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Autonomous Exploration and Digital Documentation of Great Lakes Shipwrecks: A Multi-Platform Survey Framework for Maritime Heritage

Arthur C. Trembanis

School of Marine Science and Policy, University of Delaware, Newark, DE 19716, USA; art@udel.edu

Abstract

The preservation of submerged cultural heritage depends on the ability to locate, document, and monitor sites before they are degraded or lost. Although the North American Great Lakes contain thousands of exceptionally well-preserved shipwrecks, their large geographic extent and diverse operating environments present significant challenges for efficient archeological survey. This study presents a multi-platform autonomous survey framework developed and implemented during 2021–2022 field campaigns in Lake Michigan and Lake Ontario. The framework integrates autonomous underwater vehicles (AUVs), autonomous surface vehicles (ASVs), crewed vessels, side-scan sonar, multibeam bathymetry, magnetometry, optical imaging, and field-based data review within a hierarchical workflow comprising wide-area assessment (WAA) reconnaissance, high-resolution geophysical (HRG) mapping, adaptive mission refinement, and visual confirmation. The surveys produced 19.72 km^2 of geophysical coverage, including side-scan sonar mosaics, bathymetric surfaces, magnetic anomaly maps, and optical imagery that supported archeological interpretation. A case study from Lake Ontario demonstrates the framework's effectiveness through the confirmation of a previously undocumented wooden shipwreck using complementary acoustic, magnetic, and visual datasets. Beyond the individual discoveries, the results demonstrate how integrated autonomous systems improve survey efficiency, support adaptive decision-making, and provide scalable methods for digital documentation, baseline site characterization, long-term monitoring, and preservation of submerged cultural heritage in freshwater and marine environments.

Keywords: underwater cultural heritage; autonomous underwater vehicle; autonomous surface vehicle; side-scan sonar; multibeam bathymetry; magnetometry; digital preservation

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1. Introduction

Submerged cultural heritage is inherently difficult to protect because it is difficult to see, survey, revisit, and convey to the public and site managers. Shipwrecks, inundated landscapes, and other underwater cultural resources may be damaged by storms, erosion, sediment mobility, corrosion, invasive species, recreational impacts, salvage, trawling, dredging, infrastructure development, and changing patterns of public access [1]. In deep water, the challenge is one of access and cost [2]. In shallow water, the challenge is often one of hazard, turbidity, surf-zone dynamics, vessel limitations, and intermittent exposure [3]. Preservation begins with discovery: unlocated sites cannot be evaluated, protected, or managed [4].

Maritime heritage encompasses both cultural and environmental challenges, recognizing that wrecks may be threatened by external forces while also posing risks or creating ecological structures [1,5,6]. This paper presents a case study of autonomous exploration and digital documentation in the Great Lakes region.

Remote sensing has long been central to maritime archeology [7]. Side-scan sonar, magnetometry, sub-bottom profiling, multibeam echosounders, diver survey, and visual inspection each provide partial but complementary evidence about submerged sites. Integrated geophysical surveys of wrecks such as *La Surveillante* demonstrated the interpretive value of combining acoustic and magnetic techniques [8]. Subsequent studies showed that side-scan sonar backscatter and resolution are highly dependent on target material, range, grazing angle, relief, and survey design [9], while multibeam bathymetry can identify shipwreck morphology, support site assessment, and supply repeatable metrics for monitoring change [10,11]. Comparisons between documentary inventories, side-scan sonar, and diver survey have also shown that archival positions are often incomplete or spatially inaccurate, making systematic field verification essential [12].

Site formation scholarship provides a second foundation for this work. Muckelroy's classic formulation emphasized the transformation of a ship into a wreck site through both cultural and natural processes [13]. Gibbs later argued that maritime archeologists should also model cultural responses to wrecking, including rescue, salvage, abandonment, reuse, and memory [14]. These frameworks are important for interpreting geophysical data because acoustic shadows, debris fields, scour features, magnetic anomalies, and exposed timbers are not simply "objects" but products of wrecking, post-wreck disturbance, sedimentary processes, biological colonization, and human interaction [15,16]. In the Great Lakes, the preservation of wooden hull fabric under cold freshwater conditions creates extraordinary archeological potential, but site visibility may still vary with burial, erosion, biological colonization, water clarity, and nearshore sediment dynamics.

Autonomous systems add a third foundation. Roman and Mather argued that AUVs (autonomous underwater vehicles) were becoming effective tools for locating, identifying, and surveying archeological sites, particularly where they could carry sensors close to the seabed and acquire consistent data at scales difficult to achieve with divers or towed systems [17]. Further developments in marine robotics [18] have since expanded the use of AUVs, ASVs (Autonomous Surface Vessel), ROVs (Remotely Operated Vehicle), and hybrid sensor packages for mapping, inspection, and environmental monitoring. In underwater cultural heritage, the technical problem is not simply whether a robot can collect data. It is whether platforms, sensors, human operators, historical knowledge, and post-processing workflows can be combined into a practical system that answers archeological and management questions while operating safely in the field [2].

Digital documentation links these technical advances to preservation. Underwater photogrammetry, 3D reconstruction, high-resolution acoustic mosaics, and bathymetric models support virtual access, condition assessment, repeat monitoring, and public interpretation [19,20]. Digital products cannot replace legal protection, conservation, or community stewardship, but they make submerged sites visible, measurable, and communicable. They can also preserve a record of condition at a known moment in time, which is essential for assessing later change. The most useful digital heritage products are therefore not isolated visualizations; they are spatially controlled outputs embedded within a repeatable survey and archival workflow.

The North American Great Lakes provide a valuable setting in which to develop such a workflow. The Great Lakes, St. Lawrence River, and their connecting waterways formed a transportation corridor extending more than 2400 miles into the North American interior. Over the past three centuries, they supported Indigenous travel and exchange, European and

American expansion, industrialization, fishing, lumber, grain transport, passenger travel, military conflict, and regional commerce. The Great Lakes contain an estimated 6000 shipwrecks, many of which preserve wooden hull structures, machinery, cargo, and associated artifacts in exceptional condition. Yet the scale of the lakes, the variability of known site locations, and the mix of shallow and deep environments create major challenges for systematic survey.

The present project, "Maritime Heritage in America's Inland Seas: A Multi-tiered Autonomous Vehicle-based Survey of Two Proposed Great Lakes National Marine Sanctuaries," was funded by NOAA's Office of Ocean Exploration and Research and conducted in 2021 with federal, state, academic, and commercial partners [21]. The broader project addressed areas associated with the new Wisconsin Shipwreck Coast National Marine Sanctuary and the proposed Lake Ontario National Marine Sanctuary. This paper focuses deliberately on the University of Delaware contribution within that larger effort: the development, execution, and evaluation of a multi-platform autonomous survey approach centered on AUV, ASV, crewed-vessel support, acoustic mapping, magnetometry, visual inspection, and field data processing.

The aim here is not to present the full archeological report of all project partners, but to examine the operational and methodological contribution of multi-platform and multi-sensor survey as a transferable framework for heritage operations in the Great Lakes and beyond. This allows for a more focused examination and discussion of platform performance, mission planning, sensor complementarity, field adaptation, and data products. Readers are directed to the overall project report for an examination of the broader partnership activities [21].

The four objectives of this paper are: (1) to describe a hierarchical multi-platform autonomous workflow for submerged cultural heritage survey; (2) to evaluate how wide-area assessment, high-resolution geophysical mapping, and adaptive mission refinement functioned in Great Lakes field conditions; (3) to analyze the complementarity of side-scan sonar, multibeam bathymetry, magnetometry, and optical ground-truthing; and (4) to discuss how the workflow can support digital preservation, monitoring, and workforce training toward future semi-automated exploration. Figure 1 illustrates the study regions and overall project context.

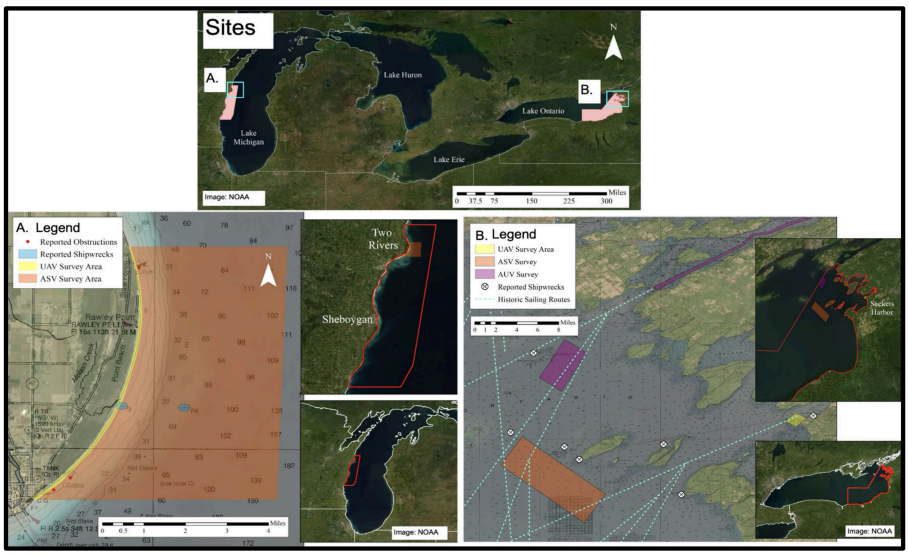


Figure 1. Study areas for the Great Lakes autonomous maritime heritage survey. Panel (**A**) illustrates the Wisconsin Shipwreck Coast area in Lake Michigan, including Rawley Point/Two Rivers and associated nearshore, open-water, and riverine survey zones. Panel (**B**) shows the eastern Lake Ontario survey region, including Sackets Harbor, Horse Island, Stony Island/Stony Point, the Duck-Galloo ridge area, and relevant St. Lawrence River survey areas.

