Final Report

Flight Software Development for the Liberdade Flying Wing Glider

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INITIAL WORK: FLIGHT SOFTWARE DEVELOPMENT 2005-2011

The following describes the work performed under the earlier of the above awards (N00014-05-1-0209). This effort formed the foundation upon which subsequent progress (via award N00014-12-1-0080) was based.

Requirements

The Liberdade class gliders (XRay and ZRay) required a main vehicle computer and associated programming logic which would support the following:

- Autonomously control a 1400 lb, 20 foot span underwater flying wing glider operating in extreme lift/drag ratio regimes.
- Enable the vehicle to exploit a variety of payloads, both internal and external.
- Run on a small, PC104 form factor computer under the Linux operating system.
- Communicate with upwards of 12 serial-based devices, at least 3 and ultimately 5 of which were control actuators.
- Enable operator/pilot status evaluation and control by at least 3 forms of communications: local WiFi, semi-local acoustic, and long-range satellite (Iridium).
- Control the vehicle using only locally sensed information in both dive and climb phases of flight using completely internally-located actuators. Then adapt to implementation of external actuators as well (flaps).
- Optionally enable realtime flight adjustment via acoustic signal.
- Optionally interact with other onboard computers to react to realtime phenomena; for example a detection algorithm running on a small embedded processor reading passive acoustic data.
- Provide robust health and safety monitoring to ensure vehicle survival.

Key Design Features

Flight software was designed to be modular and portable. For example, we insisted that the code build and run on a standard desktop computer in addition to the target PC104. This enabled development and exploitation of a desktop-based vehicle simulator. The fidelity of the simulator was such that APL/UW could accurately develop control software without the presence of the actual vehicle. In addition, an exact replica of the onboard PC104 computer was maintained at APL/UW and routinely used for regression testing to ensure compatibility.

Serial communications logic was partitioned to enable rapid addition or removal of devices; this became invaluable as the sensor and actuator suite changed during vehicle development.

Hard coding of parameter values was rigorously avoided. All configuration parameters were stored in operator-editable text files. This enabled changes to behavior without requiring source code editing and rebuilding.

Finally, source code was written and stored to permit timely and efficient modification during field operations. As noted below, this was critical to in-situ operations under varying conditions.

Accomplishments

Over the 6-year period 2006-2011, the XRay/ZRay gliders flew hundreds of missions in locales ranging from Southern California to Monterrey Bay to Hood Canal. The vehicle flew both on its own and in a configuration by which it towed an acoustic array. APL/UW's software controlled the vehicle successfully and robustly. Not surprisingly, unanticipated bugs were uncovered; however we were always able to detect, analyze, and resolve these issues, usually at sea, often between dives. We list an abbreviated list of accomplishments here.

- Enabled operator/pilot command and control of the glider when on deck, locally on the surface, underwater, and over Iridium.
- Individually but simultaneously controlled vehicle pitch, roll, and heading using a standard proportional/integral/derivative (PID) controller. Initially (2006-2007) control was actuated using the buoyancy engine, liquid roll control system, and sliding pitch mass. In 2008, software was modified to command new trailing edge flaperons. In 2010 software was changed again to reflect the split of flaperons into flaps and camber adjusters. Of note is the fact that at this point the liquid roll control system became essentially a static trim mechanism and all dynamic roll and heading control was performed via the flaps. In addition, the advent of the much more pitch-stable ZRay in 2011 obviated the need for explicit pitch control and the pitch mass was statically placed as well.
- Acoustically communicated over 1 and sometimes 2 acoustic modems. The baseline Benthos modem reliably sent vehicle flight status to a shipboard receiver, and was also commanded to ping bottom transponders for post-mission flight analysis. The optional microModem from WHOI was used during PLUSNet exercises to receive and relay PLUS-specific messages. We also designed and implemented an XRay-specific PLUSNet packet to command the vehicle acoustically. Finally, a realtime detection algorithm running on a small embedded Blackfin computer was tied to the main flight software such that detections could be used to redirect the vehicle automatically.
- Developed a simple but powerful flight scripting language. This enabled a very flexible format for detailing vehicle control in a concise form. The language became the de-facto command mechanism in 2007 and was used routinely thereafter, with minor modifications. For example, the ability to reference previously loaded scripts was developed; this allowed flight scripts to be very short (an important consideration for Iridium-based communications).
- To complement the onboard Iridium communications protocol, a shoreside Basestation was developed to enable status evaluation and remote control. This took the form of an operating system independent graphical interface which communicates with a local Iridium modem. The Basestation could be (and was) operated either aboard support vessel, or from a remote location on shore.
- Seamlessly handled the transition from the first generation glider (XRay) to the current state of the art (ZRay) with no disruption in capability.
- Implemented a detailed fault tree for anomaly handling. Non vehicle life threatening errors were handled using a dive abort mechanism, by which the vehicle abandoned its current dive for a graceful ascent to the surface. More serious problems could ultimately lead to a commanded Emergency Recovery event. The logic performed as required. The vehicle was never lost.

