UNMANNED ACOUSTIC SENSING PLATFORM WITH ENHANCED CAPABILITIES

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Abstract: *Unmanned underwater vehicles (UUV) are efficient task multipliers, able to perform dull, dirty, and dangerous jobs while freeing manned platforms to perform more complex work. As technologies and sensors mature, onboard energy and vehicle endurance continue to increase. Additionally, support of acoustic sensors requires the vehicle to exhibit a very low acoustic signature. The integration of higher energy density systems into UUVs with outer shapes optimized for low energy consumption and more efficient UUV propulsion is generating a new class of gliders with advanced capabilities.*

This paper identifies various approaches to increasing the "persistence" (long distance and long duration) of next generation UUVs while expanding on the capability of this glider to support acoustic sensors. Optimization of the lift-to-drag ratio, using modern computational fluid dynamical modeling methods, increases propulsion efficiency. Increasing the size of the vehicle also leads to increased performance due to the drag scaling with the square of the wingspan while the persistence scales with the cube of the wingspan. The larger vehicle size not only increases persistence, but also enables novel hull-mounted and towed hydrophone configurations capable of highly spatially resolved acoustic measurements in multiple dimensions simultaneously. General Atomics Electromagnetic Systems has been developing novel power and energy systems for decades in support of vehicles with unique mission requirements. These advanced power and energy systems include fault tolerant lithium-ion batteries, aluminum powered fuel cell systems, and nuclear energy sources.

The combination of an advanced power and energy system with a scaled-up blended wing glider has led to a vehicle with unprecedented persistence and a platform ideal for subsea acoustic sensing. Plans for at sea testing of a glider in 2023 will be presented with focus on improving future capabilities for autonomous acoustic sensing.

Keywords: *UUV, Glider, hydrophone, LiFT, fuel cell, hydrodynamic, range, persistence,*

1. EXECUTIVE SUMMARY

Blended-wing gliders are the ideal unmanned underwater vehicles (UUV) for persistent underwater acoustic sensing due to the lack of a continuously running propulsor and low hydrodynamic noise. Optimization of the glider's shape and integration of novel energy-dense systems enhance the persistence (long duration combined with long-distance transits) of the glider. General Atomics Electromagnetic Systems (GA-EMS) has been developing power and energy systems for UUVs and working with Scripps Institution of Oceanography (SIO) Marine Physical Laboratory (MPL) at the University of California San Diego (UCSD) to optimize the design of a blended wing glider. Starting with the existing 20-foot ZRay glider, the GA-EMS and SIO team has scaled up the glider to be large enough for innovative acoustic sensor arrays and extreme persistence. At-sea testing of the ZRay outfitted with GA-EMS sensors will take place this summer, 2023, to verify the projected performance/capabilities of the larger glider. The large wingspan will enable acoustic sensor layouts in simultaneous multiple dimensions, leading to novel acoustic sensing capabilities.

2. INTRODUCTION

Buoyancy-driven gliders propel themselves by changing the buoyancy of the vehicle, either by changing the mass (amount of water in ballast tanks), or by changing the volume of the vehicle using bladders. This change in buoyancy also changes the vehicle's potential energy in the earth's gravitational field, which is then converted to kinetic energy as the glider descends (or ascends) through the water column. At the top of the dive cycle, the vehicle pumps in water (or reduces its volume) to make it denser than the surrounding water and begins its descent. At the bottom of the dive cycle, the vehicle pumps water out of the ballast tanks (or increases its volume) to be less dense than the surrounding water and begins its ascent. The majority of the work is performed at the bottom of the dive cycles as the water is pumped out against hydrostatic pressure.

In 2004, SIO partnered with Applied Physics Lab at the University of Washington under sponsorship of the Office of Naval Research to design, fabricate, and test blended wing gliders [1]. Throughout the development program, the XRay glider was tested from 2006 to 2008, and the ZRay glider was tested from 2010 to 2014. As shown in Fig. 1, the ZRay glider was able to demonstrate a lift-to-drag (L/D) ratio of 20:1 during at sea testing. GA-EMS is now working with SIO to refurbish the ZRay and install several GA-EMS payloads. At-sea testing of the ZRay and the GA-EMS payloads will take place in the summer of 2023.