2. Methods

The 2021 campaign occurred in two Great Lakes settings: western Lake Michigan near Two Rivers, Wisconsin, and eastern Lake Ontario near Sackets Harbor, Stony Point, Stony Island, Galloo Island, and the St. Lawrence River. The Wisconsin survey area was selected because Rawley Point is a historically hazardous, shallow, sandy, dynamic feature where 19th-century vessel losses occurred and where wrecks may be deeply buried, intermittently exposed, or difficult to access by conventional survey vessels. Contemporary accounts and prior archeological work indicate that stranded vessels in this region could rapidly become embedded in sand. For a technology-centered survey, this setting created an important test of nearshore operations, shallow-water coverage, and the transition between beach/surf-zone methods and offshore platforms.

The eastern Lake Ontario study areas were selected to address several overlapping historical and methodological priorities. Sackets Harbor was a major War of 1812 naval and military landscape, while waters near Stony Point, Stony Island, Galloo Island, and the St. Lawrence River include known, reported, and suspected historic vessel losses. The broader proposal anticipated a 90 km^2 ASV survey of the Duck-Galloo ridgeline and targeted AUV surveys in areas associated with known and reported wrecks. In practice, the field campaign required adaptive operations, focusing on available weather windows, vessel access, target reacquisition, and data-processing feedback.

The University of Delaware team operated within this broader multi-partner framework. Its principal role was technical leadership and execution of AUV and portable ASV operations, supplemental crewed-vessel survey from R/V *Dogfish*, support for platform deployment and recovery, and processing of acoustic and imagery data products. Survey operations followed a hierarchical exploration strategy consisting of wide-area assessment (WAA), which emphasized efficient reconnaissance to locate, relocate, and prioritize archeological targets over large areas, followed by high-resolution geophysical (HRG) surveys designed to acquire detailed acoustic and geophysical data for site characterization and documentation. The team's assets included an Iver3 AUV, portable ASVs including EchoBoat and EMILY systems, R/V *Dogfish* as a small support and survey vessel, sonar and magnetometer payloads, and post-processing workflows for side-scan sonar mosaics, bathymetric products, optical imagery, and GIS-ready deliverables [21]. The principal survey platforms used during the campaign, together with their primary operational roles and sensor payloads, are summarized in Table 1.

Table 1. Principal platforms and survey roles utilized during the Great Lakes campaigns.

Platform	Primary Role	Principal Sensor(s)	Operational Domain
Iver3 AUV	Targeted WAA and HRG mapping	EdgeTech 2205 bathymetric side-scan sonar; color imagery	Known and suspected wreck sites in nearshore/offshore settings
EchoBoat 160 ASV	Nearshore side-scan reconnaissance	Humminbird side-scan sonar	Beach, surf-zone margin, riverine, and protected waters
EMILY ASV	Small-vehicle opportunistic survey	Humminbird/side-scan payloads	Shallow, rough, or constrained areas where larger systems were less practical
R/V *Dogfish*	Crewed support and supplemental survey	Humminbird Solix; EdgeTech 6205; towed magnetometer	Launch/recovery support, shallow-water reconnaissance, transit and logistics
C-Worker 8 ASV	WAA MBES mapping	R2Sonic 2026 MBES	Offshore bathymetry and backscatter in Lake Ontario

2.1. Conceptual Survey Framework

The University of Delaware workflow was designed as a hierarchical survey framework rather than a single-platform survey. It consisted of three linked phases: wide-area

assessment (WAA), high-resolution geophysical survey (HRG), and adaptive mission refinement. This design reflects a recurring problem in underwater archeology: broad survey is needed to find targets, but high-resolution survey is needed to interpret them. Attempting to survey large areas entirely at high resolution is inefficient, while relying on reconnaissance data alone often produces ambiguous interpretations.

Prior to field operations, archival and literature research were conducted to compile existing information on known and suspected shipwreck locations and to prioritize survey targets. Sources included historical navigation charts, shipwreck inventories maintained by state and federal agencies, museum and maritime heritage records, historical vessel registries, and published historical accounts where available. These archival efforts were led by the NOAA team members, and the collected data were synthesized with existing geospatial information to estimate probable wreck locations and provide historical context for interpreting geophysical anomalies identified during subsequent surveys.

In the WAA phase, the objective was to locate, reacquire, or broadly characterize sites and anomalies. AUV missions in this mode generally used lower-frequency side-scan sonar and greater altitude above the lakebed to increase swath and coverage. WAA surveys were conducted either from the surface using ASVs or by AUVs operating at higher altitude and lower sonar frequency, typically using approximately 600 kHz side-scan sonar when appropriate for site conditions. The exact altitude and line spacing were adjusted to depth, site relief, navigation safety, and target positioning uncertainty.

In the HRG phase, the objective shifted from detection to detailed characterization. Targets or known wreck locations were revisited with tighter line spacing, lower altitude, and higher-frequency sonar, often using approximately 1600 kHz side-scan sonar and altitudes of roughly 8–10 m above the lakebed in the 2021 campaign. In later follow-up work and shallow target investigations, even lower altitudes and closer passes could be used when safe and operationally appropriate. The aim was to improve feature definition, acoustic shadow interpretation, hull orientation, and, where possible, optical coverage from onboard or ROV cameras.

During the WAA phase, side-scan sonar was operated at 600 kHz with the vehicle maintained at a higher altitude above the lakebed to maximize operational safety while surveying these uncharacterized sites. Because the size, relief, and distribution of submerged hazards were initially unknown, maintaining greater standoff distance reduced collision risk while permitting efficient reconnaissance over larger areas. The 600 kHz operating frequency was selected because its longer effective imaging range is well suited to higher-altitude surveys, providing sufficient swath width to detect shipwreck-scale anomalies while maintaining adequate image quality. Once targets were identified, the HRG surveys transitioned to lower-altitude operations (approximately 8–10 m above bottom) using 1600 kHz side-scan sonar. The reduced survey altitude permitted the use of the shorter-range, higher-frequency system, which provides substantially improved spatial resolution and target definition for archeological interpretation. This progression from lower-frequency reconnaissance to higher-frequency site characterization reflects the fundamental trade-off between sonar range and image resolution and is consistent with established side-scan sonar survey practice for archeological investigations.

The third phase, adaptive mission refinement, was the most important operational innovation. Field teams did not simply execute a static preplanned grid. Instead, they used preliminary sonar mosaics, single-beam or side-scan reconnaissance from support vessels, operator observations, diver or ROV information, and local knowledge to update target locations and mission geometry. The *Gallinipper* sequence in Lake Michigan illustrates the method: an initial WAA mission was processed in the field to generate a georeferenced mosaic, after which a follow-up mission was planned with tracklines aligned to the wreck,

two lines on each side of the centerline, and a lower altitude to obtain improved imagery. Figure 2 summarizes the workflow.

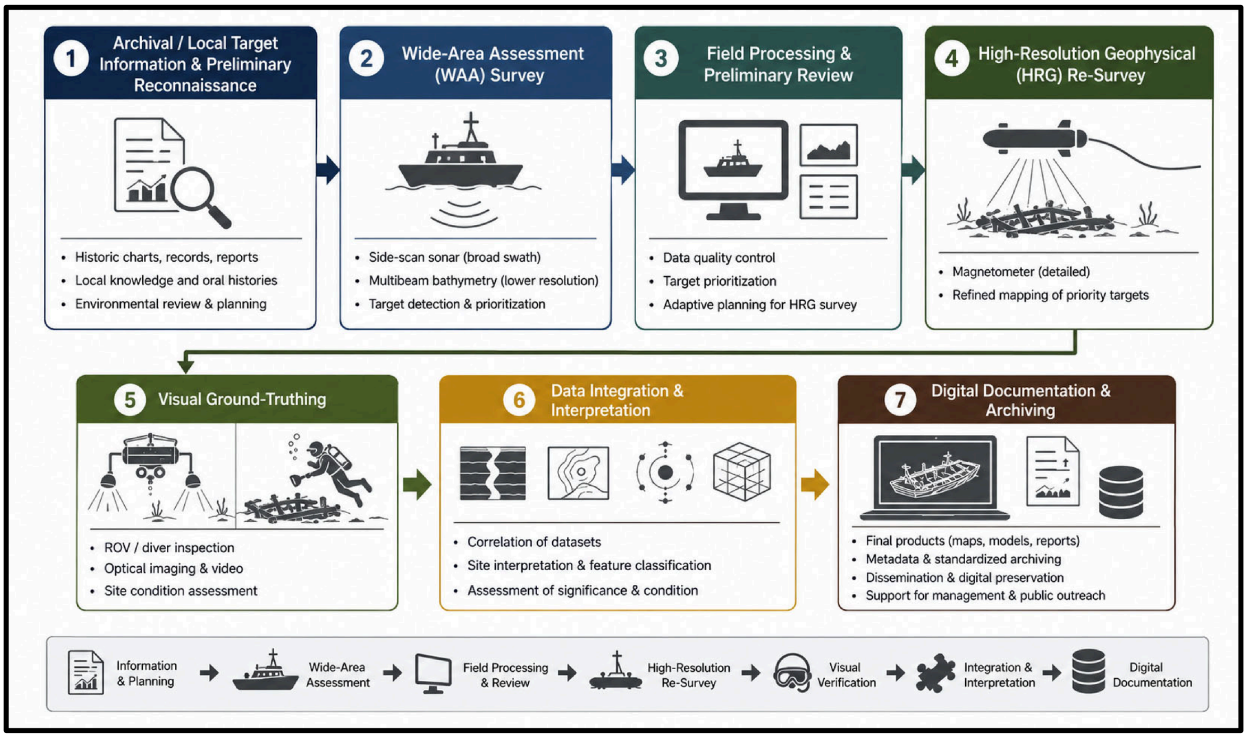


Figure 2. Hierarchical survey framework employed in this expedition. The sequence proceeds from archival/local information to WAA survey, field processing, HRG re-survey, visual ground-truthing, data integration, and digital documentation.