In addition, analysis tools were developed to evaluate flight data offloaded post-mission. These were applied to all dives and numerous performance metrics were compiled. Those metrics were particularly useful in the redesign from the original XRay to ZRay in 2009-2010, and for baselining the requirements for follow-on work.

IMPACT/IMPLICATIONS

The success of the initial development phase set the basis for follow-on work which enabled much longer-term persistent operations. That effort (described below) leveraged heavily on the software developed under this original program.

FOLLOW-ON: ENHANCEMENTS FOR PERSISTENCE TO SUPPORT TRANSITION

Per the latter of the above-referenced awards (N00014-12-1-0080), APL/UW performed the necessary software and computer modifications to enable long-term persistent flight. The results of that effort are described below in a joint report filed by our partners at Scripps Institution of Oceanography at UC San Diego.

Innovations to the ZRay/Liberdade Flying Wing Glider for True Persistence (Missions of 25+ Days over 1000+ km)

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LONG-TERM GOALS

The long-term goal of this program was to develop a new class of underwater glider (the Liberdade class) optimized for long distance, long duration (persistent) flights in the ocean. Central to this objective was to increase the horizontal transport efficiency, speed, and payload capacity of underwater gliders. The approach was to exploit the high lift-to-drag ("finesse") properties of the flying wing design. A parallel, and equally important, goal was to improve the sensing capabilities and automated decision-making capability based on the outputs of onboard sensor systems. In addition to acting as a persistent, mobile, sensing node in a future system, and providing a persistent, high-spatial-resolution, real-time monitoring capability for the presence of marine mammals, this new glider provides a novel capability for data collection in support of basic ocean science.

OBJECTIVES

The three primary technical objectives this last year in the flying wing glider program were to 1) lower the hotel load of the new flying wing autonomous underwater glider, "Liberdade/ZRay", by an order of magnitude in order to achieve true persistence, 2) demonstrate launch and recovery of ZRay off a land-based facility such as the pier at the Scripps Institution of Oceanography (SIO) and/or a ship of opportunity, and 3) demonstrate the ability of ZRay to tow a multi-element hydrophone array at sea and quantify the resulting improvement in passive sensing capability. An additional technical objective was to further advance the glider's onboard real-time signal processing capability to provide real-time marine mammal monitoring and mission adaptability, as part of ZRay's participation in

ONR's Glider-Based Passive Acoustic Marine Mammal Monitoring program. In addition to these technical objectives, a major goal this last year was to transition the flying wing glider technology to a federal government entity so it can fulfill an operational need and address specific missions.

APPROACH

The Liberdade flying wing underwater glider program was a team effort between the Marine Physical Laboratory, Scripps Institution of Oceanography (MPL/SIO) and the Applied Physics Laboratory, University of Washington (APL/UW). The purpose of this partnership was to combine the specialized expertise that exists at our two institutions in the areas of autonomous vehicle technology and automated passive detection, classification, and localization in order to develop robust, high performance gliders based on the flying wing design that can perform useful missions. This partnership was essential to the success of the program.

