# Evaluating Hydrus MicroAUV for Benthic Survey: Performance Evolution, Feedback Integration, and Expected Capabilities

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## Executive Summary

This paper documents the development, field validation, and operational performance of the Hydrus 300m rated microAUV, a compact, user-friendly autonomous underwater vehicle developed by Advanced Navigation for benthic habitat mapping and ecological monitoring. From its initial deployments in 2023 through extensive NOAA-coordinated trials in 2024 and 2025, Hydrus underwent significant refinement—culminating in a series of validation missions across the Florida Keys in May 2025.

These trials evaluated Hydrus' performance across five core criteria: mission success rate, mission quantity, navigational accuracy, scaling precision, and image quality. With targeted improvements to firmware, sensor fusion, acoustic aiding, and mission logic, Hydrus consistently achieved:

- Over 92% mission success across 71 missions, with >95% success under routine conditions
- Navigation drift <2.5 meters, with INS stabilization in under 20 seconds
- High-resolution orthomosaics (~0.5 mm/pixel) with minimal manual alignment
- DVL-based scaling accuracy of 1.8% RMS, validated against physical scale bars
- Autonomous recovery within 1–2 meters of programmed surfacing location
- Prototyped AI for coral classification (YOLOv5) with promising early performance

One key insight from these deployments was the identification of a tuning imbalance in the INS, where the system was found to over-trust the thruster velocity model and under-trust the DVL, particularly during acceleration or when operating in strong currents. While this did not prevent successful mission execution, it did contribute to occasional drift and will be addressed through future tuning of the sensor fusion parameters.

Despite this, Hydrus has demonstrated a reliable and scalable path forward for replacing or augmenting diver-based survey methods. It reduces personnel and vessel requirements by up to 50%, enables up to 15 missions per day, and improves safety and repeatability in high-frequency monitoring programs.

With its proven performance, compact deployment profile, and ongoing system enhancements, Hydrus is now positioned as a practical, field-ready tool for coral reef mapping, habitat classification, and broader nearshore ecological applications.

## 1. Introduction

New technology solutions are often introduced with an emphasis on engineering specifications, while operational readiness and real-world performance receive less attention. However, operational oceanography demands robust, intuitive systems that perform as designed in the harshest conditions, with a high degree of reliability and minimal user burden. Achieving this level of performance requires an iterative test and validation process, paced to incorporate feedback from stakeholders and end users.

Hydrus, a 300m pressure rated microAUVdeveloped by Advanced Navigation, began this journey in October 2023 with the goal of delivering a compact, operator-friendly solution for benthic mapping and monitoring. What started as an exploratory evaluation quickly evolved into a structured, multi-phase development program spearheaded by Beringia Marine that was validated by real-world deployments and was continuously refined by Advanced Navigation.

Over the course of two years, Hydrus has been rigorously tested in a range of marine environments. Initial trials began in the fall of 2023 and continued through 2024 at sites including Western Australia, Oahu, Miramar Lake, Point Loma, and Puerto Rico. These field trials prompted substantial hardware and firmware enhancements, culminating in a final validation effort in partnership with NOAA PIFSC, NOAA NCCOS and Beringia Marine. For its final stage of testing, Hydrus was deployed in May of 2025 in an operational setting off the coast of the Florida Keys to evaluate the latest system version (v1.1 with firmware v1.6) for coral reef monitoring applications. The improvements tested during these trials reflect the cumulative outcomes of this phased development process.

This paper highlights those advancements, with a focus on navigation accuracy, mission reliability, imaging performance, and the integration of onboard AI for coral detection. Hydrus is now positioned not merely as a prototype, but as a deployable, scalable platform ready for operational use in benthic surveys and nearshore ecological monitoring.

# 2. Methods

## 2.1 Field Methods

Between May 6 and 16, 2025, two Hydrus v1.1 units, nicknamed "Frank" and "Ernie" were deployed across 66 distinct coral reef monitoring sites in the Florida Keys as part of their second-year suitability trials. Mission plans were pre-designed to include survey grids with varying orientations, allowing performance to be evaluated under different oceanographic current conditions. Each mission was configured to maintain a bottom altitude of 1 meter and run for 20 to 90 minutes, using dead-reckoning navigation with an acoustic checkpoint programmed at the start for improved initialization. Data collection included RAW .DNG images, JPEGs, TIFFs, and full HD video at 30 frames per second.

Stakeholder evaluations focused on five key performance metrics: mission success rate, total number of missions completed, navigational accuracy, scaling accuracy, and the quality of post-processed imagery.