2.2. AUV Operations

AUV operations were conducted using the University of Delaware Iver3 system with integrated EdgeTech 2205 bathymetric side-scan sonar and a color camera. The vehicle was deployed from crewed support vessels and used in both nearshore and offshore environments (Figure 3). In Wisconsin, AUV work occurred over known wreck sites offshore of Two Rivers and Manitowoc, including *Henry Gust*, *Vernon*, *S.C. Baldwin*, *Floretta*, *Home*, and *Gallinipper*. In New York, AUV operations focused on sites and reported shipwreck locations including *Napoleon*, *Gitana*, *Ellsworth*, *Omar Pacha*, *Onondaga*, and other targets near Stony Island and Stony Point.

Mission planning used predefined tracklines with spacing that varied according to the survey objective, target size, depth, and uncertainty in reported positions. The survey operations utilized trackline spacing ranging from approximately 2 to 30 m depending on mission type and application. WAA missions were used when the target position, orientation, or extent was uncertain. HRG missions were used when a target had been identified, a known site was being characterized, or the team wanted higher-resolution imagery for interpretation and monitoring. Mission durations ranged from short system checks to multi-hour surveys.

AUV operations depended on tight coordination between the platform team and support vessel. The vehicle required safe launch and recovery, acoustic communications, mission monitoring, and a vessel that could remain on station or provide chase support. In Lake Michigan, NOAA (National Oceanic and Atmospheric Administration) vessel support enabled early offshore operations when other project assets were delayed. In Lake Ontario, M/V *Troublemaker* proved particularly effective for AUV work because it provided deck space, a swim platform for launch and recovery, and an extendable boom arm useful

for acoustic modem deployment. These vessel-platform relationships are central to field autonomy, and it bears stating that "low logistics" does not mean "no logistics" when it comes to field operations of autonomous systems. Rather, it means that an appropriately sized field team can deploy capable sensors without requiring a large research vessel.

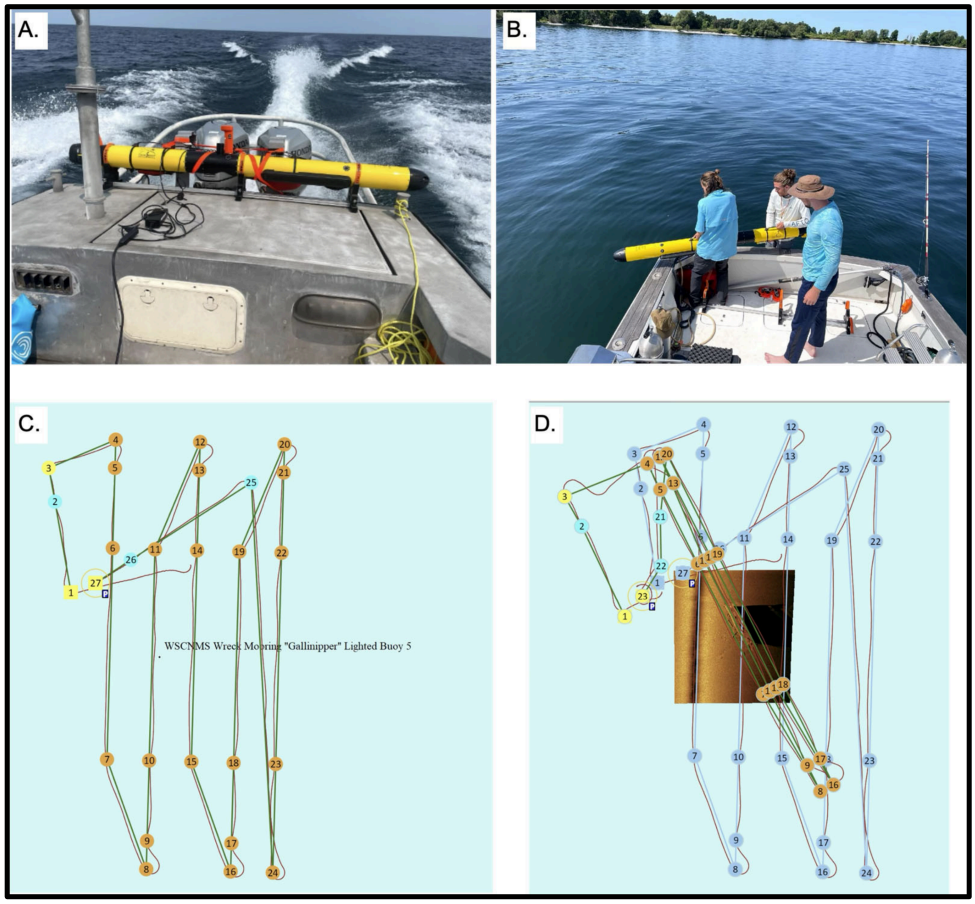


Figure 3. University of Delaware AUV operations. (**A**) Iver3 AUV on the support vessel before deployment; (**B**) AUV launch; (**C**) AUV WAA trackline pattern; (**D**) AUV HRG trackline pattern aligned to a wreck.

AUV survey data were used both for archeological site characterization and for operational decision-making. The August 3 *Gallinipper* mission illustrates how the team used AUV side-scan data to plan a refined follow-up mission. The first *Gallinipper* survey provided a WAA mosaic; that mosaic was reviewed in the field and used to align a second mission to the wreck's long axis, improving both acoustic imagery and photo coverage. Similar adaptive logic was used in Lake Ontario, where reported positions were sometimes inaccurate or unreliable. In several cases, support-vessel reconnaissance was needed before the AUV could be sent on an efficient mission.

2.3. ASV and Crewed-Vessel Operations

Portable ASVs extended the survey framework into shallow, nearshore, beach-accessible, and riverine settings (Figure 4). The EchoBoat 160, EchoBoat 240, and EMILY systems were tested or deployed in Wisconsin and New York. These platforms carried commercial sonar payloads and were used opportunistically when conditions, access, or scientific priorities favored small-vehicle operations. The EchoBoat 160 was deployed from shore and used with mission planning workflows such as Project11. Project11 is an open-source Robot Operating System (ROS)-based software framework for autonomous marine

vehicles that provides mission planning, vehicle control, and monitoring capabilities for autonomous seafloor mapping operations [22]. The EMILY ASV, with a jet-drive configuration, was useful in shallow and constrained settings but had limited endurance and, during some New York operations, experienced behavior that required mission termination and recovery [21].

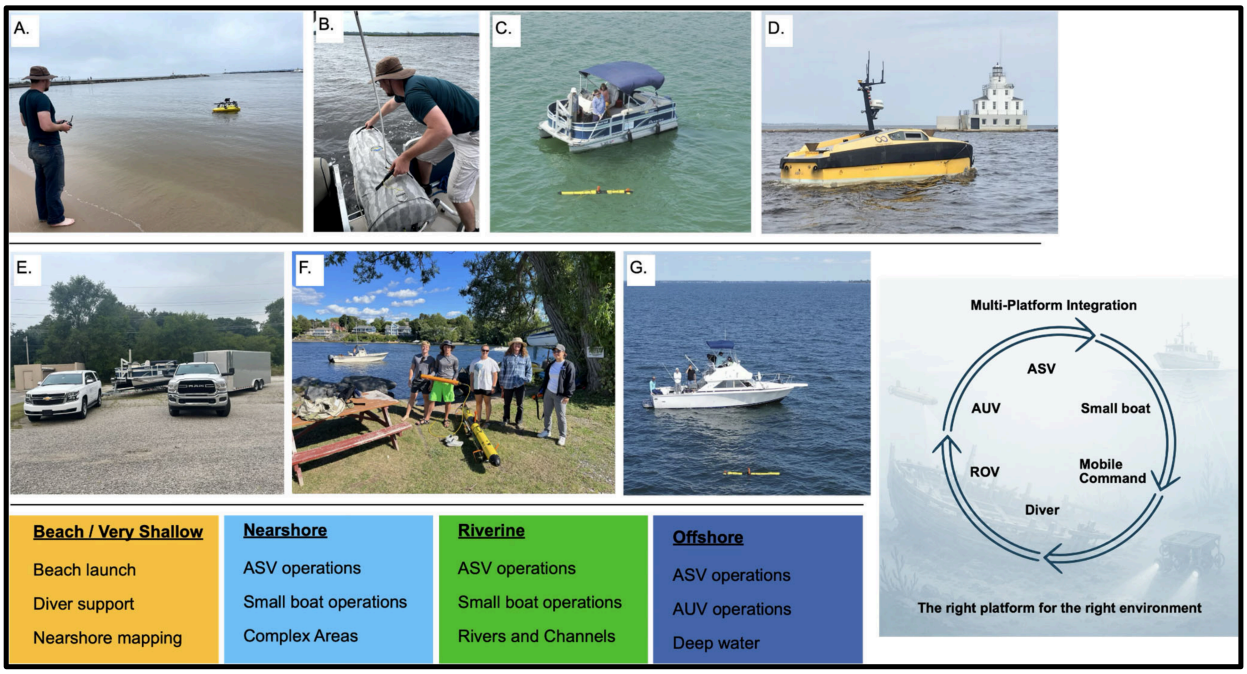


Figure 4. Multi-platform integration operations. Platforms include (**A**) EchoBoat 160 ASV; (**B**) EMILY ASV; (**C**) R/V Dogfish; (**D**) C-Worker 8 ASV; (**E**) Mobile lab/trailer; (**F**) Shoreside launch; (**G**) M/V Troublemaker.