The original concept of an underwater glider based on the flying wing design was proposed in the 2003 Glider System Study sponsored by ONR (Jenkins, Humphreys, Sherman, et al., 2003). The purpose of this study was to evaluate the present state of development in underwater glider technology, examine the various roles for autonomous underwater gliders in Navy missions, and identify additional developments in glider technology required to realize the potential of underwater gliders. The flying wing design was recommended for those missions requiring optimal horizontal transport efficiency. Horizontal transport efficiency, or specific energy consumption, is defined as the energy consumed per unit distance traveled for each unit of net vehicle weight. For an underwater glider that travels along a glide angle, γ, with respect to the horizontal, the power consumed P_e to overcome drag F_D is equal to the rate of working by gravity along the glide slope, $\tan\gamma = w/u$:

$$P_e = \vec{F}_D \bullet \vec{U} = \left(\vec{F}_b - \vec{F}_g\right) \bullet \vec{U} \Rightarrow F_D U = \left(F_b - F_g\right) w \qquad (1)$$

The quantity $\vec{F}_b$ is the buoyancy force (F_b is its modulus), $\vec{F}_g$ is the weight of the glider in air, u is the horizontal component of the glide velocity (cross country speed), w is the vertical component of the glide velocity (sink rate), and $U = \sqrt{u^2 + w^2}$ is the glide speed.

In applying concepts of horizontal transport economy to underwater gliders, the immersed weight (or net buoyancy, $F_b - F_g$) represents the net weight transported over half a dive cycle by the action of energy consumption. If an underwater glider has no immersed weight, no motion other than passive drifting occurs and no energy of forward propulsion is consumed. Energy is consumed in an underwater glider by the buoyancy engine that generates a variable displaced volume increment $\pm V_b$, allowing net buoyancy to alternately be changed between positive and negative states, $F_b - F_g = \pm\rho\, g V_b$, where ρ is the seawater density. The buoyancy engine gives the underwater glider the ability to propel itself forward in a series of descending and ascending glides. Only the horizontal component of the glide speed, *u*, results in horizontal distance traveled point-to-point. Consequently, the specific energy consumption (net horizontal transport economy) of a glider is:

$$E_e = \frac{P_e}{u(F_b - F_g)} = \frac{w}{u} = \tan\gamma = \left(L/D\right)^{-1} \qquad (2)$$

The glide slope, $\tan\gamma$, is equivalent to the reciprocal of the lift-to-drag ratio, $(L/D)^{-1}$, and provides a quantitative measure of horizontal point-to-point transport efficiency. The lift-to-drag ratio of a wing also is called its "finesse". A small glide slope (large *L/D* and large finesse) allows an underwater glider to travel a given horizontal distance in the fewest numbers of buoyancy engine cycles and therefore consume the least amount of energy in forward propulsion.

Other existing underwater gliders - Seaglider, Spray, and Slocum - are designed primarily to collect vertical profiles of water column properties and move only short distances at low horizontal speed from one profile to the next. A large lift-to-drag ratio is not a design criterion for these gliders; rather, they are well suited for their "vertically profiling" task. As such, they have revolutionized the field of oceanography. By maximizing horizontal transport efficiency, the role of the Liberdade class of underwater glider is synergistic and complementary with the role of these other gliders.

Bigger gliders are more efficient at horizontal transport. Surveys of natural and man-made flyers (McMasters, 1974) confirm this relation across 12 orders of magnitude range in size. In addition, the square-cubed law from classical aerodynamics indicates that larger flyers also achieve higher cruise speeds with greater payload capacity, two additional performance objectives in this program. This size advantage is accentuated in underwater gliders due to economies of scale in packing efficiency. All these factors suggested that to achieve the performance goals in this program, the largest glider that could be deployed from the available launch and recovery platform should be designed and built. Therefore, the Liberdade/Stingray, Liberdade/XRay, and Liberdade/ZRay gliders are scaled up to the largest size that can be easily accommodated on the work deck of R/V Sproul, the smallest of the UNOLS ships operated by the Scripps Institution of Oceanography. The resulting flying wing gliders have 20-ft wing spans and total internal volume in the 1,000 liter range.