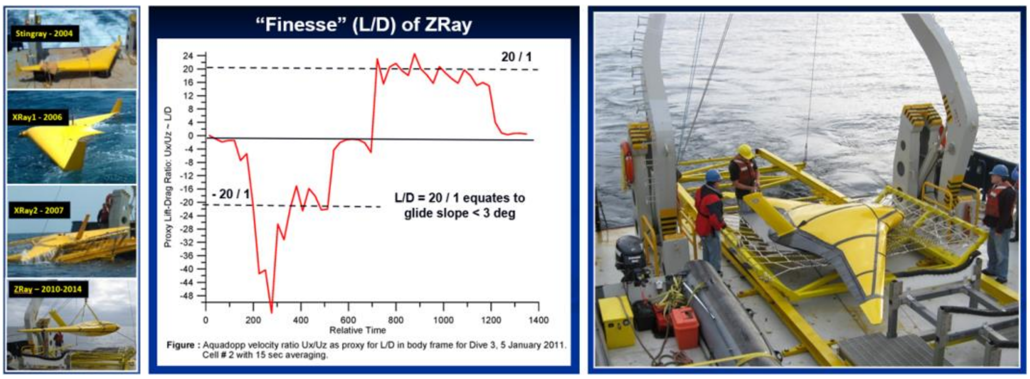

Fig. 1: The blended wing glider program led by SIO tested several gliders (left), and was able to verify the ZRay's L/D ratio of 20:1 (middle) during at-sea testing (right).

3. OPTIMIZATION OF UUV PERSISTENCE

Persistence of a UUV is one of the most important features that allows a vehicle to provide utility to the manned counterparts. The ability to be separated from the manned platform for extended periods of time gives a UUV the task-multiplying benefit. Ways to increase UUV persistence include:

1. ***Increasing the hydrodynamic efficiency*** – aspect ratio, wetted surface area, L/D
2. ***Increasing the energy density*** – use advanced chemical and/or radioactive systems
3. ***Increasing the volume for the on-board energy supply*** – scaling up the vehicle size
4. ***Decreasing the energy consumption*** – advanced controls, autonomous behaviors to decrease propulsion energy consumption, and minimize hotel load
5. ***Energy harvesting*** – generate energy from currents, thermoclines, solar, etc.

While all methods can help to increase a UUV's persistence, this paper will focus on the first two methods: maximizing the hydrodynamic efficiency by optimizing the UUV's outer shape and implementing a scalable power and energy system with a high energy density.

Maximizing the transit efficiency is accomplished hydrodynamically by minimizing the amount of lost kinetic energy. The simplicity of the (largely one-dimensional) vortex system created by the wing of a glider minimizes the drag (lost kinetic energy). A propeller-driven UUV generates a helical three dimensional vortex system, which leads to greater power demands to maintain a given vehicle speed. A hydrodynamically optimized winged glider leads to significantly less drag than a standard propeller-driven UUV [2].

Further hydrodynamic optimization of a glider is based on the mission goals. Gliders generally fall into one of two classes: 1) "profiling gliders" that have steep dive angles and are generally used to sample water column data; and 2) "cross country gliders" that are optimized to have the greatest horizontal transport efficiency. The "profiling gliders" such as the Spray [3], Seaglider [4], and Slocum [5] are based on a body of revolution with wings. As opposed to a body of revolution with small wings to generate lift, a "cross country glider" with a blended wing utilizes the entire outer surface of the glider to generate lift.

