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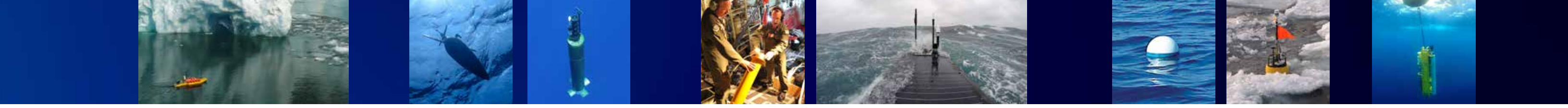
Project Recover

Extending the Applications of Unmanned Platforms and Autonomy to Support Underwater MIA Searches

By Eric J. Terrill, Mark A. Moline, Patrick J. Scannon, Eric Gallimore, Travis Schramek, Andy Nager, Robert Hess, Megan Cimino, Patrick L. Colin, Andrew Pietruszka, and Mark R. Anderson

ABSTRACT. An estimated 70,000 US servicemen remain missing from World War II, with approximately two-thirds of those losses from the Pacific Theater. Many of the missing were lost in the maritime environment. Historically, attempts to locate remains in this environment were deemed too difficult, as water-based searches can be labor intensive, logistically cumbersome, and technically difficult to execute. Ironically, despite these challenges, underwater sites are often better preserved than terrestrial sites, as they are less subject to human disturbance and negative environmental conditions. Technological advances in unmanned platforms, autonomy, sensors, underwater navigation and communications, forensic oceanography, search methodologies, and data processing are now enabling the discovery of crash sites associated with losses and stimulating new research that combines oceanography, unmanned systems, historical research, and forensic archaeological methods. Project Recover began as a two-year program funded by the US Office of Naval Research, designed to serve as a testbed for unmanned technologies and public outreach. Now, through public and private sponsorship, it has grown into providing a global survey capability.



INTRODUCTION

We report on an initiative to develop and apply ocean technology for conducting efficient, effective, and high-fidelity sensing of the seabed for purposes of finding and identifying missing aircraft, especially those that relate to the estimated 70,000 US servicemen who remain classified as missing in action (MIA) from World War II; approximately two-thirds of those losses occurred in the Pacific Theater (http://www.dpaa.mil/Our-Missing/Past-Conflicts).

After being introduced to one another in the Republic of Palau, a collaboration was established in 2013 by several of the lead authors to explore how multidisciplinary scientific methods, comprehensive intelligence gathering, and maritime-based search methodologies could be applied to the problem of finding MIA sites. A proposal was developed and submitted to the Office of Naval Research knowing that exercising and developing technologies for finding and characterizing historic sites would resonate with ongoing interests to accelerate the development of undersea technologies. Furthermore, the project offered a unique opportunity to renew public interest in wartime history, technology, and the tropical western Pacific region.

Project Recover is multidisciplinary—a confluence point of historical research, technology development, and data analysis (http://www.projectrecover.org). While the sites we seek to find have tremendous historic importance, it is important to recognize that Project Recover does not practice archaeology (a subfield of anthropology—the study of past peoples through material remains left behind). Instead, we apply archaeological, analytic, and forensic techniques, along with emerging undersea technologies, to the search and documentation of crash sites associated with MIAs for the purpose of casualty resolution. Documentation of these sites is turned over to the US Department of Defense's Defense POW/MIA Accounting Agency (DPAA), a close collaborator, whose mission is to account for missing US personnel to their families and the nation. In 2015, the National Defense Authorization Act authorized the US government to enter into private-public partnerships for "purposes of facilitating the activities" of the DPAA, and Memoranda of Understanding (MOUs) are now in place with several of the authors' organizations. Beyond an increase in POW/MIA recoveries, an anticipated future byproduct of these efforts is public messaging to stimulate the creation of education and training venues for the next-generation technical workforce in the fields of ocean technology.

Project Recover makes extensive use of unmanned underwater vehicles (UUVs). They operate with modern variants of many of the technologies that rapidly evolved through the work of the wartime applied research community, including inertial navigation, sonar, and computing. Fortunately, today's UUVs exhibit a much higher degree of reliability relative to the torpedoes of WWII in which "the only reliable feature of the torpedo was its unreliability" (Roscoe, 1949).

Until recently, research conducted using UUVs was largely relegated to tackling the practical engineering challenges associated with hardening and improving the basic vehicle platform functions, including navigation, propulsion, power storage, and communications. While these technical challenges stabilized and vehicle reliability increased, an era of sensor development began to emerge that capitalizes on the mobility of the platform to allow for measurements in the ocean environment at the right place and time. This era continues, with the development of smaller and smarter sensors that enable myriad new ocean research disciplines that couple autonomous ocean observation with enhanced sensing.

HISTORICAL RESEARCH AND SEARCH PLANNING

In September of 1944, USS *Intrepid* launched a number of air strikes against Japanese-held Palau as part of the US push to Mindanao and to soften forces in preparation for Operation Stalemate II (Battle of Peleliu). One particular mission consisted of eight TBM-1C Avenger Torpedo bomber aircraft targeting what was believed to be a power plant and nearby ammunition and fuel storage facilities; one aircraft had mechanical difficulties and returned to the carrier. Then, while six planes circled the target area at 8,000 ft (2,500 m), the flight leader executed a low altitude pass to identify the targets and give that information to the waiting aircraft. After targets were identified, the planes sequentially dropped their munitions.

One of the final planes in the formation approached the target in a shallow glide seaward, released its bomb at 1,000 ft (305 m) altitude and suffered extreme damage to the its tail in the resulting explosion, causing it to crash offshore. The declassified after-action report upon which this account is based indicates that low altitude passes were conducted by the remaining aircraft, and signs of hydraulic fluid and floating debris were observed offshore, but no survivors were observed.

