Persistent Maritime Surveillance Against Underwater Contacts using a Wave Gliders: Fleet Composition and Effectiveness

Ronald Kessel*[a], Craig Hamm[b], Martin Taillefer[c]
[a]Seamount Analytics, 1501-445 Laurier Ave W., Ottawa, Ont. Canada; [b]Sigma Ocean Research, 9 Ancroft Court, Ottawa, Ont., Canada; [c]Maritime Way Scientific, 5-1420 Youville Drive, Ottawa, Ont. Canada.

ABSTRACT

Autonomous platforms hold obvious promise for maritime operations. That promise faces reality when costs, overall effectiveness, fleet composition, infrastructure, and METOC limitations are assessed. Operational dimensions can be explored using multi-disciplinary modeling and simulation (M&S) combining platform physics (power, propulsion, sensors, communications, sea keeping) with oceanographic influences (wind, waves, currents, ice, solar energy, sound propagation and ambient noise) and economics (costs, benefits, business model)—all in light of top-down objectives. The resulting virtual demonstration can be critiqued and improved by application-domain experts. Successful demonstrations can garner the consensus that large capital projects require for advancing capability. The Innovation for *Defence Excellence and Security (IDEaS)* programme of the Canadian Dept. of National Defence (CAN DND) has therefore funded a project on wave gliders equipped with thin-line sonar arrays for autonomous persistent (multi-month) maritime surveillance against underwater contacts. This paper reviews selected key results from that analysis.

Keywords: Maritime surveillance, autonomous systems, wave gliders, thin-line passive sonar arrays, operational analysis

1. INTRODUCTION

Wave gliders are unmanned surface vessels (USVs), nominally 3 m in length, that take propulsion energy from ocean waves and battery recharge from the sun (see Fig. (1)). They travel at 1.5 to 2.25 knots in sea state 3 and higher [1, 2], they can tow payloads like sonar arrays [3], and they have been proven in multi-month deployments, mainly for oceanographic purposes thus far [4]. **Thin-line passive sonar arrays** are a new generation of sonar technology that are light-weight and low-power which can be towed by wave gliders. They have progressed alongside signal analysis and **auto-detection algorithms** for detecting underwater contacts.

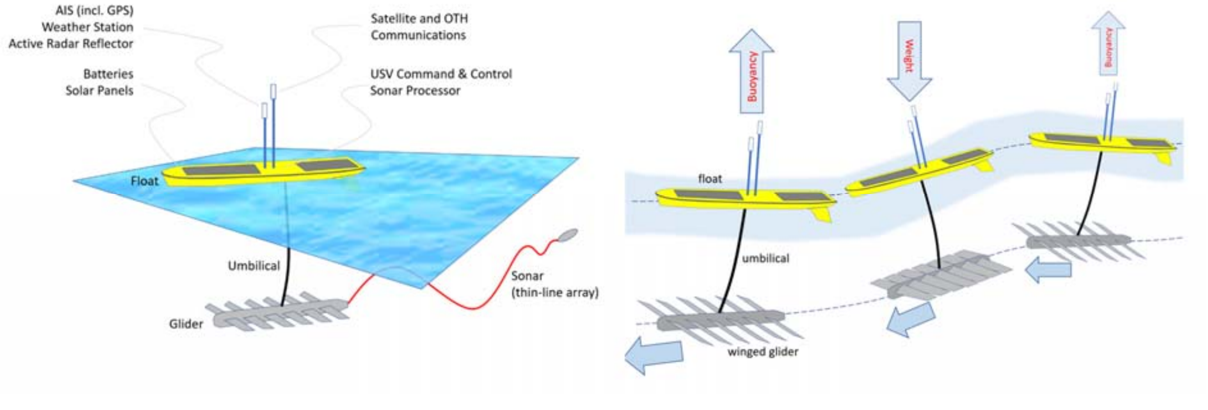

Figure 1 Schematic of a sonar-equipped wave glider (left) and its propulsion by wave action (right). Graphics based loosely on wave gliders by Liquid Robotics (USA).