In addition to size, other design factors are important to consider in reducing energy consumption in horizontal transport. Of all the outer shape properties of the glider influencing the specific energy consumption, the one with the strongest influence is the wetted-surface-to-wing-area ratio so that reducing this ratio will achieve the greatest improvements in horizontal transport economy. The smallest ratios are associated with flying wing and blended wing body geometries (such as used by birds) yielding ratios in the 2.2 to 2.4 range. The other benefit of a large wing area is that it reduces the coefficient of lift and the associated induced drag (the largest component of drag at minimum specific energy consumption). However, increases in wing area must be accompanied with increases in the wing aspect ratio, which exerts a greater reduction in specific energy consumption than does a proportionally smaller lift coefficient. Increases in aspect ratio, in turn, must be balanced with the structural limitations of high aspect wings, especially when flooded with seawater.

In order to capitalize on these findings and the results from the at-sea tests of Stingray in 2004, a team of scientists, engineers, and technicians from the Marine Physical Laboratory, Scripps Institution of Oceanography (MPL/SIO) and from the Applied Physics Lab, University of Washington (APL/UW) was formed. The major portion of the engineering team at MPL/SIO is comprised of members of MPL's Ocean Vehicle Development Group. This group has a long history of developing advanced remotely operated vehicles for deep ocean research and exploration. It also is responsible for improving, maintaining, and operating MPL/SIO's set of prop-driven AUVs. MPL/SIO also contributed personnel who participated in the ONR Glider System Study and led the design and at-sea testing of Liberdade/Stingray. The group from APL/UW has been instrumental in developing the highly successful Seaglider program. In addition, this group has a great deal of experience in underwater acoustic communications, Navy advanced system development, automated detection, classification, and localization (DCL) algorithm implementation for operational sonar systems, and in flight control and flight simulation software for advanced aircraft. Over the past two years, the light-weight, low-power array group at SPAWAR SSC Pacific joined our glider team. The work accomplished by this team of scientists, engineers, and technicians over this last year is summarized in the following section.

WORK COMPLETED

The effort in this last year of the program was devoted to finishing and testing the modifications started in 2012 to reduce the hotel load of the “ZRay” flying wing autonomous underwater glider. Completion of the effort required only the first 6 months of the fiscal year, with the effective end of the program coming at the end of the at-sea test the last week of May, 2013. The major modifications this past year included 1) replacing the PC-104 form-factor flight control computer with the advanced very-low-power LPC 3250 micro-computer that can be programmed to operate in various sleep states, 2) replacing the flight control computer’s hard drive with a flash card, and 3) porting over the flight software to this new micro-computer/flash card configuration. As part of this migration, a linux driver for a serial board had to be written to increase the number of serial lines available to the LPC 3250. The flight software and embedded system software for all major subsystems was modified to allow these subsystems to be turned on and off by the flight software during a mission in order to save onboard energy. For example, because of the inherent flight stability of ZRay, the pitch mass only has to be moved to one position at the beginning of a descent and then repositioned at a different location for ascent. The flight software now can turn off the pitch mass system for the remainder (almost the whole duration) of a dive cycle, saving nearly all the energy it previously required.

Modifications were made to the glider to allow lifting and tag lines to be readily attached and removed during launch and recovery from a land-based facility or a ship of opportunity. Detailed plans were developed, required permissions were obtained, and the infrastructure was upgraded to accommodate flying wing glider operations off the SIO pier in La Jolla, including outfitting an equipment/operations hut and upgrading a pier-launched small boat for glider operations support.

The electrical integration of SPAWAR’s 32-element Glider Towed Array System (GTAS) with the ZRay glider was completed so that the GTAS data were recorded on the same time base as the leading-edge hydrophone array in ZRay. In addition, a launch/recovery plan for the ZRay/GTAS assembly off a land-based facility or a ship of opportunity was created.