A breakthrough clue in the search for the lost plane was uncovered in 2005 by the BentProp Project, a 501c(3) organization that had spent 20 years searching for missing aircraft on annual expeditions that included numerous land-based searches and interviews of community elders. A local chief provided information that led to the discovery of a portion of the missing plane's wing in the mangroves. The wreckage contained sufficient identifying characteristics, including the USN Aviation star and bar and antenna mounting points, to identify it as belonging to a TBM1-C. However, no other pieces were found.

The case remained opened (and dormant) for eight years until the Project Recover collaboration identified this case as having a high likelihood of success for a water survey because the team had enough data to bound the search area, a critical step before initiating fieldwork.

In the underwater search planning phase, several data sets were collected, fused, and aggregated. First, aerial imagery was collected by the Coral Reef Research Foundation. Geopositioned topography was generated from these data using photogrammetry techniques enabled by commercial software (Autodesk Recap). This step was necessary as clouds were present in available commercial satellite imagery that also was of poor spatial quality. Second, raw bathymetric LiDAR data sets provided by the Naval Oceanographic Office were reformatted into a one-meter-high resolution grid to facilitate mission planning for the UUVs. Third, declassified historic imagery from March 1944 was found at the National Archives (College Park, Maryland) that suggested the locations of a present-day power plant and pier are consistent with infrastructure locations that existed in the 1940s.

The imagery was "rubbersheeted" (an alignment technique) and geopositioned to geographic control points so that historic infrastructure could be viewed alongside the modern-day aerial imagery and LiDAR-derived bathymetric data (Figure 1). Key to identifying geographic control points is the use of shallow water reef features as these bathymetric features are fixed, while the land features and mangrove shoreline are soft and subject to significant change over the past 70 years.

Fusion of these data enabled estimation of the trajectory of the missing aircraft based upon probable bomb drop sites (a temporary building near pier) and the location of the wing that was found in 2005. The search region was constrained further using witness accounts: the missing plane's wingman stated the Avenger crashed into the water in an area near the found piece of wreckage (last known point), and interviews with a Palauan elder revealed that he saw the crash occur south of his known vantage point. While the dive angle of the aircraft was not known, the location of the intended target and the found wing provided data to estimate an offshore trajectory angle, with the last known point as the critical piece of information on which to base a search.

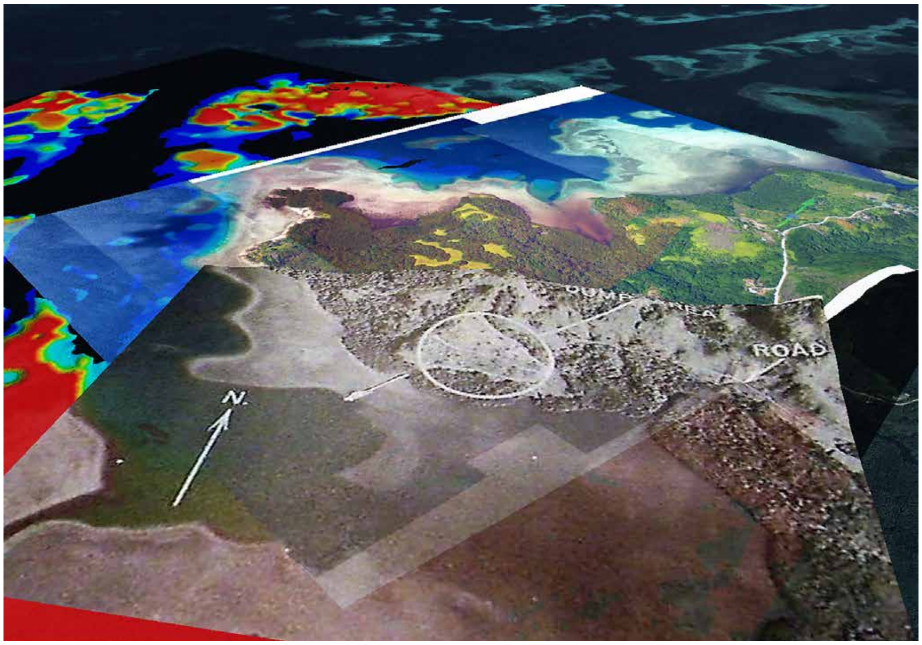


FIGURE 1. Fusion of declassified historical black and white photo reconnaissance imagery from Palau, March 1944, showing the intended target of a missing TBM1-C Avenger torpedo bomber (labeled "dump area"), modern aerial imagery, and LiDAR bathymetry gridded to 1 m resolution using raw data provided by the Naval Oceanographic Office. The fusion of geodata was used to identify the search region for the unmanned underwater vehicle (UUV), potential navigation hazards including reef edges and submerged reefs, and the probable trajectory of the damaged aircraft as it flew offshore.

On March 24, 2014, approximately 70 years after the air strike, data from a UUV equipped with side-scan sonar led to the discovery of this missing airplane.

PLANNING OPTIMIZED SEARCHES WITH BAYESIAN TECHNIQUES

Search strategies developed from Bayesian probability theory are one means to aggregate information from disparate data sources. These methods have been used for planning and informing a number of highly visible underwater searches, including the missing Air France Flight 447 (Stone et al., 2014) and Malaysia Airlines Flight 370 (Davey et al., 2016).

Bayesian search methods usually consist of four basic steps: (1) generating a prior probability distribution for the location of the target or object, (2) applying search effort with appropriate sensors, (3) computing a posterior probability distribution, and (4) planning for the next search phase. The prior probability distribution is meant to account for information that is known before the search begins. This information can be found in many forms, such as after-action reports, mission plans, visual sightings, or surveillance sensor recordings. This information is typically gathered from as many independent sources as possible, analyzed, and used to estimate the prior probability distribution for the target's location.