The use of sonar-equipped wave gliders has often featured as a bullet item in marketing brochures and slides, and their use has been demonstrated to a limited extent at sea using a single platform [5, 6], apparently unchallenged by underwater contacts. But a larger picture of capability has so far never been addressed. Selected parts of that picture are presented here, including: (1) *Requirement Reconciliation*—the match with requirements for autonomous capability given by the CAN DND IDEaS innovation program; (2) *Surveillance Coverage*—the relationship between deployed fleet size and coverage effectiveness amid seasonally changing propagation conditions (a key cost driver); and (3) *Exogenous Limits*—the impediments of harsh METOC conditions in selected Canadian waters. Space does not allow for the impact of current and waves on wave glider speed, the expected variability of sonar coverage, communications, ship carriage requirements, capability costing and business model, which are all part of the larger project. A capability demonstration video of wave glider fleets will be shown in the presentation.

2. REQUIREMENT RECONCILIATION

A brief summary of the requirements ("wish-list") for highly autonomous persistent maritime surveillance as given by the CAN DND IDEaS programme, and their answer by sonar-equipped wave gliders, are summarized in Table (1). The main discriminators between wave gliders and unmanned underwater vehicles (UUVs) and other unmanned surface vehicles (USVs) are summarized in Table (2). Much more could be said both pro and con [7], but the tables make a good case for taking wave gliders seriously for this surveillance capability.

Table 1 Requirement Reconciliation of sonar-equipped wave gliders for Persistent Maritime Surveillance against underwater contacts in Canadian maritime approaches**.**

Autonomy	**The capability must be highly autonomous with on-board automatic signal analysis—**Wave gliders self-navigate long distances between waypoints with a passive, rugged, low-maintenance persistent propulsion mechanism (waves) and payload battery recharge (solar).
Persistence	**Multi-month operation on station—**Wave gliders have proven capable of three-month continuous operation on station. Deployments are limited mainly by biologic fouling. Navigation and communications are maintained through to sea state 7, with proven survival through much higher sea states (hurricane).
Rapidly Deployable	**Must be deployable from military ships without ship engineering modifications, and deployable from shore, and operate without cable or tether—**The small size and weight of wave gliders and thin-line arrays make deployment and recovery from military ships possible with a small crane. Autonomous long-distance transits to and from station (without ship transport) do not impair time on station.
Covert	**Sensors must be passive for covertness—**Thin-line sonar arrays are passive and covert. The wave glider underwater profile is very low. They are deemed to be generally undetectable by unalerted underwater contacts.
Effective	**Must have high probability of detection with acceptable rate of false alarm—**As with passive sonar generally, **e**ffectiveness depends on ambient noise levels (shipping and wind-generated), local sound-speed profile, length of the sonar array, sonar depth in the water column, and the noise radiated by the underwater contact. Effectiveness is treated below.
Real Time Communic-ations	**Must include high-speed communications for *continuous near real time* monitoring and tasking—**Wave gliders can carry near real time satellite communications with less than 2-minute latency and permitting two-way communications (Iridium and RUDEX), enabling remote status and position updates, re-tasking, and transfer of underwater signal information for analysis at headquarters.
Scalable	**Coverage area and duration must increase uniformly without change of hardware—**Sonar-equipped wave gliders can be added to increase the extent and effectiveness of coverage.
Affordable	**Costs and value must be objectively substantiated—**Costs, including infrastructure for 24/7 C2 monitoring are treated in a forthcoming full report.

Table 2 Selected technology-class discriminators between wave gliders, other unmanned surface vehicles (USVs), and unmanned underwater vehicles (UUVs)

Real-Time Comms	Wave gliders support continuous near real time communications through satellite or radio. UUV communications require either surfacing or underwater communication systems and nodes.
Power	The unlimited propulsion and electrical power of wave gliders from waves and sun, though at low levels, provide robust simplicity (few parts), long untended endurance, relentless persistence, and low liability of fuel spills, fire, collision—all of which are key autonomy enablers. UUVs face the overhead of docking stations and behaviours, or relatively frequent recovery for recharge.
Transit to	Wave gliders can make long autonomous transits to/from station with no operational penalty apart from transit

Station	time. UUVs (prop-propelled) generally avoid long transits to station owing to power constraints.
Sea Keeping	UUVs naturally avoid extreme sea states (except during recovery, deployment, and surface comms), where USVs must face or sail to avoid them. Adverse sea conditions are therefore considered below.
Sonar Depth	UUVs can easily change the sonar operating depth to capitalize on propagation conditions, where arrays towed by USVs are generally limited to shallower depths (10 to 100 m).