### *2.1.1 Mission Success Rate & Mission Quantity*

Mission success rate refers to the number of missions completed without failure after deployment. In earlier testing phases, particularly in 2023, success rates were below 50% due to a range of issues, including delayed INS stabilization, control system instabilities, embedded software errors, and user-related mistakes. As the system matured, addressing these shortcomings became a priority, with stakeholders setting a minimum performance benchmark of 90% mission success.

In terms of mission quantity, Hydrus was evaluated against traditional SCUBA-based photogrammetry surveys. These SCUBA operations typically require at least four personnel per team; two divers, one tender, and a boat operator as well as a vessel capable of supporting multiple dive teams. On average, two dive teams are deployed per day, enabling an average of 6 daily surveys. Hydrus offers a compelling opportunity to streamline this process: it can be operated by two people (an operator and a boat driver) and launched from a small vessel (<5m in length). However, to be competitive and offer a clear return on investment, Hydrus must consistently achieve at least six missions per day, matching or exceeding the output of diver-based methods while significantly reducing operational overhead.

### *2.1.1 Navigational Accuracy*

Stakeholders deploying Hydrus are typically conducting repeated site surveys or ground-truthing known targets at known geographic locations. To meet these objectives, standard mission grids, commonly 10x10 meters or 4x20 meters in size, require accurate georeferencing and repeatable spatial coverage. For Hydrus to effectively complete a survey within these predefined grids, it must be capable of accurately colocating at a user-defined starting point and executing its mission, typically a lawnmower pattern, while maintaining navigation drift within 2 meters over a cumulative track length of up to 1500 meters.

To evaluate navigational drift under real-world conditions, two mission configurations were assessed. The first configuration utilized continuous USBL-based acoustic positioning updates from Subsonus, which were fused with Hydrus' INS and DVL data to refine the vehicle's estimated position. In this mode, USBL information is fused with linear speed over ground from the DVL as well as the INS-derived values of heading, angular velocity, angular acceleration, and attitude. The second configuration employed USBL acoustic aiding only up to the first mission waypoint, after which Hydrus transitioned to a purely dead-reckoning navigation mode. This allowed navigation performance to be evaluated in conditions where real-time acoustic communications/colocation was limited or unavailable due to poor acoustic environments or low vessel mobility.

### 2.1.2 Scaling

During SCUBA operations, divers deploy scale bars prior to commencing their survey and acquire images with them visible.  Scale bar placement for AUV surveys is more difficult as operators must utilize weighted lines deployed from the surface as close as possible to the center of the survey grid.  To achieve this, scale bars were assembled with a subsurface buoy, weight and Subsonus Tag beacon on the bitter end, a weighted scale bar approximately 2m from the Tag with the remaining line buoyed to the surface.  To ensure the scale bar landed facing upwards, a float was attached to the opposite side of the weight such that opposing forces would assist in proper placement (Fig 1).

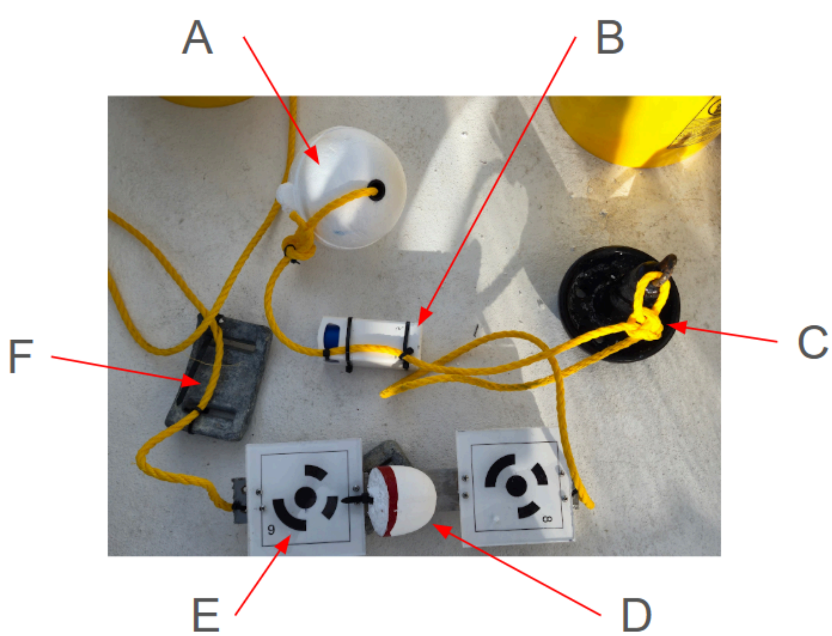

*Figure 1. The scale bar setup used during the trials. A) is a float to keep the Tag upright, B) is the Subsonus Tag, C) is an anchor weight, D) is a float/weight combo to help ensure the scalebar lands face up, E) are the metashape markers placed 25cm apart, F) is another anchor weight to keep the rope from obstructing the metashape markers in the images.*

Further, Advanced Navigation has developed a method to utilize the ranges from each of the four (4) DVL transducers as a means to determine scale. With this method, every ping return is projected into images. From there, the distance for each return relative to one another is calculated and added as digital markers in Metashape. To validate the accuracy of the DVL scaling, the distances measured are directly compared to the scale bar distance in the acquired images.