The gathered prior information may describe a series of events that occur over time. A numerical simulation may then be required to connect the events such that a complete scenario is constructed. The simulation can also be used as a tool to study the effect of uncertainty in the gathered evidence and establish the prior probability distribution for the final target location. In some cases, the number of possible scenarios that appear to fit the prior information can be large, and it might not be obvious which scenario is correct. In such a case, it becomes necessary to mathematically combine multiple prior distributions. The search team may decide that one scenario is "more likely" than the others and then the prior distribution from this scenario is weighted higher in the composite.

Physics-based models of the search sensors are used to account for effort that has been applied to the search. This process involves constructing a likelihood function that represents the sensor's effectiveness. Mathematically, the likelihood function quantifies the relationship between the known sensor response and the unknown target location. In addition to visual search, electronic sensors, such as imaging, or acoustic sensors may be used in the search.

The posterior probability distribution is obtained by combining the sensor likelihood function with the prior probability distribution. The resulting posterior distribution provides a means to monitor progress of the search. It can be used to access the effectiveness of the search and to predict the cost of continuing the effort. The posterior probability distribution is used to plan for the next phase of a dedicated search effort. Autonomous vehicles are excellent search platforms because they can be directed to very precise locations, for example, to search a specified area or to accurately position a deployable sensor.

A Bayesian search strategy was adopted for a still-open case in which a B-24 went missing in August 1944. Exhaustive research uncovered a multitude of historic data sources, including mission planning documents, after-action reports, aircrew interviews, and photographic images. The lost plane was flying in a Javelin Down Bomber formation at 13,500 ft (4,100 m) altitude and was observed to be on fire after dropping munitions on Koror (Palau's capital). The B-24 stayed with the formation before dropping in altitude and turning to avoid the other planes. Some crew members were observed to exit the burning airplane and land on the water, only to be picked up by Japanese enemy forces at some point later.

The bomber group provided multiple eye-witness accounts, many of which are in conflict with each other as to the cause of the damage (anti-aircraft fire and/or Japanese fighter aircraft), timing of the events, location of plane breaking from formation, observations of burning wreckage on the water, and locations and timing of where the crew members were picked up. The latter information has been used for confirming a suspected last known point for the aircraft. The time window from airmen exiting the airplane to being picked up by enemy forces is well known from Japanese logs found during post-war trials.

A reverse trajectory for the downed airmen was computed using both climatological winds and tidal currents estimated for the fateful day in 1944 using modern tidal analysis techniques (T_Tide) applied to modern data sets of weather and tides (as yet unpublished data from the Flow Encountering Abrupt Topography Research Program) and knowledge of the fall rate of a standard issue parachute (Figure 2a).

To frame our Bayesian search strategy for this aircraft, different scenarios were identified from the disparate data sources and weighted independently by a team of researchers to result in a composite probability for the location of the missing plane.

Scenario A (Weight = 40%)

- The airplane was hit after the breakaway turn, on the course heading back to Wakde Airfield (Papua New Guinea).

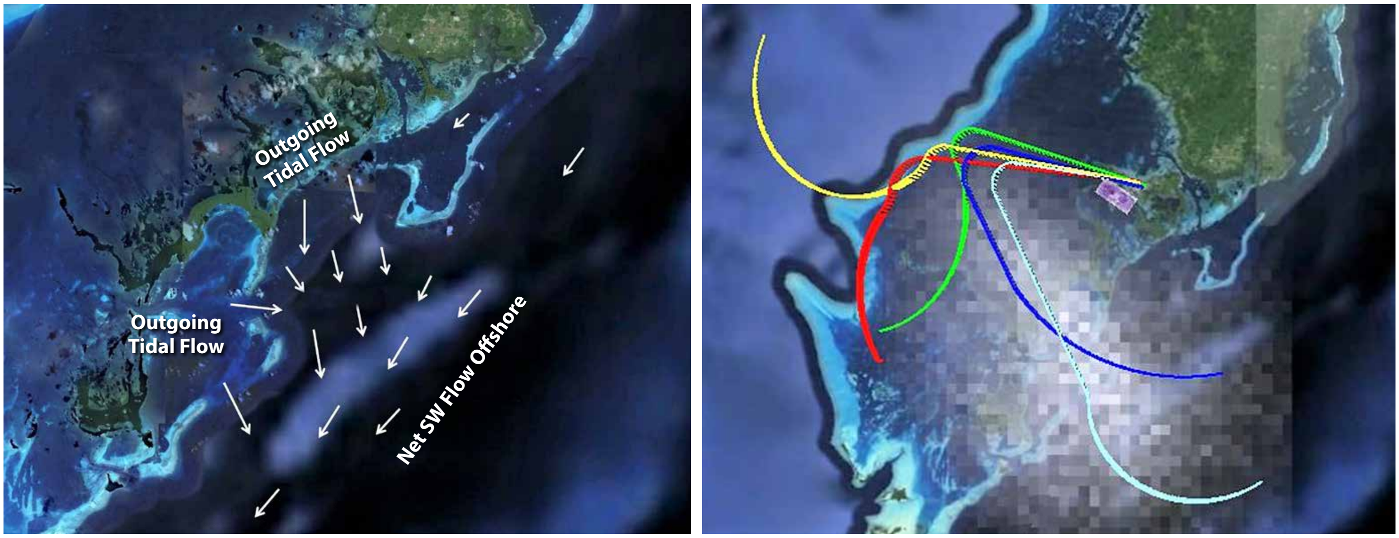


FIGURE 2. (left) Tidal analysis of the surface currents used to establish the transport of a crew member after parachuting from his WWII B-24 aircraft and being picked up by enemy forces some distance/time later. The recovery spot was well documented but the bailout location was uncertain. (right) Flight paths of scenarios A–E (yellow, red, green, blue, cyan, respectively) and the composite probability map of the resting location of the aircraft after numerous random samples are generated from a simulation of the aircraft's trajectory.