R/V *Dogfish* provided an essential bridge between autonomy and traditional survey. It supported transport, platform recovery, shallow-water operations, side-scan sonar reconnaissance, and magnetometer towing. In Wisconsin, R/V *Dogfish* supported the University of Miami UAV team, ran Humminbird Solix side-scan passes at known or suspected wreck locations, and conducted riverine surveys when offshore weather prevented lake operations. In New York, R/V *Dogfish* was configured with EdgeTech 6205 bathymetric side-scan sonar and a Coda F190 system for surveys along the St. Lawrence River and near the battlefield area. These operations underscored the value of maintaining multiple platforms and a flexible survey plan.

The C-Worker 8 ASV, operated by Ocean Infinity in the broader project, is included here as part of the multi-platform context because it contributed MBES (multibeam echosounder) coverage in Lake Ontario and because the original proposal tied its use to the University of Delaware's broader autonomous systems development. The C-Worker 8 is a state-of-the-art ASV equipped with an R2Sonic 2026 multibeam echosounder, capable of both extended-range and higher-frequency high-resolution bathymetric mapping, capable of producing 1 m cell-size products and backscatter useful for lakebed classification. Although this paper focuses on the University of Delaware team, the C-Worker data formed part of the broader sensor surveys within which UD AUV/ASV data were interpreted.

The use of small platforms created operational flexibility but also exposed practical limitations. The EchoBoat 240 experienced water ingress and thruster damage after difficult conditions and magnetometer towing in Wisconsin. The EchoBoat 160 completed successful nearshore surveys but required recovery after battery limitations and drifting during

one mission. The EMILY system was maneuverable in shallow water but experienced communications or control behaviors requiring recovery in Lake Ontario. These are not failures of autonomy as a concept; rather, they are field-based evidence that platform scale, endurance, weather, payload drag, and recovery planning must be layered and matched to archeological survey goals.

2.4. Magnetometry and Optical Ground-Truthing

Magnetometer data were collected by multiple project partners using aerial and marine systems, while the University of Delaware team contributed to marine magnetometer integration and site-specific follow-up in selected contexts. Magnetic survey is valuable in maritime archeology because many wooden wrecks contain ferrous fasteners, anchors, machinery, cargo, ballast-related materials, or associated debris. However, magnetic anomalies require careful interpretation because they may also reflect geology, modern infrastructure, pipelines, cables, or unrelated debris. For this campaign, processed residual-anomaly grids were used to identify signals likely to represent anthropogenic ferromagnetic materials, with 5 nT used as a practical noise floor threshold for marking anomalies in the final project analysis.

The project also envisioned diver-held magnetometer work and ground-truthing of anomalies shallower than 46 m, with deeper targets investigated by AUV at the highest practicable resolution. During operations, ground-truthing involved scientific diving by NOAA personnel, ROV inspection, and optical imagery acquired from vehicle systems. ROV imagery was particularly important in the 2022 follow-up to the Lake Ontario discovery case, where acoustic and magnetic evidence was combined with direct visual confirmation of wooden structural elements [23].

Optical data were used not only as illustrations but as evidence. Images of exposed timbers, frames, planking, or other diagnostic structures can confirm whether an acoustic anomaly represents natural bottom roughness, modern debris, or cultural material. Optical imaging also supports digital documentation and public interpretation. In low-visibility or complex environments, optical data may be sparse or difficult to scale, but when combined with acoustic and magnetic layers, it provides decisive interpretive value.

2.5. Data Processing and Products

The field campaign produced multiple classes of data: tracklines, coverage polygons, side-scan sonar mosaics, bathymetric point clouds and grids, sounding density products, magnetic total-field and residual-anomaly grids, processed CSV files, target reports, georeferenced imagery, and project archives. The final report organized deliverables into folders for MBES, side-scan sonar, magnetometer products, track plots, and a full archive of raw and processed data [21]. This structure is important because heritage survey products must be traceable from interpretation back to source data and processing workflow.

Side-scan sonar data were processed into mosaics for both field interpretation and post-cruise analysis. Field processing was especially important for adaptive mission operations. In the *Gallinipper* sequence, a side-scan mosaic created after the first AUV mission enabled a refined second mission oriented to the wreck. In other cases, field review of Raymarine or Humminbird side-scan imagery from support vessels helped determine whether reported target positions were reliable enough for AUV deployment.

Multibeam data supported three-dimensional interpretation of lakebed morphology and wreck relief. In the broader project, MBES products included point clouds, average grids, sounding density, and coverage polygons. The New York project area produced 10.88 km^2 of MBES coverage, while side-scan sonar and magnetometer coverage supplied complementary target and anomaly information. Magnetometry data were processed into total-field, residual-anomaly, and analytic-signal grids, along with interpreted anomaly points.

2.6. Operational Constraints and Lessons Learned

The campaign produced several operational lessons. First, weather and lake state control platform choice. Offshore conditions sometimes prevented open-lake AUV or ASV work, but nearshore, riverine, or protected-water tasks could still proceed. The ability to shift from offshore AUV survey to nearshore ASV or R/V *Dogfish* work preserved field productivity and produced additional datasets. This supports the value of bringing a portfolio of platforms rather than a single "best" system.

Second, small-platform autonomy requires careful payload integration. The EchoBoat 240 test showed that adding a towed magnetometer and operating in deteriorating conditions affected vehicle performance and contributed to water ingress and subsequent thruster failure. This is a common lesson in field robotics: payload, power, drag, stability, sealing, and recovery are coupled. Archeological missions often require sensor combinations, but each added sensor changes operational risk.

Third, accurate target positions cannot be assumed. The Lake Ontario operations showed that reported positions from charts, Google Earth, phone applications, or memory may not be suitable for direct AUV mission planning. Exporting waypoints from chart plotters or validated GPS (global position system) systems into standard formats such as GPX (GPS Exchange Format), then importing them into GIS (geographic information system) and mission-planning software, should be treated as a core best practice.

Fourth, public and recreational traffic must be considered. AUV operations near popular boating areas require clear surface support, monitoring, and communication. Field notes from Lake Ontario record passing watercraft and jet skis near operational areas. For future campaigns in similar settings, surface markers, notices, outreach, local coordination, and safety buffers should be integrated into mission planning.

Finally, local knowledge is indispensable but must be translated into geospatially precise data. Local researchers, divers, and avocational historians supplied valuable target information, but the campaign demonstrated that knowledge must be converted into reproducible geospatial records to support autonomous survey. The best outcomes occurred when local knowledge, sonar reconnaissance, and robotic survey were combined.

3. Results

3.1. Survey Coverage and Data Products

The combined project produced a substantial archive of geophysical and visual products. In Wisconsin, processed geophysical products covered a merged geographic footprint of 1.76 km^2, with 1.88 km^2 of total sensor-area coverage when overlaps were counted. Sensor-specific products included 0.67 km^2 of magnetometer coverage and 1.21 km^2 of side-scan sonar coverage. In New York, processed products covered a merged geographic footprint of 17.96 km^2, with 18.43 km^2 of total sensor-area coverage when overlapping products were counted. Sensor-specific products included 0.53 km^2 of magnetometer coverage, 7.01 km^2 of side-scan sonar coverage, and 10.88 km^2 of MBES coverage [21]. The processed geophysical coverage for each study area, including total geographic coverage and sensor-specific contributions, is summarized in Table 2.

Table 2. Summary of processed geophysical coverage by study area. "Total area" sums overlapping sensor products; "total coverage" represents the merged geographic footprint of the survey products.

Study Area	Total Coverage (km^2)	Total Area (km^2)	MAG (km^2)	SSS (km^2)	MBES (km^2)
Wisconsin/Lake Michigan	1.76	1.88	0.67	1.21	0.00
New York/Lake Ontario	17.96	18.43	0.53	7.01	10.88

The Wisconsin operations grouped into three operational zones: nearshore Rawley Point, open-water wreck sites offshore of Two Rivers and Manitowoc, and riverine surveys in the East and West Twin Rivers. The nearshore zone included aerial magnetometer, ASV side-scan, and supplemental crewed-vessel work. The open-water zone included AUV side-scan surveys of known wrecks. The riverine zone was surveyed opportunistically by the UD team when offshore weather limited operations, exemplifying the adaptive nature of the exploration framework.