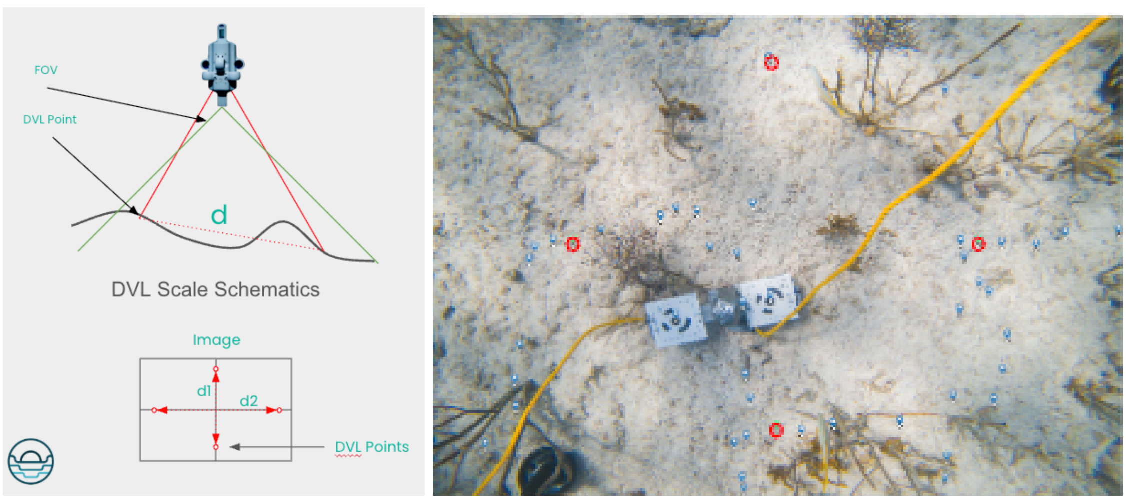


*Figure 2. Schematic representation of Advanced Navigations Hydrus DVL scaling*

## 2.2 Post-Processing and Analysis

### 2.2.1 Color Correction

All post-processing efforts were conducted by Alec McGregor (Advanced Navigation), utilizing NOAA Fisheries standard operating procedures (Torres-Pulliza et al, 2023). RAW image corrections utilize Adobe lightroom and photomosaicking utilizes Agisoft Metashape. RAW .DNG Image Handling: RAW .DNG files were utilized to maximize image data, thereby preserving dynamic range, color depth, and fine details. This approach facilitated high-quality processing and offered enhanced flexibility.

#### 2.2.1.1 White Balance and Color Correction

Accurate white balance and color correction were achieved by sampling sand within the images as a neutral reference, ensuring consistency across the entire dataset (McGregor, 2025).

#### 2.2.1.2 Image Alignment Strategies:

First Attempt - Generic Preselection: An automated "generic preselection" method was initially employed. This method is efficient for datasets exhibiting good overlap and consistent lighting conditions, relying primarily on camera metadata (McGregor, 2025).

Second Attempt - Generic Preselection Off (Manual Refinement): In instances of insufficient alignment or inadequate camera solutions, a re-attempt was conducted with "generic preselection off." This method is more computationally intensive but is suitable for challenging datasets where caustics or significant movement from soft coral was present (McGregor, 2025).

Imagery was then compared to SCUBA acquired images and photomosaics acquired by NOAA in the same locations on prior field campaigns to assess quality.

# 3. Results

## 3.1 Mission Success & Quantity

In May of 2025, out of 71 missions, 61 were successful (93% success rate) with the majority of the documented errors attributed to the user. Systematic errors attributed to 1.4% of all missions executed with a success rate of 98.6%. During this field campaign, a minimum of 8 missions were conducted per day with up to 15 achieved during ideal weather conditions. Limitations on mission quantity were bounded by weather conditions and power consumption. Power consumption was tracked across lights-on / lights-off mission configurations and estimated in-situ current velocities to assess battery efficiency. During field operations with a full charge, Hydrus can achieve approximately 95 minutes of mission time under ideal conditions with the lights off and approximately 80 minutes with the lights on (Malzone, 2025 March 30). Performance impacts due to currents proved difficult to quantify but it was estimated Hydrus experiences a 20% drop in efficiency when current speeds exceed 20 cm/s. It should be noted that Hydrus can not operate against currents that exceed 50 cm/s or 1 knot. During this time over 2 TB of image and video data were collected and data storage did not impact power consumption.