A 4-day engineering sea trip was conducted in May, 2013 to conclude the efforts in the flying wing glider program. The objectives of the sea trip were to 1) test all the modifications made to the glider to lower its hotel load, 2) demonstrate launch and recovery off a ship of opportunity, 3) conduct continuous multi-day missions solely through the Iridium satellite system, 4) tow the GTAS towed array for improved passive monitoring at low frequencies, and 5) monitor marine mammal calling activity with ZRay’s onboard passive monitoring systems and simultaneously with John Hildebrand’s bottom-mounted High-frequency Acoustic Recording Packages (HARP) and a single-hydrophone mini-HARP system towed by his Waveglider. The ship of opportunity (required only to have sufficient deck space for the glider cart and 20-ft operations/support van, and an onboard crane capable of lifting 5,000 lb) was the R/V New Horizon. To conduct multi-day glider missions through the Iridium satellite system, a group of volunteers from the Scripps Birch Aquarium came on the sea trip and were trained at sea on the use of the glider base-station. Although rough weather and a shortened at-sea schedule (due to a delay in returning to port from the previous cruise) reduced the amount of in-water time available, all 5 objectives listed above were accomplished during the sea trip. A discussion of some of the results is provided in the next section.

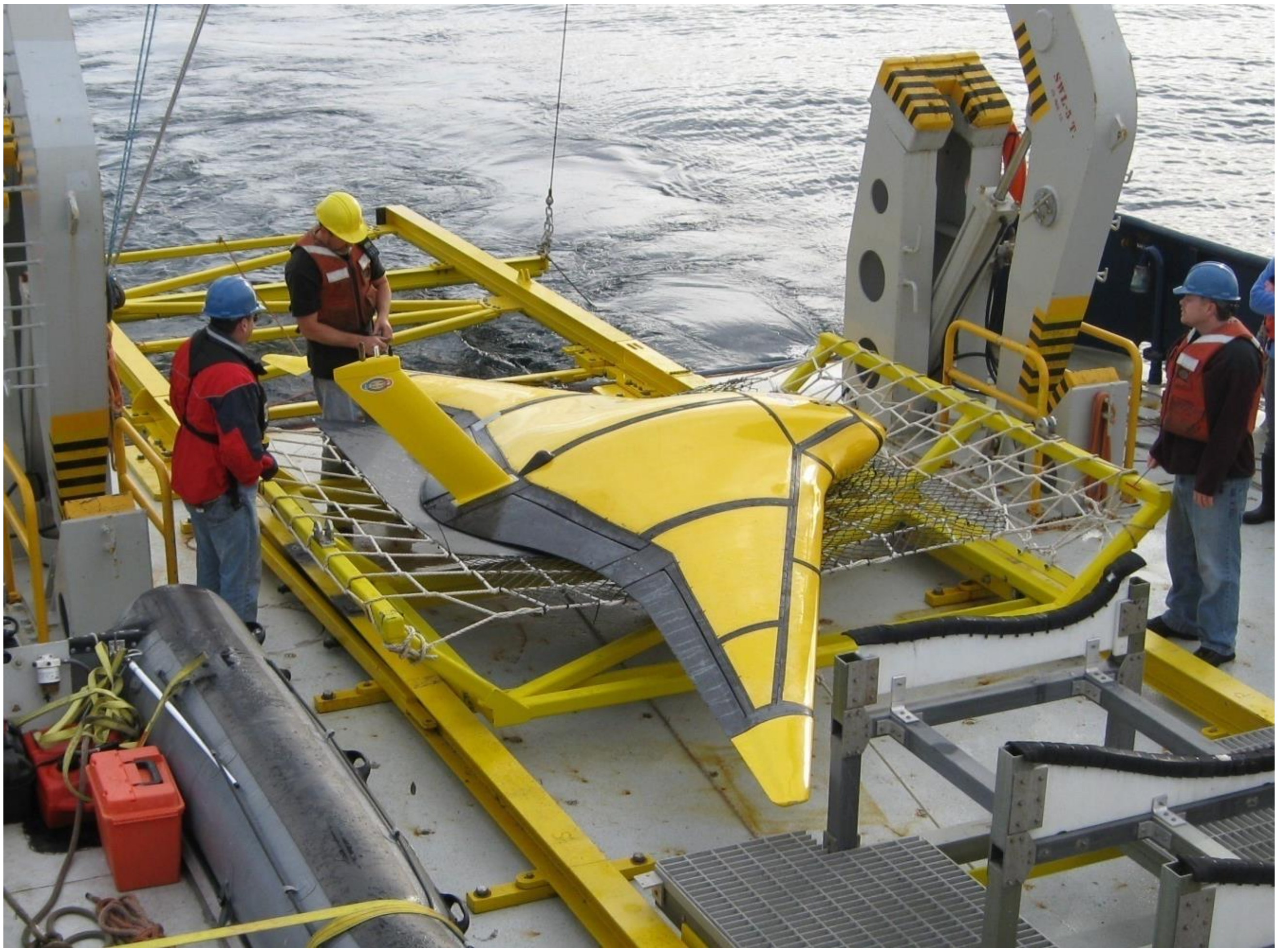

Figure 1. Photograph of ZRay resting on its deployment cart on the fantail of the R/V Sproul during the Range Validation Test, January, 2011. The glider's outer shroud is made of ABS plastic and is mounted to a titanium inner strength structure. All subsystems required for the glider's fully autonomous flight also are mounted to this internal strength structure.