The New York operations similarly grouped into three geographic/operational zones: the St. Lawrence River near Clayton and Fishers Landing; the Sackets Harbor and Horse Island nearshore/battlefield area; and the Henderson/Stony Island/Stony Point/open-water area. The New York dataset included AUV side-scan surveys, portable ASV side-scan surveys, R/V *Dogfish* side-scan and bathymetric side-scan operations, aerial and marine magnetometer products, and C-Worker 8 MBES products [21].

The resulting archive was structured as a reproducible geospatial dataset with track-lines, coverage polygons, processed mosaics, bathymetry grids, anomaly layers, and raw/processed data directories (Figure 5). This archival structure is a key element because it transforms field observations into reusable heritage documentation. For managers, this supports future comparison, target relocation, and survey planning. For stakeholders, it provides data suitable for method development, algorithm testing, and site interpretation.

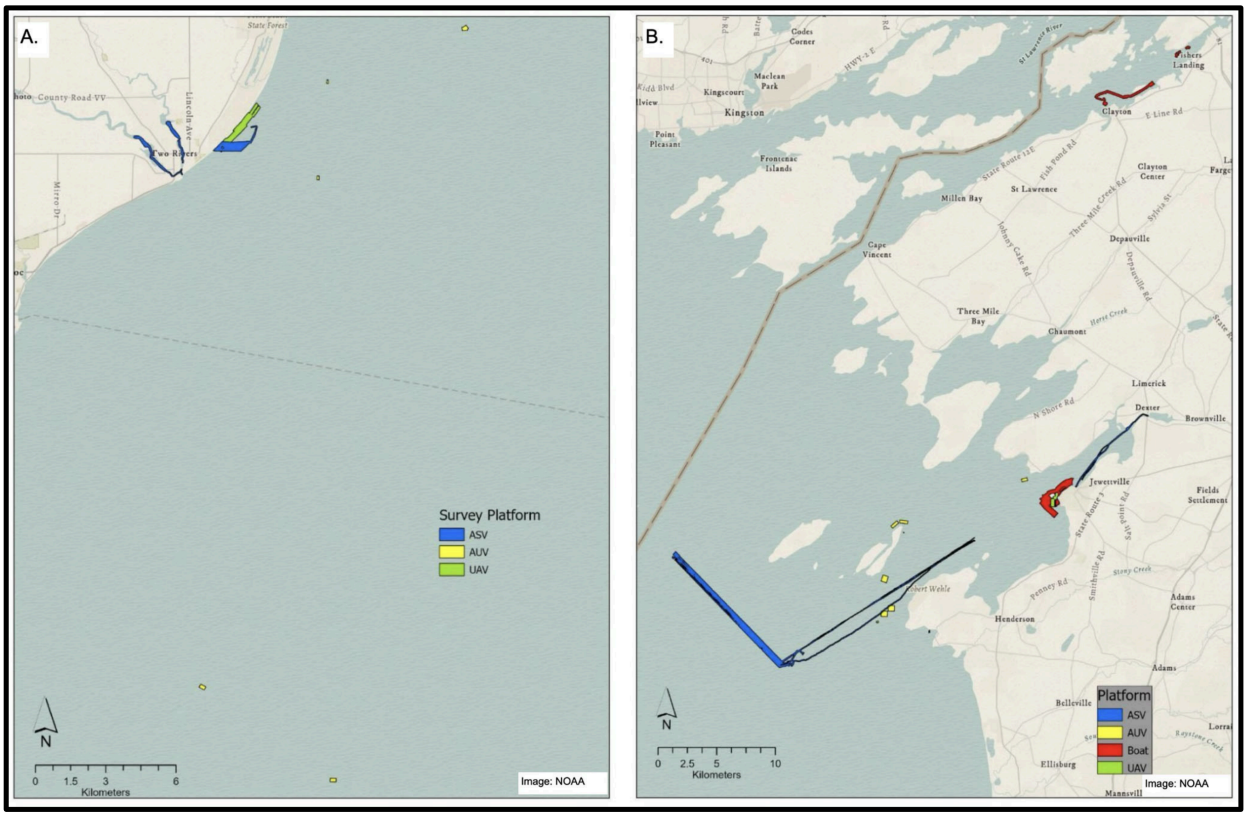


Figure 5. Survey coverage and data products. (**A**) Wisconsin platform coverage map showing AUV, ASV, and crewed-vessel contributions; (**B**) New York coverage map showing side-scan, magnetometer, and MBES contributions.

3.2. AUV Survey Outcomes in Lake Michigan

Lake Michigan AUV operations began early in the field campaign after project logistics shifted because the larger ASV team was delayed. This pivot allowed the University of Delaware team to use available NOAA vessel support for offshore AUV missions. On 2 August, the team conducted an operations check near *Henry Gust* and then performed

WAA missions over *Henry Gust*, *Vernon*, and *S.C. Baldwin*. Divers inspected *Henry Gust* before AUV operations, providing information about wreck relief and visibility that helped inform safe mission planning.

On 3 August, the AUV team returned offshore and conducted additional missions over Vernon, Floretta, and *Gallinipper*. The second Vernon mission represented a refined HRG survey after the first WAA pass: the team planned a tighter mission with lines parallel to the wreck. The Floretta WAA survey was aligned sufficiently well from single-beam reconnaissance that only one mission was needed. *Gallinipper* provided the clearest example of adaptive mission refinement. A first WAA mission was processed on the boat to generate a georeferenced mosaic; the follow-up HRG mission then used four lines aligned with the wreck, two on either side of the centerline, at approximately 7 m above the lakebed. This produced strong photo coverage and acoustic imagery.

These AUV results demonstrate three points. First, reported or assumed wreck locations can be sufficiently accurate for initial WAA mapping but still require acoustic confirmation before HRG survey. Second, field processing materially improves mission quality by allowing tracklines to be aligned with site orientation rather than arbitrary grid direction. Third, in this campaign, AUV imagery close to the lakebed appeared to offer data quality equal to or better than a comparable crewed-vessel side-scan survey because the sensor is decoupled from surface motion and avoids towed layback uncertainty.

The final products include AUV-based side-scan sonar images of *Vernon*, *S.C. Baldwin*, *Henry Gust*, *Gallinipper*, *Ellsworth*, and *Onondaga*, indicating that AUV products were suitable for archeological site characterization and monitoring (Figure 6). These products show wreck outlines, acoustic shadows, site orientation, and, in favorable cases, structural features such as hull remnants or machinery. Figure 6 presents examples of the *Gallinipper* and *Onondaga* sites, illustrating both the Wisconsin and New York applications, respectively.

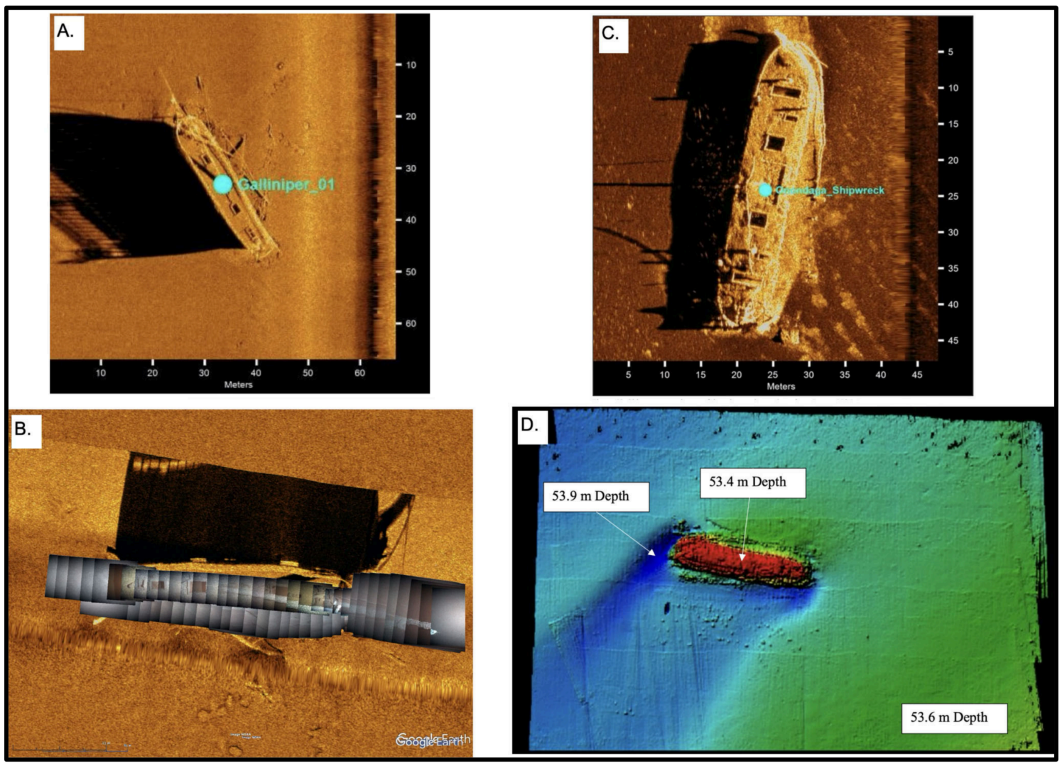


Figure 6. Examples of AUV side-scan survey results. (**A**) Gallinipper WAA mosaic; (**B**) Gallinipper HRG mission result with side-scan sonar and photo overlay; (**C**) Onondaga shipwreck AUV side-scan sonar; (**D**) AUV multibeam bathymetry of Onondaga shipwreck.