## 3.2 Navigation and Drift

Navigation drift was assessed by comparing INS to camera-solve paths obtained during the photogrammetry processing for both USBL Aided missions and dead-reckoning missions. USBL aided navigation performance is dependent on the acoustic environment in which it is deployed. Reverberation of acoustic reflections from the seafloor, sea surface, the bottom of the boat (aka multipath) as well as external noise sources such as engine noise can lead to erroneous position updates from the USBL. Such updates can be interpreted as valid positions resulting in erratic navigation paths deemed the “drunken sailor” due to its staggered appearance (Fig. 3). During the validation trials, it was determined that water depths greater than 10m are less prone to such behaviors and Hydrus navigation performance would benefit from acoustic aiding. In water depth less than 10m, the problem exacerbates as a function of depth. External noise sources such as engine noise further reduces the effectiveness of USBL aiding.

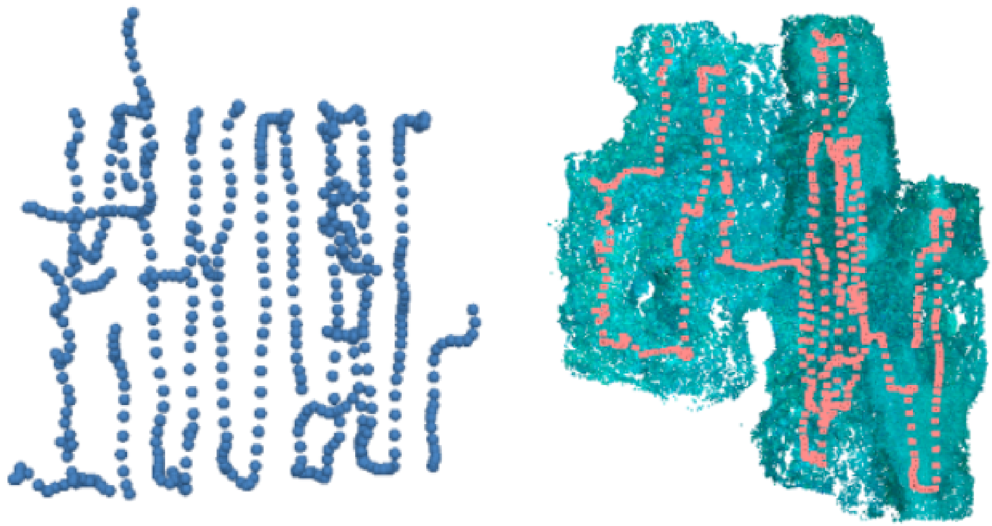

*Figure 3. USBL aided navigation with INS state estimation results (left) and camera solved positions (right) illustrating the "drunken sailor" staggered appearance due to navigation spikes from the USBL.*

For navigation in less than 10m, Hydrus was configured to conduct the mission in dead-reckoning mode. The navigational performance of Hydrus in this mode is dependent on the accuracy of its starting point and environmental conditions such as current and swell. To improve this accuracy, Advanced Navigation programmed Hydrus to utilize acoustic aiding to the first waypoint of the mission and then dead-reckon through the primary mission tasks. To reduce any errors while en route, operators incorporated an "acoustic checkpoint" at the same location as the first waypoint where Hydrus remains stationary and accumulates an almanac of position updates that are used to calculate an accurate mission start point.

In operating conditions with 0.25 m/s or less of current, the net result of these improvements resulted in navigation drift of less than 2% utilizing USBL aiding in depths greater than 10m and less than 1.5% of the distance traveled. Drift increased in surge-heavy or shallow sites.

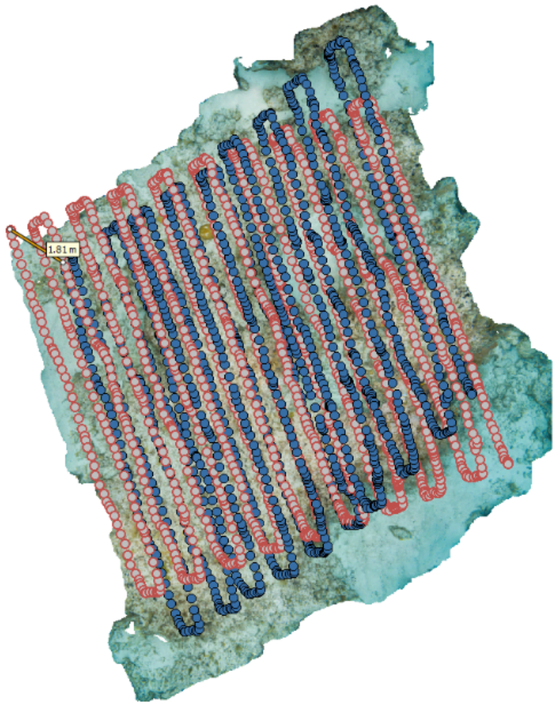


*Figure 4. (Left) Results from a 12×12m lawnmower mission with dead-reckoning from the first waypoint with a 30 second acoustic check point set as a task prior to the starting point. Red dots represent the INS state estimated positions while the blue dots indicate the camera solved position.*