The propulsion energy (E_p) required for a glider to transit a horizontal distance (R) is shown in Equation 1 where $\eta_+(h)$ is the efficiency of the pump as a function of depth, ρ is the density of water, g is the acceleration of gravity, dV is the change in volume (where the maximum value is the buoyancy tank volume), and L/D is the lift-to-drag ratio.

$$E_p \approx \frac{\eta_+(h)[\rho g]dV}{2\left(\frac{L}{D}\right)} R \tag{1}$$

The lift-to-drag ratio is inversely proportional to the energy required to transit a certain horizontal distance. Therefore, to minimize the propulsion energy, the vehicle's lift-to-drag ratio needs to be maximized. GA-EMS developed a computational-fluid-dynamics-based software package to analyze glider performance as a function of 15 non-dimensionalized parameters. Utilizing a mix of proprietary and industry standard tools such as Missile DATCOM, XFLR5, Ansys Fluent, and MATLAB, comparative performance data for gliders of all shapes and sizes was generated. A glider database was developed based on the 2D air-foil cross section's interaction with fluid flow across a wide range of Reynolds numbers and angles of attack, followed by 3D analysis of the glider, see Fig. 2.

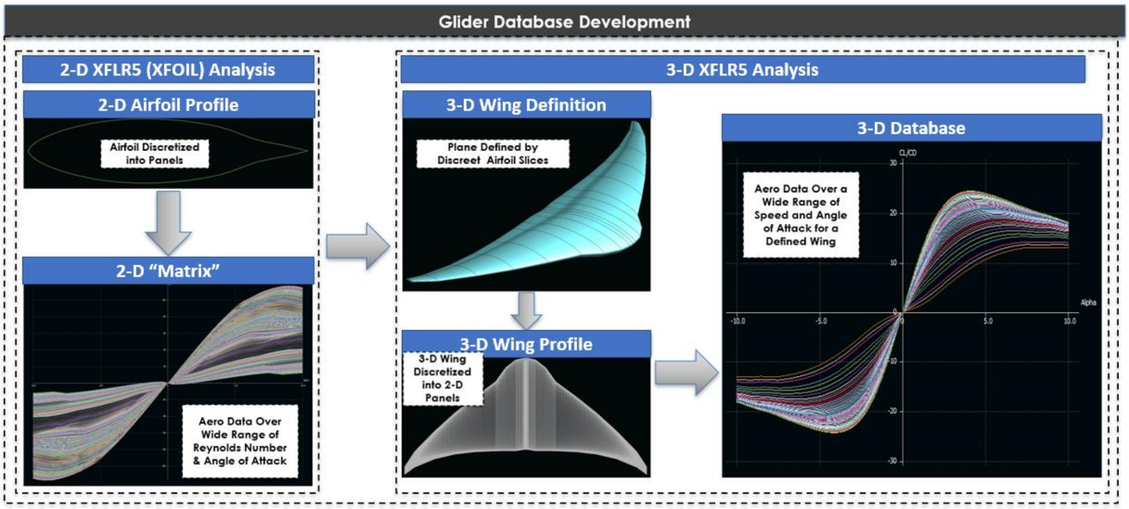

Fig. 2: GA-EMS developed a glider performance database to quantify performance as a function of Reynolds number, angle of attack, air-foil shape and 3D glider shape.

The Glider Database was used to power a glider optimization tool shown in Fig. 3. This numerical analysis, which accounts for the nonlinear terms in the fluid equations, agrees qualitatively with previous analytical results in the literature [2], showing that blended wing gliders exhibit up to 40% better range than body-of-revolution gliders; however, the blended wing gliders are optimized to operate at a slower speed. Additionally, the tool verified that as the gliders increase in size, their performance and overall transport efficiencies also increase. This result was expected as the surface area (drag) scales roughly with the size squared and the volume (energy) scales with the size cubed, leading to a higher ratio of stored energy to drag for the vehicle.