3. SURVEILLANCE COVERAGE

A key cost driver of surveillance is the number of platforms required for effectiveness. The wave glider coverage will follow that of passive sonar coverage generally, which determines the spacing and number of wave gliders required for each deployment. The results generalize to other towing platforms, autonomous or manned.

Sonar modeling was carried out using three-years of monthly propagation conditions at locations within each operating area in Fig. (2), all in waters of roughly 200 m deep. The propagation model was a ray model (*Bellhop* extended to NX2D). Wave-gliders were arranged in a picket-fence surveillance pattern of variable spacings *S* between 1 and 30 km as in Fig. (3); sonar depths varied between 10 and 100 m; sonar capability was varied through a set of directivity indices 6 to 18 dB; and targets varied between depths 20 to 200 m, with 3 radiated tones varied between 100 and 1000 Hz, with strengths corresponding to *slow-quiet* targets (90 to 100 dB SPL re 1 m narrowband tones for target speed 2 to 6 knots) to *loud-fast* targets (110 to 120 dB SPL re 1 m tones for target speeds 14 to 20 knots).

The sonar integration time was 10 seconds, the probability of false alarm was 0.0001, and the receiver operating characteristic (ROC) curves were Swerling II for narrowband processing. The sonar array towed by each wave glider was horizontal (HLA), with beams ± 30° to broadside. The ambient noise level was the classic Wenz shipping and wind noise, where the shipping level was varied uniformly between light and heavy, and wind speeds were the 3-hourly now-casts from historic wind data over 3 years at locations in each operating site in Fig. (2).

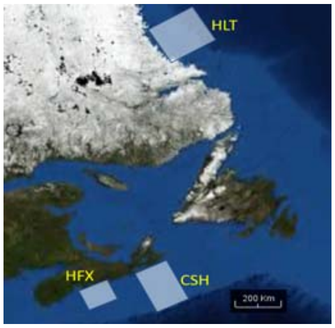

Figure 2 Operating areas on the east coast of Canada selected by the project team.

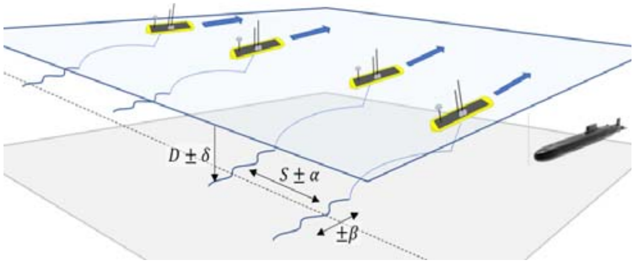

Figure 3 Picket-fence surveillance pattern assumed for persistent maritime surveillance. The separation distance is *S* in the figure. The modeling included positioning uncertainties that are beyond the scope of this paper.

Monte Carlo simulation was used to explore coverage versus separation distance using over 90000 randomized picket-fence/sonar/operating-area/target combinations. Coverage effectiveness was based on the *cumulative probability of detection CPD* for each target sailing through the picket fence, computed from the cumulative combined single-look probabilities of detection for all wave gliders in the picket fence for each target sail-through. The best sonar depth was found for each season in each operating area against slow-quiet targets and used in all ensuing coverage analyses. No optimization against target depth was used because the target depth was presumed unknown.

Surveillance *Effectiveness* was defined as the portion of simulated target encounters with *CPD* > 80 %, where *CPD* is the probability of detecting a target at some time during its transit through the picket-fence surveillance.

Effectiveness > 80 % was considered *highly effective* surveillance capability (i.e., over 80 % of target encounters across the full range of realistic operating conditions have an overall probability of detection of over 80 %).

Effectiveness > 50 % was considered *moderately effective* surveillance capability (i.e., over 50 % of target encounters across the full range of realistic operating conditions have an overall probability of detection of over 80 %).

Fig. (4) shows the surveillance *Effectiveness* as a function of wave-glider separation distance *S* for the entire the set of randomized target encounters, at all operating areas (sites), across all seasons, with seasonally optimized sonar depth, for 32-element sonar arrays with directivity index 15 dB. The shaded region of the graph shows the large effectiveness variation with site, season, and target. Large variation of effectiveness is typical for passive sonar across the set of realistic conditions. Each surveillance deployment must be tailored for the seasonal conditions, as one generally must for passive sonar, adjusting search operations for the conditions on hand.