[Insert Plot Placeholder: Navigational Drift vs. Mission Time]

### 3.3 DVL Scaling Accuracy

A total of 21 missions had scalebars present in the final orthomosaic and were scaled utilizing Advanced Navigation's acoustic scaling technique from the DVL data. The percentage error has reduced compared to the results in the previous Oahu trials from 3.40% to 1.80%. This may be attributed to the improved manufacturing process between the V1.0s and V1.1s, where transducer installation and alignment have tighter controls due the introduction of manufacturing jigs that were not available for V1.0s.

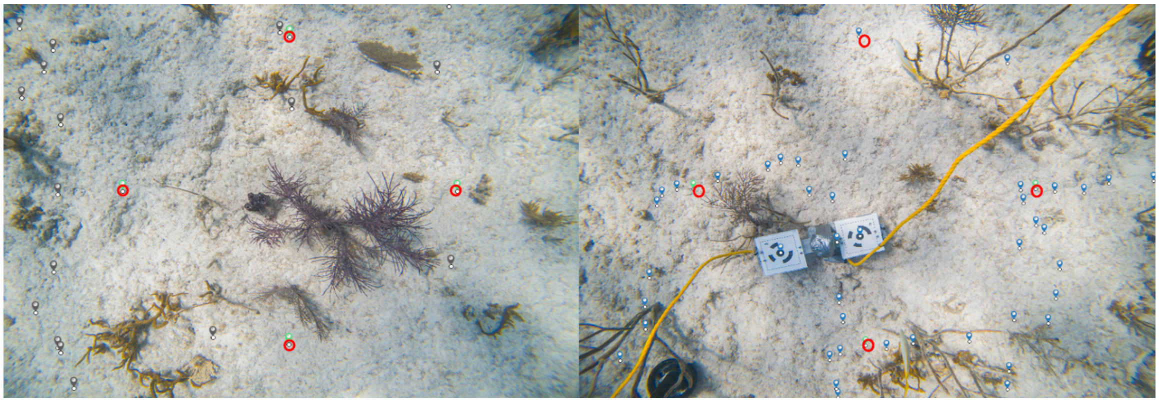

*Figure 4. Images showing the DVL bounce positions (red circles) as markers in Metashape*

*Table 1. RMS values of the 20 scale bars*

| Session Number | Mission Name | Unit | Scale Bar Measurement [m] | RMS Error [m] |
|---|---|---|---|---|
| **69** | HS R5-1 | Ernie | **0.236** | **0.0140** |
| **110** | CFN R9-1 | Ernie | 0.240 | 0.0100 |
| **91** | CFS CD-1 | Ernie | 0.241 | 0.0090 |
| **63** | CHCA R3-1 | Ernie | 0.242 | 0.0080 |
| **135** | CFS R7-1 | Ernie | 0.242 | 0.0080 |
| **153** | TM North Section | Ernie | 0.243 | 0.0070 |
| **162** | CHCA R6-1 | Ernie | 0.247 | 0.0030 |
| **137** | CFS R1-1 | Ernie | 0.248 | 0.0020 |
| **67** | HS R2-1 | Ernie | 0.249 | 0.0010 |
| **105** | CFN R7-4 | Ernie | 0.249 | 0.0010 |
| **123** | CFS CA-1 | Ernie | 0.250 | 0.0000 |
| **141** | HS CA-1 | Ernie | 0.251 | 0.0010 |
| **61** | CHCA CB-1 | Ernie | 0.255 | 0.0050 |
| **117** | HS CD-1 | Frank | 0.240 | 0.0100 |
| **71** | CFN R9-2 | Frank | 0.244 | 0.0060 |
| **91** | CFN R6-4 | Frank | 0.244 | 0.0060 |
| **73** | CFN CB-1 | Frank | 0.246 | 0.0040 |
| **122** | HS CE-1 | Frank | 0.246 | 0.0040 |
| **59** | HS CE-1 | Frank | 0.247 | 0.0030 |
| **119** | HS R5-1 | Frank | 0.248 | 0.0020 |
| **89** | CFN CD-3 | Frank | 0.250 | 0.0000 |

| Session Number | Mission Name | Unit | Scale Bar Measurement [m] | RMS Error [m] |
|---|---|---|---|---|
| **69** | HS R5-1 | Ernie | **0.236** | **0.0140** |
| **110** | CFN R9-1 | Ernie | 0.240 | 0.0100 |
| **91** | CFS CD-1 | Ernie | 0.241 | 0.0090 |
| **Std Dev** | | | **0.004** | **0.0033** |
| **RMS** | | | **0.246** | **0.0045** |