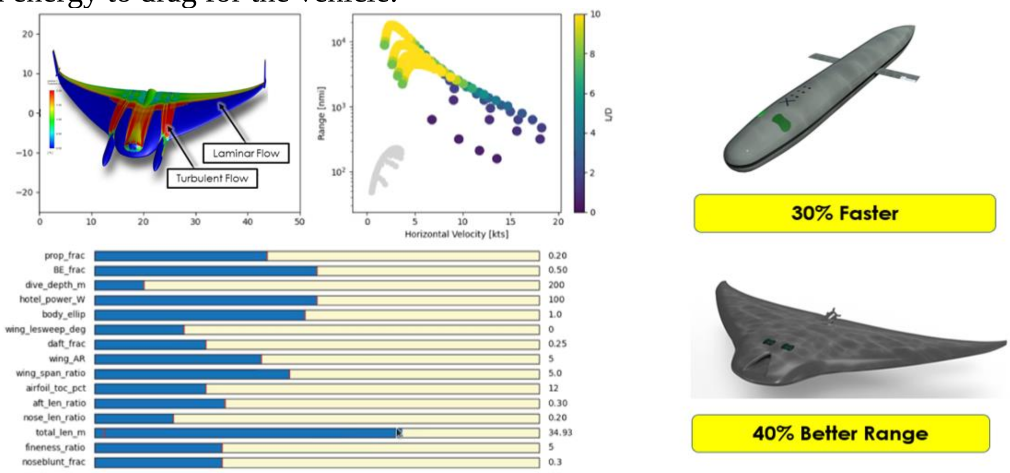

Fig. 3: The major conclusion of the GA-EMS tool is that greater range is achieved with blended wing gliders and greater speed for body-of-revolution gliders.

In addition to the optimization of the vehicle's form factor, persistence can be increased through maximizing the vehicle's energy storage. Power hungry sensors and systems, and the desire for longer range and more time on station, drive up the energy requirement. The ultimate goal of realizing unlimited persistence through energy harvesting is under investigation [5,6]; however, it is yet to be widely utilized in underwater vehicles. The added complexity, size, and weight of the energy harvesting system needs to be accounted for, and the source of the energy harvesting will dictate where (geographically and in the water column) and how the vehicle can operate. The added complexity, strain on vehicle requirements, and operational limitations have generally led to battery powered vehicles.

GA-EMS specializes in developing safe, reliable power and energy systems for extreme environments. GA-EMS has developed a Lithium-ion Fault Tolerant (LiFT^{TM}) battery system that prevents uncontrolled cascading failure, ensuring the safety of personnel and equipment while keeping power available for high mission assurance. The assumption is that at some point, a lithium-ion cell is going to go into thermal runaway, and the LiFT system will protect the remainder of the battery (and vehicle) from a catastrophic failure.

LiFT Battery Systems offer a flexible, scalable architecture that can be configured to suit different platform form factors, energy storage, and redundancy specifications. LiFT battery systems take advantage of the latest advancements in commercial off-the-shelf (COTS) lithium-ion cell technologies to provide high energy capacity with safe operation for the most demanding requirements. The LiFT system has been approved for use by the U.S. Navy and classified by Det Norske Veritas (DNV) and Germanischer Lloyd (GL).

Fuel cell systems have been under development for decades and have recently experienced exponential growth in the commercial sector driven by the transportation industry. A fuel cell system has the ability to store several times the energy of a battery of comparable size and weight. GA-EMS has been working on fuel cell systems for UUVs for the past 2 decades and has developed an Aluminum Power System (ALPS) based on the generation of hydrogen from an aluminum alloy. Aluminum stores more energy per unit volume than any other viable non-nuclear source. However, with typical aluminum alloys, an oxide layer protects the raw aluminum, thereby eliminating the reaction between the aluminum and seawater. The GA-EMS alloy developed for ALPS prohibits the formation of this protective oxide layer, enabling the necessary reaction which occurs according to the following equations (with the mid-range temperature most common for UUV applications):

$$\begin{aligned} < 280\ °C \ \ldots\ldots\ 2Al + 6H_2O &\rightarrow 2Al(OH)_3 + 3\ H_2 \\ 280 - 480\ °C \ \ldots\ldots\ 2Al + 4H_2O &\rightarrow 2Al(OH) + 3\ H_2 \\ > 480\ °C \ \ldots\ldots\ 2Al + 3H_2O &\rightarrow Al_2O_3 + 3\ H_2 \end{aligned} \tag{2}$$

ALPS's simple system design and control scheme provides a clean, robust, reliable power source for long endurance underwater missions. With primarily passive components for quiet operation, ALPS is well suited for acoustic applications. This system was developed for the Large Displacement Unmanned Underwater Vehicle (LDUUV), as shown in Fig. 4.