Figure 2. Photographs of the deployment of ZRay from the R/V New Horizon during the Engineering Test the final week of May, 2013.

RESULTS

All modifications to the ZRay glider performed flawlessly when tested at sea. In particular, the LPC 3250 micro-computer and modified flight control software performed without a single problem. The glider's hotel load was reduced by nearly 75%. With a few additional modifications, it could be reduced slightly further to values around 10 W, all while maintaining full flight control. The pitch mass system also operated without any problems. ZRay was launched and recovered from the New Horizon without incident (re Fig. 2 above), although improvements to the procedures were identified.

A multi-day mission was conducted, with the Birch Aquarium volunteers holding the nighttime watches. Software was written for the base-station to display warning lights when any of the glider parameters contained in the Iridium master Short Burst Data (SBD) packet (transmitted after the end of each dive cycle) exceeded specified limits – only once did a warning light appear and it was caused by the limits in the software being set too narrowly. All glider-to/from-ship communications were conducted through the Iridium system during the sea trip.

The GTAS towed array was successfully deployed two separate times. Unfortunately, the array did not boot up correctly on the deployment for the multi-day mission so that no data were recorded. However, it did successfully record high quality data during its other deployment. Fig. 3 shows a 1-min duration spectrogram of a single element from the GTAS array along with the corresponding frequency/wavenumber plot.