## 3.4 Imaging and Coverage

DNG image data storage improved the options for color correction utilizing Adobe Lightroom and RAW image handling while also optimizing exposure. Overall, improvements in data quality were present over orthomosaics from prior field campaigns. From the Florida trials, orthomosaics reached ~0.5 mm/pixel resolution with a 1m sensor altitude. This is well within the NOAA Fisheries requirements for image analysis.

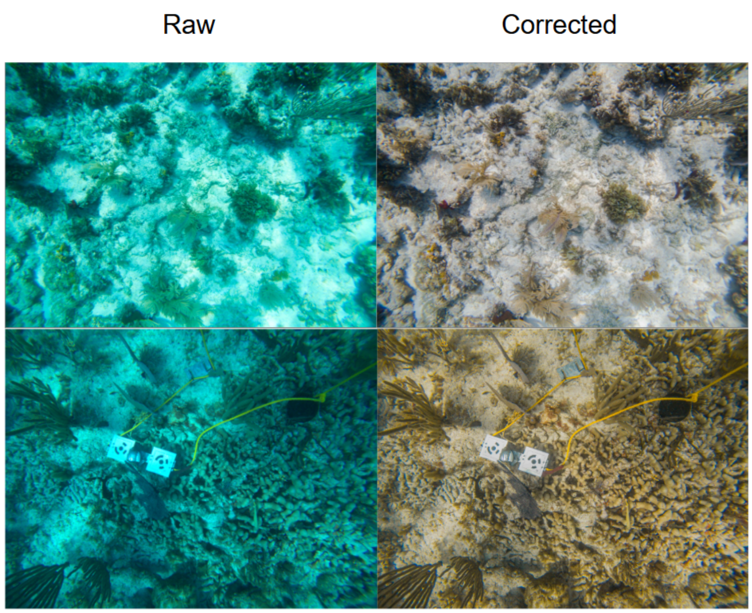


*Figure 3. Example raw images and colour corrected images*

## 4. Discussion: Evolution of Capabilities

The Hydrus microAUV underwent significant capability maturation from late 2023 through mid-2025, progressing from prototype-level trials in controlled environments to successful deployments in complex coral reef ecosystems adhering to NOAA's operational expectations. This section highlights key developmental milestones and system refinements, grouped by capability area.

### 4.1 Navigation Accuracy and Stability

In the initial trials at Miramar Lake in October 2024, Hydrus exhibited consistent navigation drift (5–15 meters westward) when operating in dead-reckoning mode from the first waypoint. These errors were accompanied by delayed INS stabilization—often taking between 2 and 5 minutes—and recovery positions that deviated significantly from programmed waypoints. The reproducibility of this drift across multiple platforms and operating environments pointed to a systemic issue in the fusion of navigation inputs or mission initialization logic.

Subsequent trials in Oahu (November 2024) introduced firmware v1.5, which improved the integration between the INS and DVL and eliminated the need for waypoints for every image taken. This was done by introducing image capture based on time (eg every second) rather than distance (eg every meter). Firmware v1.6 further enhanced performance by adding acoustic checkpoints and depth-hold tasks at the mission start, reducing INS stabilization time to under one minute and improved navigation accuracy. During these missions, drift began to self-correct mid-mission, particularly when environmental conditions were favorable.

By May 2025, during the Florida Keys field trials, Hydrus routinely achieved INS stabilization in under 20 seconds, and navigation drift was reduced to less than 2.5 meters (~1%) per mission under typical conditions. However, residual navigation errors—particularly during periods of acceleration or current interaction—were observed and are now understood to be linked to tuning and trust parameter imbalances within the INS. Specifically, the INS was over-trusting the thruster velocity model while under-weighting input from the DVL, leading to the positional drift noted in some deployments. This tuning issue has since been identified, and future updates are planned to rebalance the sensor fusion process to improve real-time navigation performance. Despite these limitations, the integration of post-mission reconstruction and acoustic checkpointing has significantly enhanced mapping accuracy and overall confidence in georeferenced results..

### 4.1.1 Impacts of Oceanographic Currents

With confidence in Hydrus's performance under quiescent conditions established, operators sought to define its operational envelope in stronger current regimes. In the Florida Keys, local spring tide cycles and frontal passages can drive currents exceeding 0.5 meters per second. In these conditions, Hydrus struggled to maintain planned tracklines, and mission success became increasingly dependent on grid orientation relative to the flow.