3.3. ASV and Nearshore Survey Outcomes

Portable ASV operations were most valuable where conventional vessels were limited by shallow water, access, weather, or mission scale. In Wisconsin, the EchoBoat 160 completed a three-hour nearshore survey along lines approximately 0.5 km long, spaced about 30 m apart, from roughly the 2 m to 5 m depth contours. The total travel distance approached 10 km, with the final lines approximately 1 km from shore. A subsequent mission extended coverage shoreward and lakeward, although battery and recovery issues limited data from the second day.

Nearshore operations also demonstrated the value of switching platforms when offshore conditions deteriorated (Figure 7). On August 6, offshore conditions prevented lake work, so the University of Delaware team used R/V *Dogfish*, EMILY ASV, a Chasing M2 ROV, and other assets to explore the East and West Twin Rivers. This weather-driven shift produced useful riverine side-scan coverage rather than losing the day entirely and demonstrated that the Two Rivers riverine survey was conducted opportunistically due to inclement offshore weather.

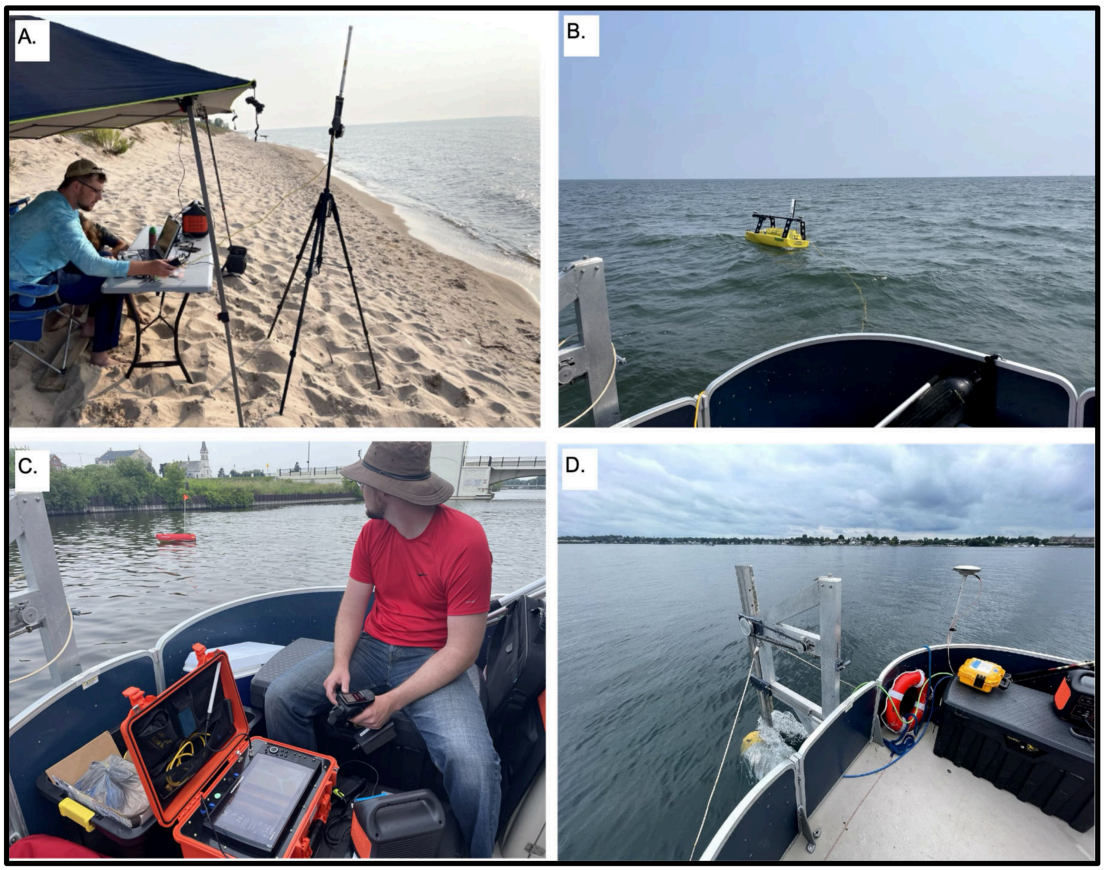


Figure 7. ASV and nearshore survey operations. (**A**) EchoBoat 160 beach control; (**B**) EchoBoat 240 survey with magnetometer; (**C**) EMILY ASV survey in river setting; (**D**) R/V Dogfish configured with EdgeTech 6205 bathymetric side-scan sonar.

The EchoBoat 240 test illustrates the sensitivity of small ASVs to payload integration and field conditions. With a Teledyne T50 MBES, POS-MV, and an added SeaSPY magnetometer tow, the system was tested in approximately 6 m of water. Initial lines suggested real-time coverage in HYPACK, but deteriorating conditions, payload drag, and thrust issues led to recovery. Water ingress damaged the port thruster servo motor. This result is important because it shows that adding sensors to small platforms changes hydrodynamics, power requirements, and risk. Figure 7 illustrates the adapted configuration of small autonomous and crewed platforms for nearshore operations.

In Lake Ontario, EMILY ASV operations demonstrated both utility and limitation. The jet-drive system was well suited to shallow and choppy conditions near Stony Point, but limited endurance constrained mission duration to roughly 10–15 min. On later missions, the vehicle entered an errant spinning behavior that required recovery and suspension of operations. These results support a practical conclusion: small ASVs are useful for targeted, opportunistic, and constrained surveys, but they need robust mission control, watertightness, recovery planning, and environmental envelopes appropriate to the mission for scaled operations.

3.4. Magnetic and Acoustic Target Detection

Magnetometer products contributed a complementary layer of evidence. In Wisconsin, the final magnetic data produced a residual-anomaly grid, and all residual-channel signals of 5 nT or greater were marked as anomalies. The largest magnetic anomaly in the south-eastern corner of the Wisconsin area was associated with a known shipwreck site; other anomalies required follow-up visual inspection to determine whether they represented cultural material or other sources.

In New York, the Horse Island area produced a residual-anomaly grid with 57 marked anomalies. The final report emphasizes that these anomalies were of unknown origin and did not coincide with known historic site locations [21]. That result is important for both archeology and management: magnetometry is sensitive but not self-interpreting. It can locate ferrous concentrations and guide follow-up work, but anomaly origin must be evaluated through acoustic correlation, visual inspection, historical context, and modern-infrastructure awareness.

The 2022 Lake Ontario discovery case provides a more integrated example. The UDaily report [23] describes a composite map in which a long linear magnetic feature oriented northwest-southeast was centered over the newly confirmed shipwreck, while a separate, intense northeast-southwest anomaly coincided with a known water pipeline. This juxtaposition is illustrative of sensor complementarity: magnetic anomalies are not automatically shipwrecks, but when anomaly geometry, acoustic structure, bathymetric form, and optical evidence converge, interpretive confidence increases substantially (Figure 8).

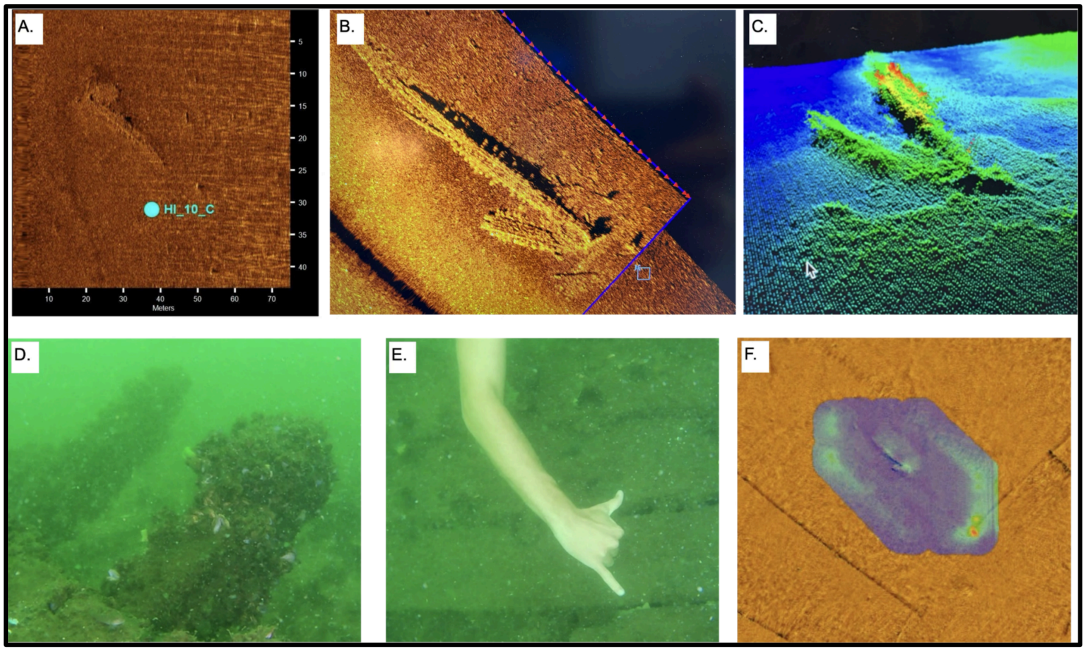


Figure 8. Lake Ontario discovery case. (**A**) 2021 side-scan target that initiated the case; (**B**) 2022 high-frequency side-scan mosaic; (**C**) multibeam point cloud rendering; (**D**) ROV image of exposed wooden timbers; (**E**) diver hand-scale image; (**F**) magnetic and side-scan sonar overlay showing estimated wreck extent.