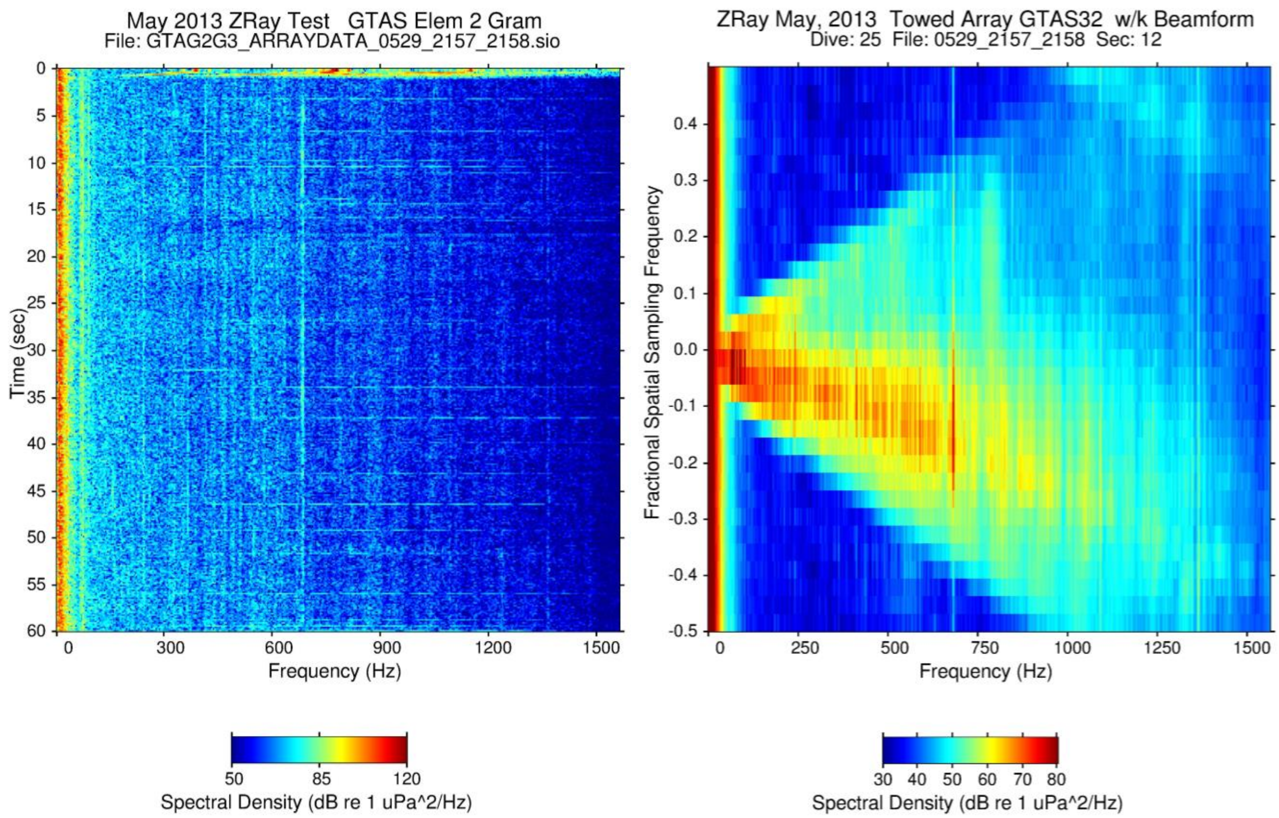

Figure 3. (Left) One-minute spectrogram over the 1562.5 Hz band of the GTAS array and (Right) the corresponding frequency/wavenumber plot during this time period, from the data collected during the Engineering Test the final week of May, 2013.

Although the GTAS spectrogram in the left-hand plot of Fig. 3 appears to contain a significant amount of background noise, the right-hand plot shows that these sounds are acoustic in nature since the non-acoustic noise levels - the dark blue triangles in the upper and lower left of the right-hand plot in Fig. 3 - are 10 dB or so lower than the background levels in the acoustic "cone". These very low self noise levels attest to the high quality of the data from the GTAS array while being towed by the ZRay glider.

The GTAS towed array is designed in a segmented fashion with hydrodynamically-optimized hydrophone/preamp casings. Figure 4 below shows the results from a computational fluid dynamical modeling simulation of a GTAS element submerged in a 2 m/sec flow. No flow separation occurs even at this high 2 m/sec flow speed, thereby minimizing drag. This segmented approach, in contrast to the typical constant diameter towed array hose design, minimizes both array drag and the amount of water displaced by the array when submerged. Previous at-sea measurements demonstrated that the GTAS drag is always less than 1 lb, and typically averages around 0.5 lb during steady-state flight. This array's very low drag properties, combined with its very low electrical power consumption, make it an ideal system for persistent passive surveillance missions when high array gain and high spatial resolution in the low frequency band (below 1 kHz) is required. Because of its low drag, the array has little effect on the speed and flight control of ZRay.