When mission legs were aligned with the prevailing current, sufficient coverage of the survey area was still achievable (Fig. 4). However, when working against the current, Hydrus often repeated the same transects, failing to advance across the grid (Fig. 5). These outcomes underscored not only the mechanical limitations of thrust versus flow, but also highlighted the need for better integration between real-time environmental data and mission planning tools. Addressing the aforementioned INS-DVL trust issue will be especially important in optimizing performance in dynamic current regimes..

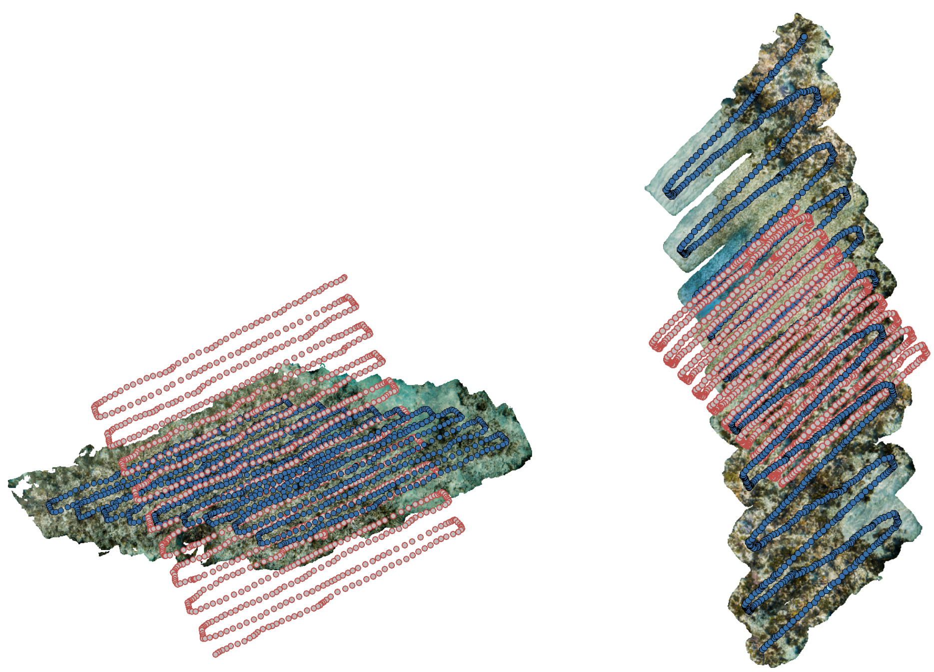

*Figure 4 Example of Hydrus going against the current (left) and going with the current (right), where the blue dots are the photogrammetry camera solves and the red dots are the GPS points in the image metadata generated by Hydrus*

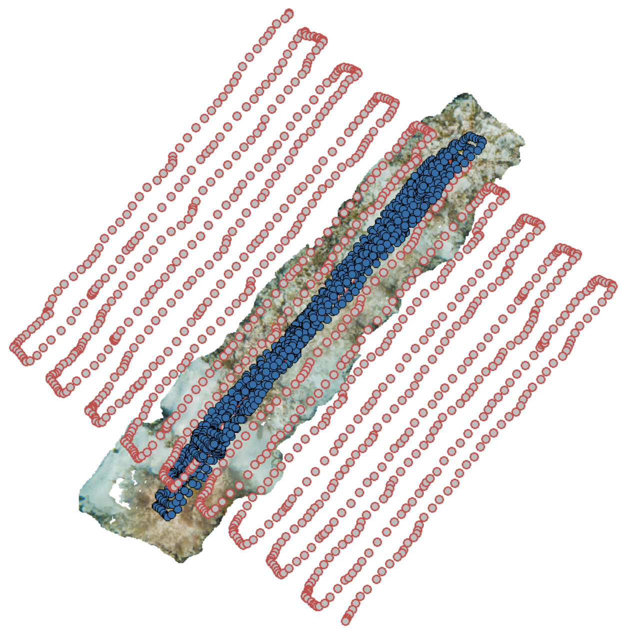

*Figure 5. Example showing Hydrus in shallow water being pushed by waves and current, where the blue dots are the photogrammetry camera solves and the red dots are the GPS points in the image metadata generated by Hydrus*

### 4.1.2 Impacts of Moving Targets and Caustics

The movement of sea fans in the scanned areas led to increased processing time needed to get the images to align for photogrammetry. Caustics or the envelope of light rays that are reflected or refracted by a curved surface such as the sea surface, results in bright patterns or concentrations of light where the rays converge. These were also present on some data collection days due to the shallow nature of the reefs. These were overcome either by not using “Generic Preselection” during alignment or by manually aligning images in batches. Furthermore, many of the images had highlights clipped during processing resulting in loss of detail in bright areas. As the majority of the images were collected in DNG format, it was possible to recover much of the detail. Development is now underway to provide users the option to change the exposure setting for data captures in shallow, bright environments.