3.5. Lake Ontario Shipwreck Discovery and Confirmation Case Study

The Lake Ontario discovery and confirmation sequence provides the clearest test of the workflow. In August 2021, the University of Delaware team identified an interesting underwater target during survey operations near Sackets Harbor. The target appeared man-made and possibly wooden on side-scan sonar, but it was found during the final half-hour of the last day in the harbor, leaving no opportunity for detailed mapping at that time. The team logged the position and preserved it as a target for future investigation.

In summer 2022, the team returned to Sackets Harbor during a University of Delaware AUV boot camp involving graduate students and United States Naval Academy midshipmen. The target was reacquired and surveyed with a combination of Norbit multibeam, EdgeTech side-scan sonar, and magnetometer measurements from an Iver3 AUV. ROV photography and video were then used to visually inspect the site. The combined datasets confirmed that the remains were those of a wooden ship. The sensitive information was turned over to the New York State Historic Preservation Office to support preservation and further identification [23].

The ROV inspection showed wooden structure, with the observed remains estimated at approximately 15 m in length. The UDaily news article account describes exposed lower timbers, possible ribs, planks across the wreckage floor, high-frequency side-scan imagery, colorized multibeam points showing wreck shape, and a diver used for scale (Figure 8). This convergence of evidence transformed a suggestive 2021 acoustic anomaly into a documented cultural resource.

The discovery case also highlights the social and educational dimensions of autonomous heritage surveys. The follow-up took place during a field training exercise, and the data subsequently became useful for laboratory training and educational purposes (Figure 8). This case demonstrates that well-designed survey campaigns can produce both management-relevant discoveries and reusable datasets for workforce development in marine robotics, hydrography, and maritime archeology.

4. Discussion

4.1. Survey Efficiency and the Benefit of Hierarchical Design

The principal methodological finding is that hierarchical survey improves efficiency in heritage contexts where target positions are uncertain and site-resolution needs vary. WAA missions allow teams to test reported locations, identify target orientation, and evaluate bottom conditions without committing excessive time to high-resolution mapping. HRG missions can then be reserved for confirmed or high-priority targets. This is consistent with broader geophysical practice in maritime archeology, where survey design must balance detection probability, resolution, coverage, and interpretation [8–10,24].

The UD campaign illustrated that this hierarchy must be operationally flexible. Reported target positions in Lake Ontario were sometimes inaccurate by hundreds of meters or more. During August 15 operations, the Napoleon site was approximately 140 m from the provided location, while *Ellsworth* was found almost a mile from the provided location through the opportunistic use of Raymarine side-scan reconnaissance before a subsequent AUV mission was planned. This pattern reinforces the need for an adaptive search workflow even when local knowledge and prior reports are available.

The hierarchical approach also reduces risk. Sending an AUV on a low-altitude HRG mission over a poorly constrained target can be inefficient and unsafe, especially if topographic relief, fishing gear, boulders, or modern infrastructure may be present. A WAA mission or support-vessel reconnaissance can establish the presence and orientation of the target before the vehicle is tasked at closer range. By design and execution, the WAA phase is not just “lower resolution” but is critically a risk-reduction and mission-design phase.

4.2. Sensor Complementarity and Interpretive Confidence

No single sensor in the campaign was sufficient for target interpretation. Side-scan sonar was the primary tool for acoustic detection and structural visualization. It could reveal wreck outlines, acoustic shadows, frames, machinery, debris, and bottom texture. However, side-scan interpretation depends on target orientation, range, grazing angle, bottom roughness, and processing choices [25,26]. It may also produce ambiguous results where natural features or modern debris mimic cultural forms.

Multibeam bathymetry provided three-dimensional relief, helping to distinguish flat texture from raised structure and to map local lakebed morphology. Prior work has shown that MBES can identify shipwreck sites and support archeological assessment [10]. In this campaign, MBES was valuable in the Lake Ontario case study and broader New York operations, where bathymetric grids and point clouds added morphology context. Repeat MBES in future surveys could also support monitoring of scour, burial, or disturbance, as demonstrated in other shipwreck contexts [11,27].

Magnetometry contributed a different type of evidence: ferrous mass and magnetic contrast. It was particularly relevant for buried or low-relief materials, but it also required caution because pipelines, geology, and other modern debris can also produce strong signals. The discovery-case contrast between a wreck-aligned anomaly and a separate pipeline anomaly illustrates this point (Figure 8). Magnetometry increased confidence only when interpreted together with acoustic, bathymetric, visual, and contextual evidence.

Optical imagery supplied the most direct confirmation of material and construction. ROV and diver observations of exposed timbers, ribs, planks, or machinery could resolve ambiguities left by geophysics. However, optical inspection is limited by visibility, depth, safety, time, and site access. The strongest interpretations therefore emerged from convergence: a coherent acoustic target, three-dimensional relief, an appropriately aligned magnetic signal, and visual confirmation of wooden structure.

4.3. Adaptive Mission Planning

Adaptive mission planning was more than an operational convenience; it was an archeological method. It allowed the team to transform provisional evidence into improved evidence while still in the field. The *Gallinipper* sequence is the clearest example: a first AUV survey produced a mosaic, the mosaic revealed orientation, and the second mission was aligned to the wreck to obtain better sonar and optical coverage. The *Gallinipper* represents an ideal validation site for the proposed multi-platform survey framework because it is a historically significant and exceptionally well-preserved archeological resource. Originally built in 1833 as the *Nancy Dousman* to support Great Lakes fur trade operations, the wooden schooner was later rebuilt, renamed *Gallinipper*, and employed in the Lake Michigan lumber trade. *Gallinipper* was lost in a sudden squall in 1851 between Sheboygan and Manitowoc, Wisconsin. In 1994, the wreck was found upright and largely intact in approximately 64 m of water and is recognized as Wisconsin's oldest known shipwreck and is listed on the National Register of Historic Places. This well-documented historical record provided valuable archival context for mission planning while offering an archeological target against which to evaluate the integrated survey methodology. In Lake Ontario, the challenge of inaccurate target positions from the archival phase required a similar application of adaptive mission planning, with support-vessel sonar used to reacquire targets before committing AUV dives.

This approach is particularly important for cultural heritage because archeological targets are rarely distributed like uniform environmental transects. Wrecks are discrete, oriented, often partially buried, and historically contingent. Survey lines that are ideal for covering an area may not be ideal for imaging a hull, and the optimal geometry may not be

known until after the first pass. Adaptive planning recognizes that field interpretation and mission design are coupled.

The approach also creates a path toward future automation. At present, human operators reviewed mosaics, interpreted targets, and replanned missions. In future systems, machine learning could assist by identifying candidate targets, estimating orientation, recommending line spacing, and prioritizing revisits. However, this campaign suggests that automation should augment rather than replace archeological judgment. Historical context, local knowledge, site sensitivity, and regulatory considerations remain essential.

4.4. Implications for Maritime Heritage Exploration and Workforce Development

The University of Delaware workflow demonstrates that autonomous systems are most powerful in heritage exploration when they are integrated into a survey ecology: platforms, sensors, operators, vessels, local knowledge, historical research, and data processing all contribute to interpretation. The contribution is not merely that an AUV or ASV can collect sonar data, but rather a practical framework linking together detection, confirmation, and digital documentation.

This framework responds to a central need in maritime heritage management. Many submerged cultural resources are known only through archival accounts, local reports, approximate coordinates, or low-resolution acoustic targets. Managers need methods that can efficiently sort these possibilities into categories: no target detected, natural or modern object, possible cultural material requiring follow-up, documented wreck site, or high-priority resource requiring protection. The WAA-HRG-ground-truthing sequence supports this triage.

The approach is critically relevant to sanctuary and proposed-sanctuary settings. National marine sanctuaries must manage cultural resources across broad geographies, often with limited staff and vessel time. Autonomous and semi-autonomous survey methods can extend coverage, support repeat monitoring, and produce public-facing digital products. However, they also require data management capacity, field expertise, and protocols for handling sensitive archeological locations. The project data-sharing plan recognized that some cultural-resource coordinates and imagery require protection under applicable policy and law [21].

The campaign and the 2022 follow-up also demonstrate the educational value of field robotics applied to heritage questions. The Sackets Harbor boot camp gave students and midshipmen hands-on experience with AUVs, multibeam, side-scan sonar, magnetometry, and ROVs in a real archeological landscape. The discovery of a wooden shipwreck was a tangible and impactful outcome of the training component built into the campaign.

The future of underwater cultural heritage depends on a growing workforce who can work across archeology, oceanography, robotics, hydrography, conservation, data science, and public communication. Autonomous systems do not reduce the need for human expertise; they merely redistribute the expertise. Field teams must understand vehicle behavior, sensor physics, archeological interpretation, regulatory requirements, and ethical stewardship. Therefore, structured training campaigns like this, which produce useful data while developing personnel, have added value.

Collaborative practice also matters. The focus here is on the University of Delaware contributions, but the campaign depended on NOAA and state historic preservation partners, University of Miami for UAV work, and commercial support from Marine Magnetics and Ocean Infinity operators. This manuscript acknowledges the broader ecosystem while focusing on the UD team operations and analysis efforts related to the exploration methods.