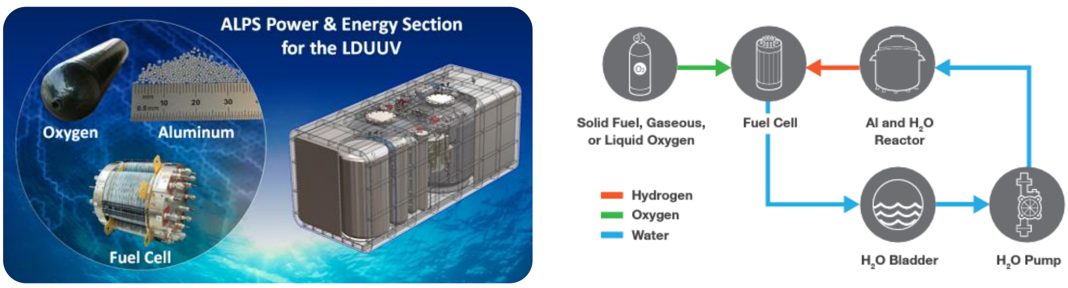

Fig. 4: The ALPS fuel cell system for the LDUUV (left), system schematic (right).

GA-EMS has also been developing nuclear batteries, that are orders of magnitude more energy dense than lithium-ion batteries and fuel cell systems. These batteries take the heat from a nuclear source and convert the heat to electricity using a thermophotovoltaic (TPV) cell. Between the heat source and the TPV, a specially-designed emitter absorbs the heat and selectively emits photons matched to the TPV's optimum band gap to maximize the overall efficiency, as shown in Fig. 5.

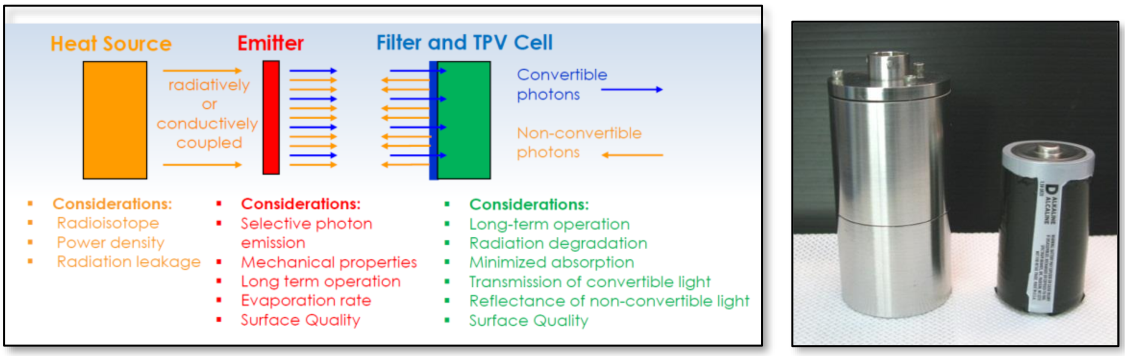

Fig. 5: Nuclear battery energy flow (left); GA-EMS 1 W nuclear battery is slightly larger than a standard D-cell (right).

Fig. 5. also shows one of several nuclear batteries fabricated and tested by GA-EMS. The battery shown produces 1 W, and is comprable in size to a standard D-cell battery. Although the power output is lower than the D-cell, it will provide 1 W for decades. GA-EMS has designed nuclear batteries ranging from mW up to several hundred watts.

GA-EMS is leveraging decades of work in these leading edge, high energy density systems to optimize the power and energy system for UUVs. These advanced power and energy systems paired with the blended wing glider body will lead to an acoustic sensing platform with unprecidented persistence.

4. THE GLIDER AS AN ACOUSTICS PLATFORM

A glider's intermittent buoyancy engine noise is typically emitted only 2-3% of the total flight time, an important differentiator compared to the 100% duty cycle of a propeller in a prop-driven UUV. The ZRay glider was outfitted with numerous acoustic sensors (see Fig. 6) for at-sea testing to demonstrate its capability of operating as an acoustic platform.