- When the #3 engine (inboard starboard) engine failed, the aircraft veered to the right of its current heading.
- The aircraft remained intact (but possibly unpiloted) until it hit the water or ground.

Scenario B (Weight = 29%)

- The airplane was hit after the breakaway turn, on the course heading back to Wakde Airfield.
- When the #3 engine (inboard starboard) engine failed, the aircraft veered to the right of its current heading.
- The onboard fires and damage were severe enough that the aircraft broke apart in the air.

Scenario C (Weight = 10%)

- The airplane was hit and damaged during the breakaway turn.
- When the #3 engine (inboard starboard) engine failed, the aircraft veered to the right of its current heading.
- The aircraft remained intact (but possibly unpiloted) until it hit the water or ground.

Scenario D (Weight = 7%)

- The airplane was hit after the breakaway turn, on the course heading back to Wakde Airfield.
- Once hit, the aircraft maintained a straight, wings-level flight path (no turns) until it hit the water or ground.
- The aircraft remained intact (but possibly unpiloted) until it hit the water or ground.

Scenario E (Weight = 14%)

- The airplane was hit and damaged during the breakaway turn.
- When the #3 engine (inboard starboard) engine failed, the aircraft veered to the right of its current heading.
- The onboard fires and damage were severe enough that the aircraft broke apart in the air.

These scenarios are coupled with an engineering model of the trajectory of the aircraft using the appropriate engineering parameters for a B-24 aircraft (e.g., turn rate, glide angles, bank angles, elevation, speed) to develop a composite probability model for the crash location (Figure 2b).

SEARCH APPROACH

The process that has evolved in our research efforts for finding underwater wreckage has several parallels with the "find, fix, finish, exploit, analyze, disseminate" (F3EAD) concept used in defense, security, and intelligence communities. In this concept, current operations provide data that are analyzed and fed forward to guide future operations. In our case, wide-area searches are conducted in regions thought to have a high probability of containing a target crash site. This assessment is conducted during the pre-mission phase, and requires assimilation of available historical reports (e.g., Missing Aircrew Reports, deck logs), human intelligence (interviews, tips), and environmental data as described in the previous section.

Through the different phases of this process, different modalities of sensing technology and undersea platforms are considered based upon trade-offs between resolution and area coverage rate (ACR). Typically, these two parameters are inversely proportional (sensors that "see" far underwater do so with reduced resolution), so there is a trade-off in sensing performance. Table 1 summarizes how we map available undersea technologies to the different phases of a search.

The objective of a wide-area search is to find targets for further evaluation. This involves a combination of mobility platforms (UUVs, small vessels) with suitable search sensors. UUV platforms offer significant advantages over towed sensors in this phase: they can maneuver closer to targets, interrogate deep targets with higher imaging frequencies, and provide a stable platform with very small turning radii. When the coverage area is searched at the high resolution afforded by UUV-based sensors, potential targets are not missed, and the ability to confirm each target is made easier by the excellent navigational capability of these platforms.

For the "find" phase of this program, we primarily leverage propeller-driven REMUS 100 UUVs. Variants of these vehicles are used for applications throughout the scientific and military communities, and our application shares significant similarities with the mission of explosive ordnance disposal (EOD) teams responsible for clearing mines (von Alt et al., 2001). The systems we use

TABLE 1. Mapping of technologies into the "find, fix, finish" model for searching, finding, and documenting underwater wrecks.

Wide-Area Search **FIND**	Target Reacquire **FIX**	Target Identification **FINISH**
UUV REMUS 100 Variant • Dual-frequency side-scan sonar operation in lower frequencies (600–900 kHz) • Transponder navigation with GPS and Doppler velocity log (DVL) • Mow-the-lawn search pattern	**UUV REMUS 100 Variant** • Dual-frequency side-scan sonar operation in high frequency (1,200 kHz or 1,800 kHz) • Magnetometer • Multibeam • Low light imager • Targeted reacquisition	**Barracuda ROV** • DVL, ultra-short baseline (USBL), and GPS for navigation • HD camera • Blueview 900 kHz/2,250 kHz imaging sonar • Manipulator arm
Small Vessel • Multibeam sonar (200–400 khz) • Magnetometer		**Diver-Based Survey** • Shark Marine Navigator with Blueview sonar, GPS • Digital imaging, photogrammetry

are equipped with either inertial or magnetic heading sensors, Doppler velocity logs (DVLs) for speed and altitude over the bottom, pressure sensors for depth, GPS receivers for surface navigation fixes, and acoustic transponder systems for precise underwater navigation (Allen et al., 1997; Moline et al., 2005). With a nominal internal energy capacity of 1.2 kW-hr, the platform can survey at 1.5 m s^{-1} for about 10 hours.

Side-scan sonar is a complementary technology deployed on a UUV for wide-area sensing due to the inherent transparency of water to underwater sound. Large swaths of seafloor can be mapped at the resolution required to resolve objects the size of aircraft and, more challenging, aircraft debris. A principal trade-off with these sensors is that using the higher frequency mode results in higher resolution maps but a decrease in acoustic ranges and resultant rates of area coverage. Table 2 presents the range/resolution trade-offs with the CHIRP-style side-scan sonar that is installed on our vehicles (Marine Sonic Technology Arc Scout). Figure 3 graphically illustrates the differences observed in scanning a P-38 aircraft lost near the Scripps Research Pier in 1943.