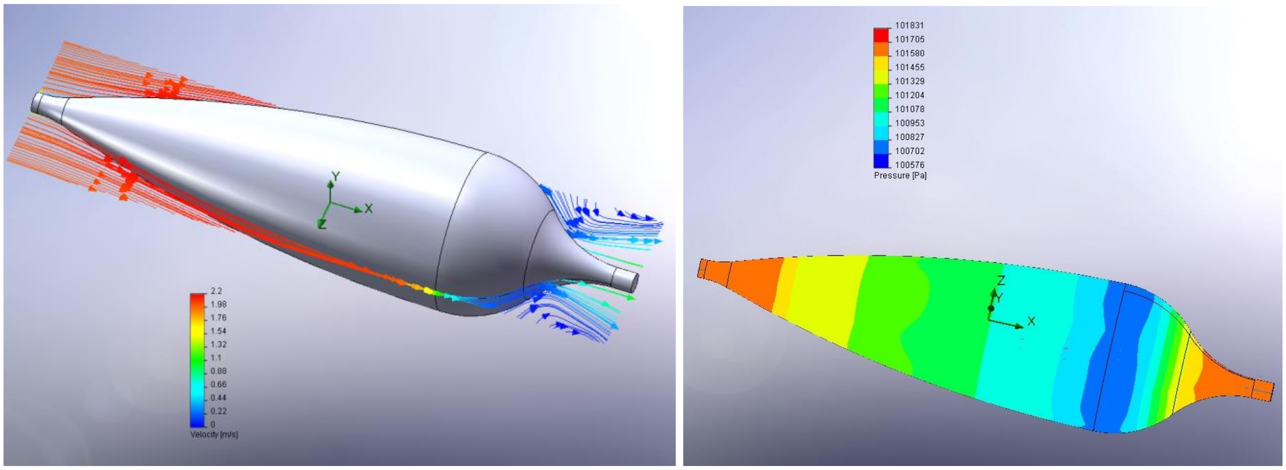

Figure 4. (Left) Fluid velocity around a GTAS element when placed in a uniform 2 m/sec flow from left to right in the figure, and (Right) the resulting pressure distribution.

Unfortunately, the GTAS array did not record any low frequency marine mammal calls during its deployment.

In addition to the GTAS towed array, ZRay's passive acoustic data recording systems included the 27-element hydrophone array located along the leading edge of the glider and the 3-channel Digital acoustic MONitoring (DMON) system provided by Woods Hole Oceanographic Institution. The DMON, configured with two mid-frequency channels and one low-frequency channel, was carried in the nose of ZRay. Both this system and the leading-edge hydrophone array successfully recorded data during almost all ZRay deployments in the engineering sea trip (the hard drive on which the leading-edge hydrophone array data were recorded filled up before the completion of the multi-day glider mission). Results from the simultaneous phase-coherent processing of the GTAS and leading-edge hydrophone arrays presently are being prepared for publication in the Journal of Underwater Acoustics.

IMPACT/APPLICATIONS

Existing underwater gliders (Seaglider, Spray, and Slocum) are highly successful underwater platforms for collecting vertical profiles of water column properties to provide near real-time environmental characterization. In contrast, prop-driven AUVs are designed for level flight, a highly desirable feature for imaging the ocean bottom as required to address the mine countermeasure problem. The types of missions suited for the Liberdade class of underwater gliders is distinctly different from those of these other two classes of autonomous underwater vehicles. In particular, the flying wing gliders ("Stingray", "XRay", and "ZRay") have demonstrated the capability to minimize energy consumed in horizontal transport while at the same time carry wide-band, multi-channel, high-data-rate payloads and have sufficient physical size to provide large array aperture at low and mid frequencies. The Liberdade class of flying wing underwater glider is well suited for a wide range of Navy missions as well as for long range, energy-efficient sensing of the ocean for basic science and civilian resource monitoring purposes.

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14. ABSTRACT
This report covers work carried out under both the above ONR grant and a previous grant (N00014-05-1-0209) logically connected to the same program. This program concerned development of a computer control system for a very large underwater glider. In addition, APL/UW partnered closely with the Scripps Institution of Oceanography who developed the vehicle hardware. A copy of the equivalent final report from Scripps is attached to this report as it covers work performed by both institutions in successful operation of the glider.

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					Peter Brodsky
					19b. TELEPHONE NUMBER *(Include area code)*
Unclassified	Unclassified	Unclassified	UU	14	206-543-4216