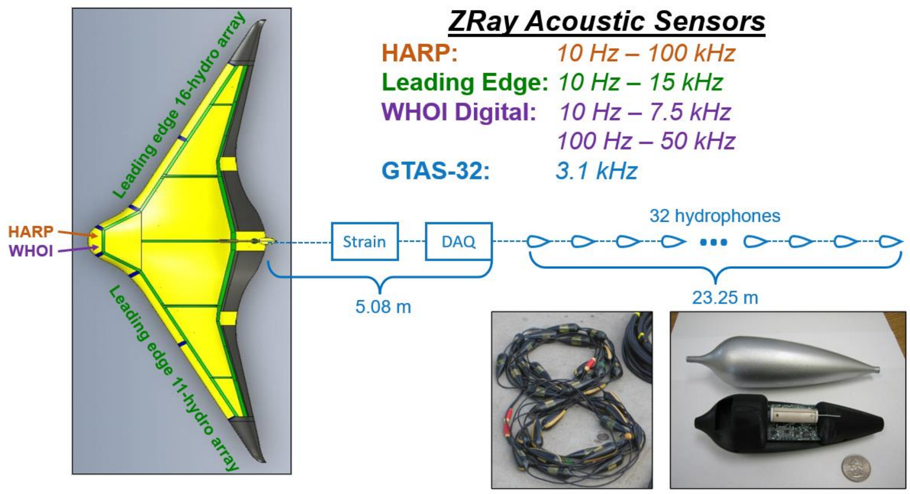

Fig. 6: The ZRay has been outfitted with multiple passive acoustic sensor systems.

Fig. 7 presents a single element spectrogram for the Glider Towed Array System (GTAS), designed and built by Naval Information Warfare Center San Diego, along with the frequency/azimuth (FRAZ) adaptive beamforming result obtained by averaging over the 5-sec period highlighted in the spectrogram. The 10-sec duration tone at 1000 Hz was transmitted by an underwater acoustic source deployed from the host ship. It arrives from the same direction as the broadband noise radiated by the ship itself - at about 140º relative to forward endfire. Other signals visible in the spectrogram also were transmitted by the underwater source, e.g., the wideband linear FM upsweep starting about 43 sec into the spectrogram whose higher frequency content reflects back into the fundamental band due to temporal aliasing. The broadband transients every 10 seconds in the spectrogram were created by transmissions from the glider's acoustic modem to the ship to provide glider status updates. The arc of energy in the upper right corner of the FRAZ plot is the spatially-aliased noise from the deployment ship. Other than this aliased energy, the GTAS forward endfire direction towards the ZRay glider has quite low received levels, attributable to the silent nature of glider's operation over most of its dive cycle.

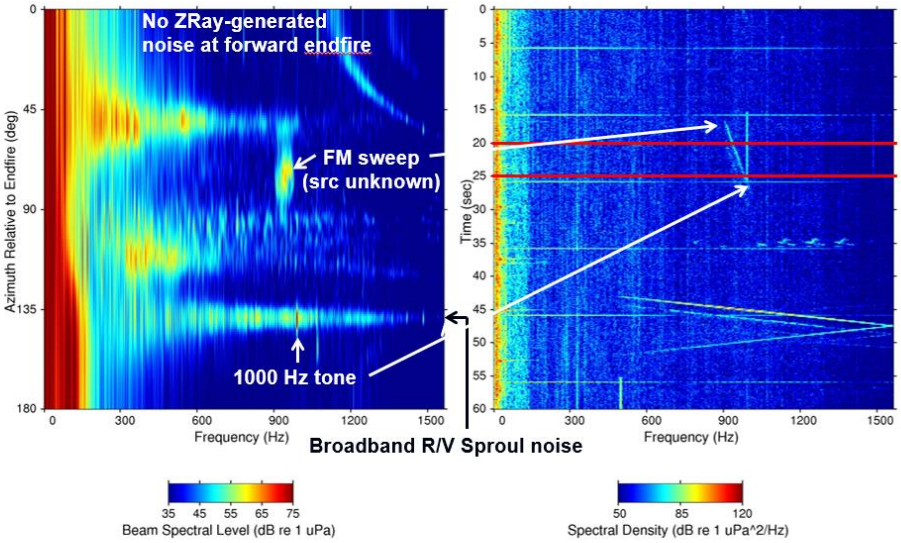

Fig. 7: Adaptive beamforming as a function of azimuth relative to forward endfire and frequency (left). A GTAS single element spectrogram over a 60 sec period (right).