For this phase of survey, the UUV platforms are typically programmed to operate in a "mow-the-lawn" mode (Figure 4). Because side-scan sonar is unable to image directly beneath the side-scan transducers (the "nadir"), a staggered lane spacing with overlap is used to image the area missed by the vehicle on a previous survey lane. Based upon our experiences in finding aircraft debris, we have determined that an area of about 4 km^2 can be surveyed effectively by a single vehicle in an eight-hour span using a navigation pattern with lane spacing of 37.5 m and 112.5 m, sonar operating at 600 kHz with 75 m range, and an altitude of 10 m above the seafloor. A 75 m sonar range represents a conservative search parameter; depending on the operating environment (mud/sand, acoustic noise levels), this range may extend beyond 100 m, significantly reducing the survey time. Shifting to a lower acoustic frequency would provide larger area rate coverage, but would not have high enough resolution to detect debris common with WWII wreckage.

Despite the many advantages of an unmanned platform, practical limitations still exist in reliably operating around complex coastlines and topography in a manner that ensures vehicle safety and 100% sonar coverage. These limits are due in part to immaturity in both forward-looking sonar technology and the appropriate vehicle autonomy to interpret and react to large data feeds—a grand challenge to the field of undersea robotics given the complex, fractal nature of coral reef topography. As a result, "person-in-the-loop" technologies are necessary, either through traditional diver-based surveys or through use of vessel-mounted sonars.

Advances in high-frequency multibeam sonar now allow for high-resolution mapping from a compact form factor sonar head that can be deployed from vessels of opportunity. Vessel-based surveys complement UUV surveys, as UUVs designed for wide-area searches are challenged in extremely tight quarters or areas of very sharp bathymetry. Though purpose-built, hovering UUVs do work in these environments, they do not provide

TABLE 2. Side-scan operating frequencies, their maximum swath width, and range resolution for the dual-frequency Marine Sonic CHIRP-style sonar (Arc Scout).

Side-Scan Acoustic Frequency	Typical Swath Width	Maximum Along-Track Resolution	Typical Across-Track Resolution
600 kHz	150 m	15.24 cm	7.50 cm
900 kHz	75 m	10.16 cm	3.75 cm
1,200 kHz	45 m	7.62 cm	2.25 cm
1,800 kHz	25 m	5.08 cm	1.25 cm

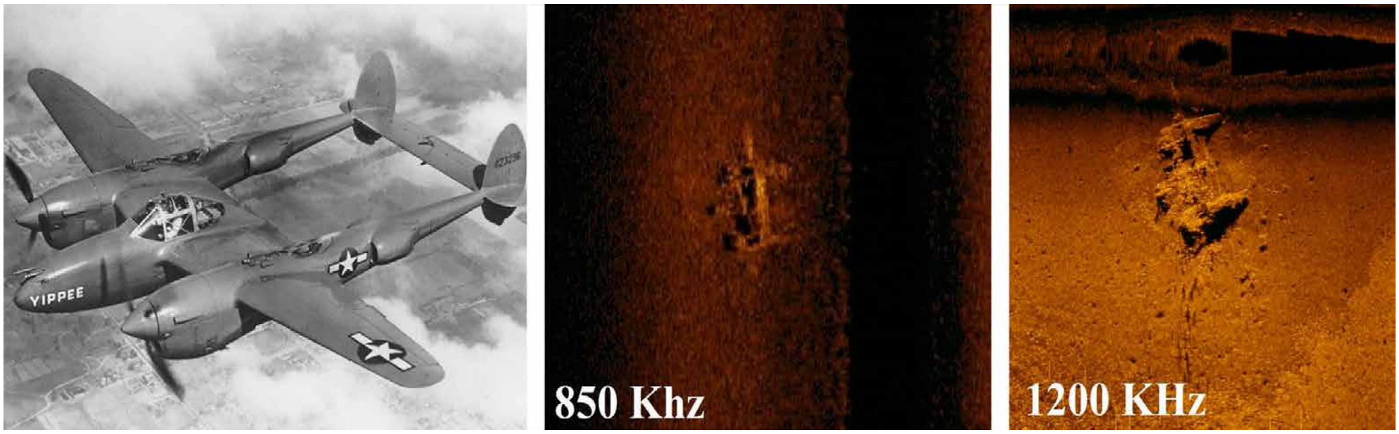


FIGURE 3. Known P-38 aircraft wreck site where Lt. Gaston Hensley ditched and survived on May 28, 1943, near the Scripps Research Pier in La Jolla, California. The two panels on the right, obtained during two UUV missions in May 2016, demonstrate the impact of side-scan acoustic frequency on image sharpness of seabed crash sites.

high search rates. Having the sonar vessel-mounted allows for real-time feedback to the vessel operator, and permits the small vessel to navigate in close quarters with nearby obstacles and hazards. The data are georeferenced with a high-accuracy GPS receiver and an inertial measurement unit and can be used for both identifying wreckage and providing high-resolution bathymetry maps for UUV path planning and dive operations.

We have used the Teledyne Reson T-50 sonar in generating data of sufficient quality to distinguish large aircraft components (e.g., wings) or entire fuselages on the seabed. The high precision of the sonar head motion reference unit and the use of differential GPS permits mapping of the seafloor at sub-meter accuracy (horizontal) and centimeter-level vertical resolution (Table 3). The form factor of the sonar system allows it to be deployed from a range of vessel sizes. This multibeam sonar operates with a beamformer that illuminates the seabed with 512 discrete sonar beams up to 40 times a second to generate an underway map of the seafloor topography. This system can be optimized for water depth over a range of acoustic frequencies (200–400 kHz. Figure 5 shows some examples of WWII wreckage imaged using this sonar.