Surveillance effectiveness is ***high*** above the dashed line "HIGH", and moderate above the dashed line "MEDIUM" in Fig. (4).

The mean in Fig. (4) indicates that a 2000 m nominal wave glider spacing *S* spacing can assumed for high effectiveness. A 20 km picket-fence of high effectiveness therefore nominally requires a fleet of about 10 wave gliders. Considering the shaded region in Fig. (4), however, one expects that the same fleet will provide a high effectiveness in some operating areas, and for some seasons, with spacing over 10 km, across a picket line of length of over 100 km.

The mean in Fig. (4) similarly indicates that a 25 km nominal wave glider spacing *S* spacing can assumed for moderate effectiveness. A 20 km picket-fence of moderate effectiveness therefore nominally requires a fleet of about 1 wave glider. The variation in passive sonar coverage results in the large variation on the deployed fleet size and coverage performance. The variation is a property of long-range passive sonar across the full range of realistic operating conditions. It true of passive sonar generally and is not unique to surveillance using sonar-equipped wave gliders.

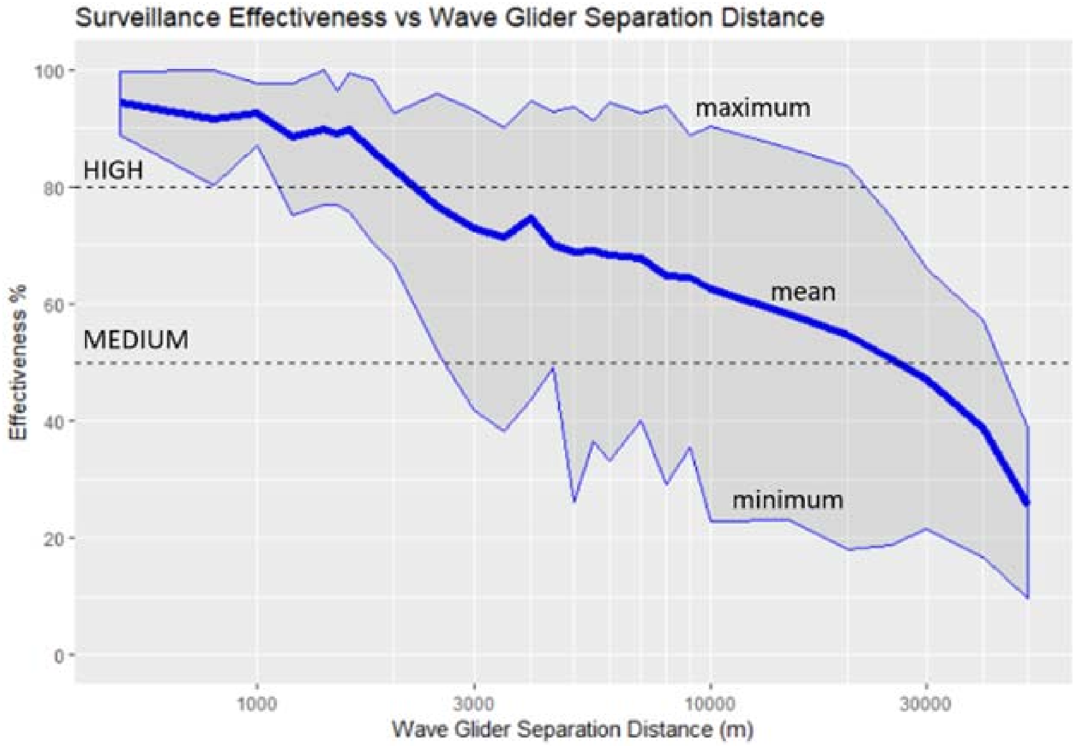

Figure 4 Surveillance effectiveness versus wave glider separation *S* across all simulations of operating area, season, and target saliency. The passive sonar properties assumed are described in the text.