In comparison, Fig. 8 presents similar results using the hydrophone array mounted inside the glider's outer shroud along its leading edge (highlighted in green in Fig. 6).

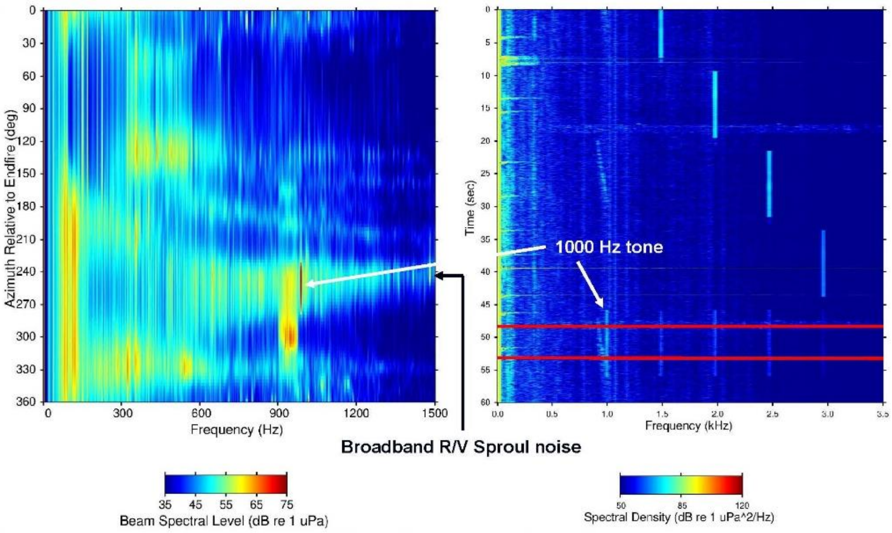

Fig. 8: Adaptive beamforming FRAZ plot for the 5-sec period shown by red lines (left). 60-sec spectrogram from a single element in the leading-edge hydrophone array (right).

Due to the two-dimensional geometry of the leading-edge array, it does not suffer from the left/right ambiguity of the towed array. Therefore, the azimuth relative to forward endfire spans the full 0º to 360º. Although the spatial resolution is not as good as the GTAS array (since inter-element spacing is 5 times smaller), it shows the true direction of the acoustic source. Although forward endfire is the same direction for both the GTAS and leading-edge arrays, the results differ in direction by 20º-25º. This difference is likely due to GTAS array tilt. The data in these two figures were recorded as ZRay was at 28 m depth and descending. Its nose was slightly pitched 0.5º up to create upward lift and its roll was within a few degrees of "wings level" so the leading-edge array was approximately horizontally oriented. In contrast, since the GTAS is slightly positively buoyant and being towed downward as the glider descends, its orientation deviated from horizontal.

5. CONCLUSIONS

Persistence in underwater surveillance can be achieved through careful engineering design and implementation of appropriate subsystems. By optimizing the design of a blended wing glider, and integrating energy-dense energy storage systems, the blended wing glider can have extraordinary range and time on station. Due to how a buoyancy-driven glider operates, the vehicle is acoustically (and electromagnetically) virtually silent for the vast majority of the operational time, making it an ideal acoustic sensor platform. GA-EMS is working with SIO to scale up the ZRay significantly to produce a platform with over 100 ft wingspan. This large glider will not only have unprecedented persistence, but also a unique structure capable of towing parallel acoustic arrays with significant separation in addition to fixed horizontal and vertical arrays. GA-EMS and SIO will be testing the ZRay at sea several times a year for the next few years, aiming to develop novel acoustic sensing capabilities. GA-EMS is looking for novel sensors that can be deployed and tested on the ZRay to demonstrate future capabilities of a much larger glider.

6. ACKNOWLEDGEMENTS

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