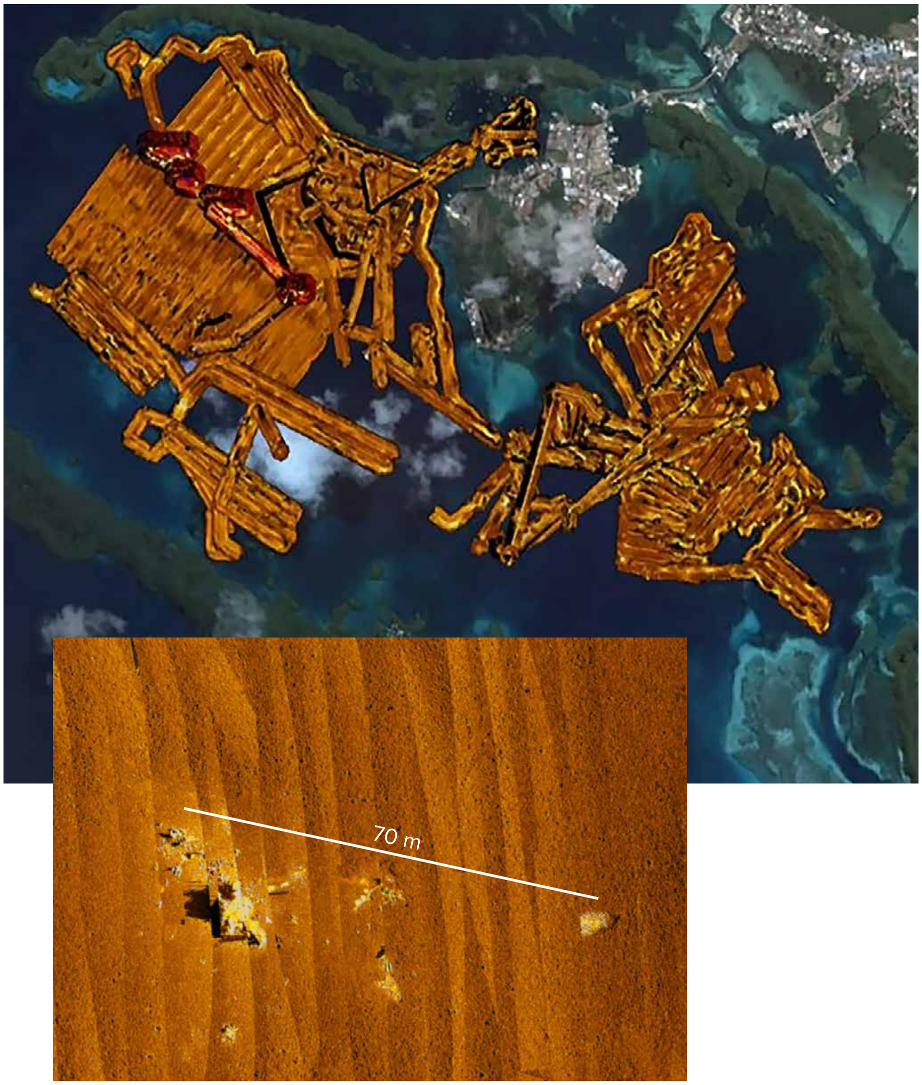


FIGURE 4. (top) Example side-scan sonar mosaic generated from multiple REMUS 100 UUV sorties during a wide-area ("mow-the-lawn") search. Several targets were later prosecuted and shown to contain aviation wreckage dating from WWII. (bottom) A side-scan image of the TBM1-C Avenger found by the authors. The crash is spread across a 70 m debris field. The search and discovery of this crash site was documented in a public outreach video produced by GoPro (Woodman Labs) and was seen by over one million viewers.

At the conclusion of the wide-area search phase, the "fix" phase begins. In this phase, trained subject matter experts identify targets for further prosecution. This involves collecting additional, higher resolution data using a more diverse set of sensing modalities to reject false targets (coral, rocks, trash). This process is very similar to the target reacquisition process used by the EOD community to identify mine-like objects on the seafloor (Wilcox and Fletcher, 2003), and the operations in this phase are often called "reacquires," accordingly.

If the water clarity allows, optical imaging sensors deployed on UUVs are effective and efficient tools in this phase. They allow rapid characterization of each target without the need for divers, and the precision navigation provided by the UUV platform ensures both repeatability and accuracy in documentation. Image post-processing techniques extend the utility of these data, with tools now available that allow stitching of neighboring images to generate wide-area scenes that could not be captured using traditional techniques due to the nature of light propagation in seawater. The optical imagers we use are modular instruments that can be easily attached to and removed from vehicles in the field.

Additionally, high-frequency side-scan sonar can be towed over targets of interest to image them in high resolution from different angles. Most of our UUVs are equipped with dual-frequency sonar, so the same vehicles used for broad-area survey (in the "find" phase) are used in this phase, but with the higher-frequency sonar operating.

The finish phase of this process is the complete prosecution and documentation of targets and often requires a "person in the loop." This can be accomplished with remotely operated vehicle (ROV) surveys of the targets or, when depths are suitable, the use of divers experienced in identifying aviation wreckage.

Navigation is a critical issue for the

final phase, and it requires accurate geopositioned data collected from the previous two phases. Ideally, the sensing systems have consistent navigation methods. Diver technologies such as the Shark Marine Navigator, which integrates a short range, high-resolutio–n sonar with navigation capability, provide the means to position a diver reliably on target in order to maximize bottom time.

Geopositioned imagery offers an efficient means for evaluating many targets quickly and for characterizing sites for future recovery teams. Imagery is stitched to generate high-resolution mosaics (Figure 6). The photogrammetric stitching process is accomplished using commercially available software that extracts structure from motion and correlation algorithms to optimize the resultant two- or three-dimensional image.

Site documentation adheres to strict archaeological and forensic protocols to ensure the highest level of detail and provenance. The end product of this effort is a Site Survey Form modeled after DPAA's internal reporting guidelines. The primary function of the form is to document the site to a degree of detail such that DPAA personnel can accurately evaluate the probability of a successful MIA recovery without ever having visited the site. This provides significant cost and time savings to the US government by increasing the rate at which underwater sites are prosecuted by DPAA. Pertinent information provided in the form includes site type, location, size, water conditions (such as depth, visibility, and currents), search methodology, site descriptions, aircraft identity, surface features, evidence, sediment composition, disturbance, safety concerns, and a recommendation for excavation provided by an independent forensic archaeologist. Detailed imagery derived from the project's technology is also provided with the final report. The forensic recovery of MIA remains from underwater sites is logistically challenging, expensive, and lengthy even when it utilizes the assets of the US military. The detailed documentation provided in the Site Survey Form is critical to the recovery planning process both in terms of logistics and excavation strategies.