The impact of changing conditions such as operating area, season, and target saliency can be explored using the Monte Carlo simulation. Table (3) summarizes some of the variation assessed using the mean of the surveillance effectiveness for subsets of the Monte Carlo simulations, grouped by operating area and target saliency. The variation with operating area and target saliency is large, as expected with passive sonar generally.

Table 3 The nominal (mean) wave glider separation distance by operating area and target saliency.

	Separation S (km)							
	FULL Target Set (0 to 120 dB)		QUIET Targets (90 to 100 dB)		MEDIUM Targets (100 to 110 dB)		LOUD Targets (110 to 120 dB)	
Operating Area	HIGH Effectiveness	MEDIUM Effectiveness	HIGH Effectiveness	MEDIUM Effectiveness	HIGH Effectiveness	MEDIUM Effectiveness	HIGH Effectiveness	MEDIUM Effectiveness
HFX Outer Halifax Harbour	15	40	5	12	20	40	42	> 50
CSH Coastal Shelf	2	20	1.5	4	2.6	30	9	50
HLT Labrador Sea	2	10	0.6	2.1	2.6	10	7	45

4. EXOGENOUS LIMITS

Wave gliders survive sea state 6 and higher, but the performance of passive sonar arrays is expected from experience to be limited to sea state 6 and less owing to noise and motion. As with small craft generally, sea states above 8 should be avoided using METOC forecasts. Table (4) summarizes the frequency of sea states greater than 6 and 8. Similar limitations are faced in sonar operations by surface platforms, manned and autonomous.

Table 4 Relative frequency in % of sea state greater than sea state 6 and 8 in 3-hour intervals over three years (2005-07) in the operating areas in Fig. (2).

	% Sea State > 6—Surveillance Suspended				% Sea State > 8—Area Avoidance			
Area	**Spring**	**Summer**	**Fall**	**Winter**	**Spring**	**Summer**	**Fall**	**Winter**
HFX	6.9	0.2	7.7	15.8	0.00	0.11	0.23	0.48
CSH	7.2	1.1	6.8	20.2	0.26	0.19	0.17	0.44
HLT	18.0	2.7	18.1	32.6	0.74	0.22	1.43	1.59

Battery recharge by solar panels can limit operations if a platform's power load exceeds recharge. Exceedance is more likely in winter and at higher latitudes. Fig. (5) plots the solar power captured based on actual historic now-cast solar data in the operating areas for one year (2014) assuming a 1 W average hotel and communication load, a 3.5 W sonar 32-element-array load, a 10 W processing load, and a 2 m^2 sonar panel with 80 % efficiency. Low battery power and possible recharge down time may occur when sonar recharge approaches or falls below that level (dashed line in Fig. (5)). The resulting recharge down time depends on battery size and the low-power strategy of the wave gliders (not included here).

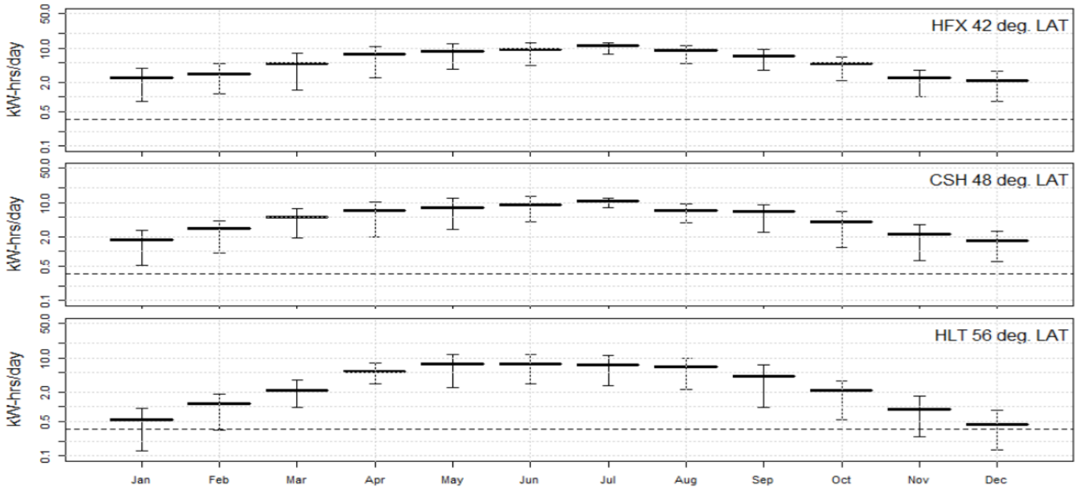

Figure 5 Mean daily solar power acquired by each wave glider. The 80 % confidence interval is indicated. The dashed line is the minimum required to maintain battery charge level.