4.5. Digital Preservation

Digital preservation should not be construed as suggesting that a digital model replaces the site. Rather, it means that high-resolution spatial and visual data become part of the preservation record. Side-scan mosaics, MBES grids, magnetic anomaly maps, ROV imagery, and photogrammetric models capture site condition, support interpretation, and enable future comparison. In the Great Lakes, where some wooden wrecks are well preserved but may be affected by invasive mussels, sediment dynamics, diver visitation, or changing exposure, baseline documentation is essential.

The project's data products are directly relevant to monitoring. Side-scan and MBES products can be repeated to assess changes in relief, scour, burial, or damage. Time-lapse bathymetric survey has been shown elsewhere to quantify morphological change at shipwreck and artificial reef sites [11,27]. In this campaign, the 2021 and 2022 sequence already demonstrates the value of target relocation and repeat investigation: a target noted in 2021 was revisited, mapped, and confirmed in 2022.

Digital products also support public access. Many shipwreck sites are inaccessible to non-divers, located in sensitive areas, or unsuitable for broad visitation. Carefully curated imagery, 3D visualizations, story maps, and interpretive figures can make these sites visible while limiting the release of sensitive coordinates. This aligns with recent work emphasizing photogrammetry and 3D documentation as tools for underwater cultural heritage preservation, communication, and research [19,20,28].

4.6. Great Lakes and Broader Transferability

The Great Lakes are not simply an inland substitute for the ocean. They have distinctive preservation conditions, weather patterns, legal frameworks, communities, histories, and survey challenges. Cold freshwater can preserve wooden hulls, but nearshore sand mobility can bury sites rapidly; invasive mussels can obscure details and alter site surfaces; and shallow lake conditions can change quickly with wind. These factors make the Great Lakes a particularly valuable laboratory for methods that must handle both exceptional preservation and difficult visibility or accessibility.

At the same time, the workflow is transferable. The principles of hierarchical survey, sensor complementarity, adaptive mission planning, and digital archiving apply to marine shipwrecks, submerged paleo landscapes, artificial reefs, aircraft crash sites, and other underwater heritage contexts [29]. Saltwater applications may require different assumptions about corrosion, biofouling, water-column variability, and acoustic scattering, but the logic remains: use broad survey to find, close survey to interpret, visual inspection to confirm, and standardized archives to preserve and revisit.

Transferability also depends on cost and logistics. One of the original project goals was to develop multi-vehicle autonomous methods for unexplored nearshore areas using systems that reduce operational footprint. The campaign showed that this is feasible but not automatic. Small vehicles reduce vessel requirements, yet they require skilled operators, batteries, spare parts, weather windows, processing capacity, and recovery plans. Future work should quantify cost-per-area, resolution-per-hour, and probability-of-detection metrics across platform combinations.

4.7. Toward Semi-Automated Heritage Exploration

The implemented and suggested workflow (Figure 9) points toward a future in which autonomous systems assist not only with data collection but with interpretation and decision support. Potential developments include real-time sonar mosaicking, onboard anomaly detection, automated target classification, adaptive replanning based on target orientation, and integrated dashboards that combine acoustic, magnetic, and optical evidence. Ma-

chine learning could help screen large datasets for candidate cultural targets, while human experts would evaluate historical plausibility, site sensitivity, and preservation implications.

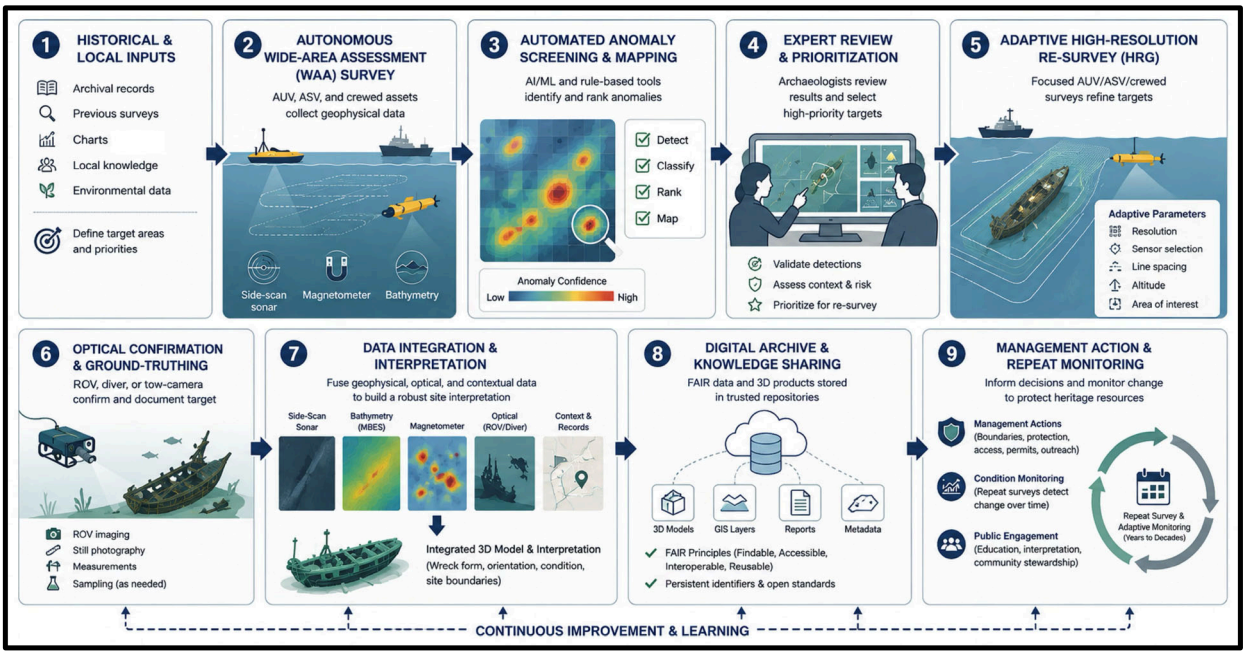


Figure 9. Workflow for multi-platform, multi-sensor autonomous exploration of underwater maritime heritage.

Heritage data differ fundamentally from generic object-detection datasets. False positives may waste field time, while false negatives may leave resources undocumented. Training datasets must represent site diversity, sensor variability, natural bottom complexity, and modern debris. Algorithms must also respect cultural-resource sensitivity; automated discovery pipelines should include protocols for data security and consultation before public release of precise locations.

The Great Lakes campaign provides a useful foundation for this future because it generated diverse labeled and semi-labeled datasets: known wrecks, suspected targets, negative searches, magnetic anomalies, side-scan mosaics, bathymetry, ROV imagery, and field notes. Such datasets can support algorithm testing, but they are also valuable because they preserve the human reasoning that connected survey evidence to archeological interpretation.

5. Conclusions

This paper has presented a University of Delaware-centered framework for autonomous exploration and digital documentation of submerged cultural heritage in the Great Lakes. Developed within the broader 2021 NOAA OER (Office of Ocean Exploration and Research) "Maritime Heritage in America's Inland Seas" campaign and extended through follow-up work in Lake Ontario, the workflow integrates AUVs, portable ASVs, crewed support vessels, acoustic mapping, magnetometry, optical inspection, field processing, and adaptive mission planning.

The principal conclusion is that effective robotic heritage survey is hierarchical and iterative. Wide-area assessment identifies or reacquires targets; high-resolution geophysical survey characterizes them; field processing informs mission refinement; and optical or diver/ROV inspection confirms material and condition. This sequence produced useful data across Wisconsin and New York survey areas, including 1.76 km^2 of merged geophysi-

cal coverage in Wisconsin and 17.96 km^2 in New York, as well as side-scan mosaics, MBES products, magnetic anomaly grids, target inventories, and geospatial archives [21].

A second conclusion is that sensor complementarity is essential. Side-scan sonar provides structural imagery, multibeam bathymetry provides morphology, magnetometry identifies ferrous anomalies, and optical imaging confirms material evidence. No single sensor is sufficient for interpretation in all contexts. Confidence emerges from convergence among independent evidence streams, particularly when combined with historical context and local knowledge.

A third conclusion is that field autonomy remains human-centered. Skilled operators, archeologists, vessel crews, students, local experts, and data processors shaped every stage of the workflow. Autonomous systems expanded what could be surveyed, but human judgment determined how to adapt missions, interpret ambiguity, manage risk, and communicate results. The 2022 confirmation of a previously undocumented wooden shipwreck in Lake Ontario illustrates this point: the discovery depended on an initial acoustic observation, careful retention of target information, a return survey, multiple sensors, and ROV confirmation, and it led to formal reporting to the New York State Historic Preservation Office [23].

The broader contribution of the work is a scalable model for exploration-to-preservation practice. As underwater cultural heritage faces increasing environmental and anthropogenic pressures, managers and researchers need methods that can locate unknown sites, document known sites, create baselines for monitoring, and translate inaccessible underwater places into digital records. The Great Lakes campaign shows that multi-platform autonomous surveys can support that work today, while also providing datasets and training models for future semi-automated heritage exploration.

Fundamentally, preservation begins before conservation treatment, legal designation, or public interpretation. It begins with the act of finding and recording. By connecting autonomous exploration to archeological documentation and digital stewardship, the University of Delaware framework helps move submerged cultural heritage from hidden resources toward documented, interpreted, and effectively managed places.

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Data Availability Statement: Project data products are archived through NOAA and UD associated project repositories as described in the final project report. Sensitive archeological location information may be withheld or restricted in accordance with applicable cultural resource protection policies and law. University of Delaware-derived data products used for this manuscript are available upon request and have been archived also in NOAA repositories through the grant program.

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