DISCUSSION

The remains of many US airmen and sailors lost in military conflicts remain unaccounted for. In addition to the sheer volume of individuals lost in this environment, underwater sites often provide a greater degree of crash-site preservation in comparison to terrestrial losses as they are less subject to human disturbance and negative environmental conditions (Pietruszka, 2014). However, conventional water-based searches are labor intensive, logistically cumbersome, and technically difficult to execute. Present underwater search capabilities in routine use by archaeologists are typically limited by the amount of specialized training, access to tools, and financial support required to conduct underwater investigations.

Our team has developed a set of novel robotic, remote-sensing, and supportive technologies, coupled with a search methodology that we have successfully applied to the problem of searching for crash sites associated with MIA personnel. Using

TABLE 3. Operating specification of the Teledyne Reson T-50 Multibeam Sonar.

Operating Frequency (Variable)	Across-Track Receiver Beam Width	Along-Track Beam Width	Typical Range	Depth Resolution
200 kHz	.5 degree	1 degree	0.5–400 m	0.6 mm
400 kHz	1 degree	2 degree	0.5–200 m	0.6 mm

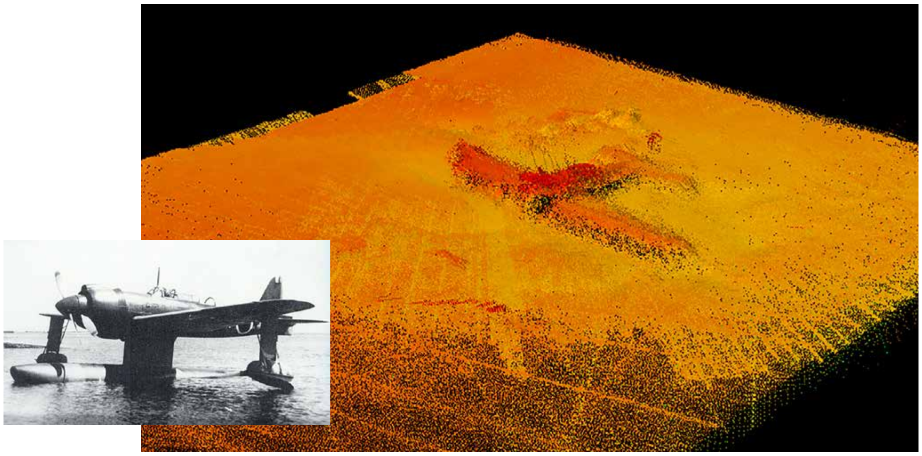
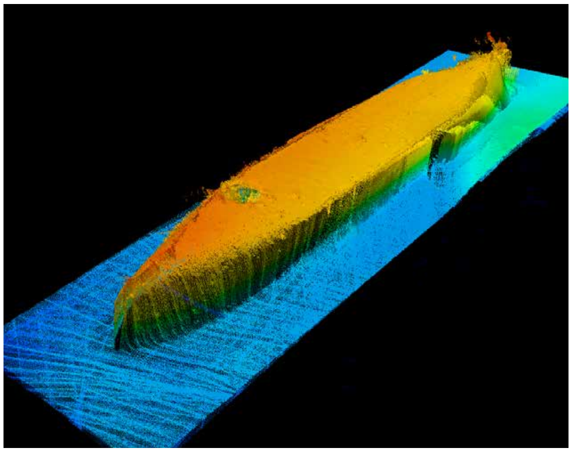


FIGURE 5. (above) Multibeam sonar data of a rare Japanese surveillance plane (inset photo) found resting in 33 m of water. The water visibility is approximately 2 m. (right) Multibeam data of the Japanese vessel *Sata* sitting upside down at 37 m depth in Republic of Palau waters. It was sunk during Desecrate I, World War II. The hole in the hull that led to the sinking is visible in the image.



these tools, Project Recover has documented 13 US aircraft associated with 54 MIAs, and the detailed documentation by our team of discovered sites has already allowed DPAA to immediately transition to the recovery process.

Use of these tools and methods to locate and recover MIAs offers significant advantages over earlier approaches.

Broader and more effective searches. UUVs incorporating multiple sensor capabilities such as side-scan and multibeam sonar, low light cameras, and magnetometers make large area searches feasible. This advanced technology makes recoveries viable at sites that were previously avoided because of imprecise last-known sighting and location information. Additionally, in the case of multiple losses, the entire area can be interrogated and effectively used to discriminate wreck sites.

Time savings and more efficient use of available funds. Improved modeling, for example, Bayesian methodologies applied to archival data, can be used to effectively reduce the size of the search area and direct more efficient searches. Integrated with maritime search technologies (e.g., UUVs, ROVs), search times per site can be greatly reduced. Underwater robots operate independently of surface conditions and can cover much larger search areas using navigation and data resolution superior to surface-vessel techniques.