5. CONCLUSIONS

Overall effectiveness requires a good match with operational requirements, a high probability of detection, and acceptable down-time due to exogenous conditions, which were briefly reviewed here for persistent maritime surveillance using sonar-equipped wave gliders.

It is believed that no platform lends itself so well to persistent surveillance with high autonomy as sonar-equipped wave gliders. None meets capability requirements so well—for multi-month persistence, ease of deployment and recovery from port or ship, for near real time communications (for monitoring and re-tasking), and for absence of anchor and cabling, to cite a few key requirements.

Most importantly for extended use in home waters, no other class of autonomous maritime platforms afford equally high autonomy and independence with such low liabilities of operation owing to the wave glider's combination of light weight, slow relentless speed, its few moving parts, and the absence of combustible, spillable fuels. Low liability is paramount for the distant operation of autonomous systems outside of combat.

The Technology Readiness Levels (TRLs) of the key technologies for persistent maritime surveillance were estimated to be TRL7-8 for wave gliders, TRL 6 for thin-line acoustic arrays, and TRL 5 for highly autonomous autodetection for passive sonar.

A plausible fleet size in Canadian waters is on the order of 10 wave gliders, giving *moderate* surveillance effectiveness for a picket-fence line on the order of 300 km under favorable sonar conditions, and 30 km under challenging conditions, while giving *high* surveillance effectiveness on the order of 200 km under favorable conditions, and 10 km under challenging. In practice, the wave glider spacing, overall picket-fence line of coverage, and deployed fleet size would be determined for a given operating area and season ahead of each deployment using modeling of the kind used in this study.

The operational footprint of the sonar-equipped wave glider fleet includes procurement costs, maintenance, deployment, recovery, intervention in the event of failed platforms, satellite communications, and 24/7 command center watch (excluding response measures prosecuting detections). This project also estimated the operational costs ($/month/km-picket-fence) for a given fleet size, and the incremental costs of adding one wave glider. A business model in which surveillance services are contracted from a commercial enterprise was assumed, as opposed to government/military ownership of the capability. Contracted services capitalize faster and more efficiently on capability updates and developments—expected in satellite communications, autonomous behavior sets, and autodetection with accumulated data, wave glider platforms, and thin line arrays, and so forth [8]. Persistent surveillance lends itself to contracted services insofar as surveillance operations remain bounded, stopping short of legal enforcement and the use of force, which remain the task of government agencies who act on the information provided by the surveillance provider. It is a natural division of labour. Autonomous surveillance is allocated to commercial enterprise(s), while law enforcement, sovereignty assertion, and use of force are allocated to government agencies acting on the information provided by the contracted surveillance. A precedent for the commercial services model exists in manned aerial maritime surveillance, contracted from PAL Aerospace by the Canadian Government (Maritime Security, Fisheries and Oceans) [9]. PAL Aerospace provides airframes, pilots, flight crew, sensors, and data management to the Canadian government for large-area aerial surveillance, mostly routine but some special tasking as well. They provide a complete aerial ISR service. A similar business model is proposed here for persistent underwater maritime surveillance.

This project provides realistic qualitative and quantitative reference points in the vision for the new capability. The proposed way ahead [8] aims to support continual rapid advance of high autonomy for Canadian maritime surveillance, and to maximize the larger benefit to the emerging maritime robotic sector in Canada. It is therefore based on standardized open architectures for autonomous systems, and on an inclusive business model for contracted surveillance services, which together:

- avoid stifling progress with exclusive proprietary systems
- provide avenues for contributions to capability from diverse players, including Canadian industry, universities and allies (USA, AUS, NATO)
- streamline at-sea collaboration between industry and university partners by ensuring compatibility between their systems and the fielded system

- motivate innovation and speeds their uptake into at-sea surveillance capability
- support the export of maritime surveillance services to clients in addition to the Canadian government
- support the wider use of subsystem components (broaden their market) in applications other than maritime surveillance

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