things. (2024). DARPA. Retrieved 3/28/2024 from https://oceanofthings.darpa.mil/

Randolph, M. (2018). The Road to G/ATOR: Corps Delivers Next-Gen Radar to Marines. https://www.marcorsyscom.marines.mil/News/News-Article-Display/Article/1465486/the-road-to-gator-corps-delivers-next-gen-radar-to-marines/

Rubin, U. (2023). Russia’s Iranian-Made UAVs: A Technical Profile. https://www.rusi.org/explore-our-research/publications/commentary/russias-iranian-made-uavs-technical-profile

Schogol, J. (2023). Army combat advisors testing military version of Elon Musk’s Starlink. *Task & Purpose*. https://taskandpurpose.com/news/army-sfab-starshield-spacex-elon-musk/

Sky Fortress. (2024, January 11, 2024). *Interview with Sky Fortress Developers* [Interview]. MS Teams;

Space Development Agency. (2022). *Space Development Agency Makes Awards for 126 Satellites to Build Tranche 1 Transport Layer* https://www.defense.gov/News/Releases/Release/Article/2948229/space-development-agency-makes-awards-for-126-satellites-to-build-tranche-1-tra/

Tenney, S., Mays, B., Hillis, D., Tran-Luu, D., Houser, J., & Reiff, C. (2004). *Acoustic Mortar Localization System Results from OIF* Proceedings of the Army Science Conference, Orlando, FL.

Thales. (2023). *Helmet Mounted Cueing System (HMCS)*. Retrieved March 14 from https://www.thalesdsi.com/our-services/visionix-2/hmcs/

Trevithick, J. (2024). Ukraine Using Thousands Of Networked Microphones To Track Russian Drones. *The War Zone*. https://www.twz.com/land/thousands-of-networked-microphones-are-tracking-drones-in-ukraine

Trofimov, Y., Cullison, A., Forrest, B., & Simmons, A. M. (2022, Feb. 25, 2022). Ukrainian Capital Rocked by Explosions as Russia Intensifies Attack. *Wall Street Journal*. https://www.wsj.com/articles/russia-attacks-ukraine-drawing-broad-condemnation-11645682406

U.S. Department of Commerce. *Global Drifter Program*. Retrieved March 12 from https://www.aoml.noaa.gov/proj/global-drifter-program/

Department of Defense. (2023). *DOD 7000.14 - R Financial Management Reglulation*. Under Sectretary of Defense (Comptroller)

Urick, R. J. (1972). Noise Signature of an Aircraft in Level Flight over a Hydrophone in Sea. *Journal of the Acoustical Society of America*, *52*(1), 172-+.

USINDOPACOM. (2024). *About USINDOPACOM*. Retrieved 3/27/2024 from https://www.pacom.mil/About-USINDOPACOM/

van Sebille, E., Zettler, E., Wienders, N., Amaral-Zettler, L., Elipot, S., & Lumpkin, R. (2021). Dispersion of Surface Drifters in the Tropical Atlantic. *Frontiers in Marine Science*, *7*. https://doi.org/10.3389/fmars.2020.607426

WeaponSystems.net. (2024). *9K38 Igla, NATO: SA-18 Grouse*. Retrieved 4/2/2024 from https://weaponsystems.net/system/770-9K38+Igla

Wetzel, T. (2022). Ukraine air war examined: A glimpse at the future of air warfare. Retrieved 3/20/2024, from https://www.atlanticcouncil.org/content-series/airpower-after-ukraine/ukraine-air-war-examined-a-glimpse-at-the-future-of-air-warfare/

The White House. (2022). *Indo-Pacific Strategy of the United States*. Retrieved from https://www.whitehouse.gov/wp-content/uploads/2022/02/U.S.-Indo-Pacific-Strategy.pdf

Yoo, B., & Kim, J. (2016). Path optimization for marine vehicles in ocean currents using reinforcement learning. *Journal of Marine Science and Technology*, *21*(2), 334-343. https://doi.org/10.1007/s00773-015-0355-9

Zabrodskyi, M., Watling, J., Danylyuk, O. V., & Reynolds, N. (2022). *Preliminary Lessons in Conventional Warfighting from Russia's Invasion of Ukraine: February–July 2022*. https://static.rusi.org/359-SR-Ukraine-Preliminary-Lessons-Feb-July-2022-web-final.pdf