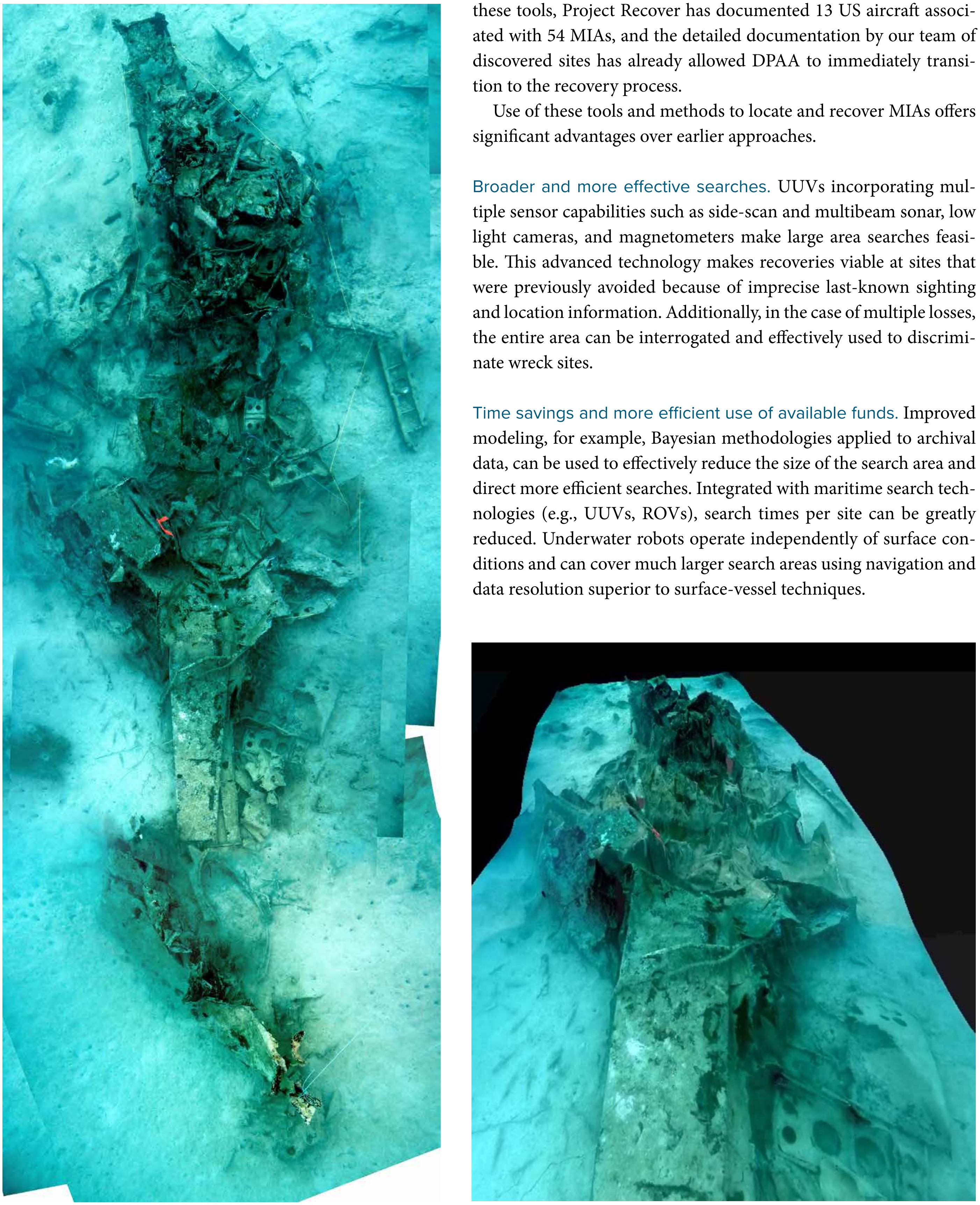


FIGURE 6. Image-stitching algorithms of varying sophistication can be applied to targets found where visibility is poor to generate large views of a crash site that would otherwise be difficult to characterize. Using this technique, a composite image was generated from 25 still images of another TBM1-C airplane wreck found in 2015 at 33 m depth in Malakal Harbor of Palau. The footprint of this mosaic is approximately 5 m wide by 18 m long. Water visibility was estimated to be less than 1 m. The image at left is an overhead view of the fuselage, and the right-hand image shows the same scene in a three dimensional perspective.

Improved field documentation. High-definition photomosaic and acoustic images along with related virtual documentation derived from data collected by UUVs and divers minimize time spent on more traditional and lengthy site survey alternatives (e.g., archaeological site plans). Furthermore, this "hands-off" documentation establishes baseline provenance and permits improved recovery planning of the site.

Better diver safety. Use of underwater remote-sensing technologies (e.g., UUVs, ROVs) reduces the need for large scuba search teams, prolonged underwater hyperbaric exposure, and exposure to variable environmental conditions (e.g., visibility, temperatures, currents).

Improved logistical planning for recoveries. The resultant remote-sensing data package and reporting provides critical planning information for any future recovery team. Detailed mapping of the debris field and terrain, whether localized or broadly distributed, assists in deciding the size and complexity of the recovery footprint and guides future personnel requirements for the recovery.

Higher quality communications. Detailed site documentation with standardized digital products elevates the quality of information and graphics, offering improved communication to MIA families by DPAA, host country officials, other federal agencies, and public relations staffs.

Ongoing operational proficiency. These improved search technologies can be readily passed on to future users of this MIA application, with flexibility to readily incorporated future technology developments.

PUBLIC OUTREACH

Significant public interest has resulted from this program's outreach efforts. Our STEM component is directed at the inspiration, engagement, and education of the public, and it has resulted in visibility through coverage in both the most-watched "60 Minutes" television program of 2015 (17 million viewers) and a video produced by GoPro and distributed by YouTube (1.3 million views). These media can be viewed at:

- » http://www.cbsnews.com/news/a-forgotten-corner-of-hell-bentprop-in-palau
- » https://www.youtube.com/watch?v=9wB6i7i7fKU

POSTSCRIPT

As this issue of *Oceanography* went to press, the Defense POW/MIA Accounting Agency publicly announced that two of the three aviators aboard the TBM Avenger Bomber downed offshore Palau, previously identified as Missing in Action in 1944, have now been accounted as a result of the crash site identification by the Project Recover team.

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