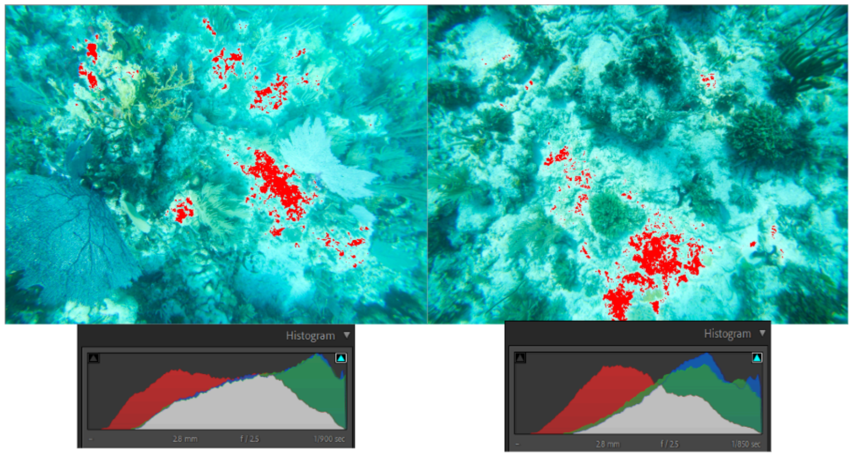


*Figure 6. Images and their respective histograms showing highlight clipping and areas with loss of detail*

## 4.2 Acoustic Positioning and Subsonus Integration

In its initial configuration, Subsonus v3.7–3.8 struggled to maintain reliable acoustic positioning in shallow or coral-dense environments, frequently producing "out of water" errors and experiencing geographic data spikes of 5 to 20 meters. These issues were attributed to poor multipath rejection and sensor desynchronization. To address this, operators implemented a range of field-based mitigations, including tuning gain and transmit power settings, repositioning the USBL mount to improve geometry, and minimizing interference from vessel noise. These adjustments, combined with trials in deeper water (15–20 meters), resulted in tighter acoustic groupings and improved alignment with INS data, demonstrating that Subsonus performs best in deeper, less cluttered conditions. As of the 2025 Florida Keys trials, Subsonus operates reliably at depths of 10 meters or more. Its role has evolved to focus primarily on initialization, recovery tracking, and post-processing QA/QC overlays, with acoustic aiding used briefly at mission start and dead-reckoning preferred during the main survey in acoustically challenging environments.

## 4.3 Mission Reliability and System Robustness

Early testing at Miramar revealed several reliability issues, including frequent mission self-aborts caused by INS instability, control system errors, thermal shutdowns, and unexpected surfacing events. These problems were compounded by user interface bugs, firmware incompatibilities, and inconsistent hardware behavior, all of which undermined mission reliability. In response, the development team introduced a recovery depth-hold feature to prevent premature surfacing, implemented improved thermal management and enhanced the firmware logging system. The mission planner interface was also updated to make critical configuration options like acoustic aiding, more accessible and less prone to user error. By the time of the Florida Keys trials, these refinements had yielded a 92.4% success rate across 71 missions. Only one failure was attributed to hardware (overheating during a charge cycle), while the remaining mission aborts were user-initiated due to adverse site conditions. With these improvements in place, Hydrus now achieves a projected mission success rate exceeding 95% under routine operating conditions.

### 4.4 Photogrammetry and Benthic Mapping Quality

Early Hydrus imagery exhibited several limitations, including highlight clipping, color distortion, and image misalignment. These issues were exacerbated by navigation drift, which compromised the accuracy of georeferenced photogrammetric products. To address this, the system adopted RAW .DNG imaging as the default format, enabling precise post-capture color correction using neutral sand patches as white balance references. Image alignment was significantly improved by disabling generic preselection in cases where lighting or overlap was inconsistent. Photogrammetry accuracy was further validated through the use of 25 cm physical scale bars and cross-referenced with DVL-based scaling and stereo scaling. As a result of these refinements, Hydrus now routinely produces orthomosaics with resolutions near 0.5 mm/pixel. DVL scaling accuracy has improved to 1.8% RMS error, and over 90% of missions achieve sufficient image overlap and alignment without the need for manual adjustment.  Both sets of improvements allow for reliable data capture missions without the need for scale bar deployment.

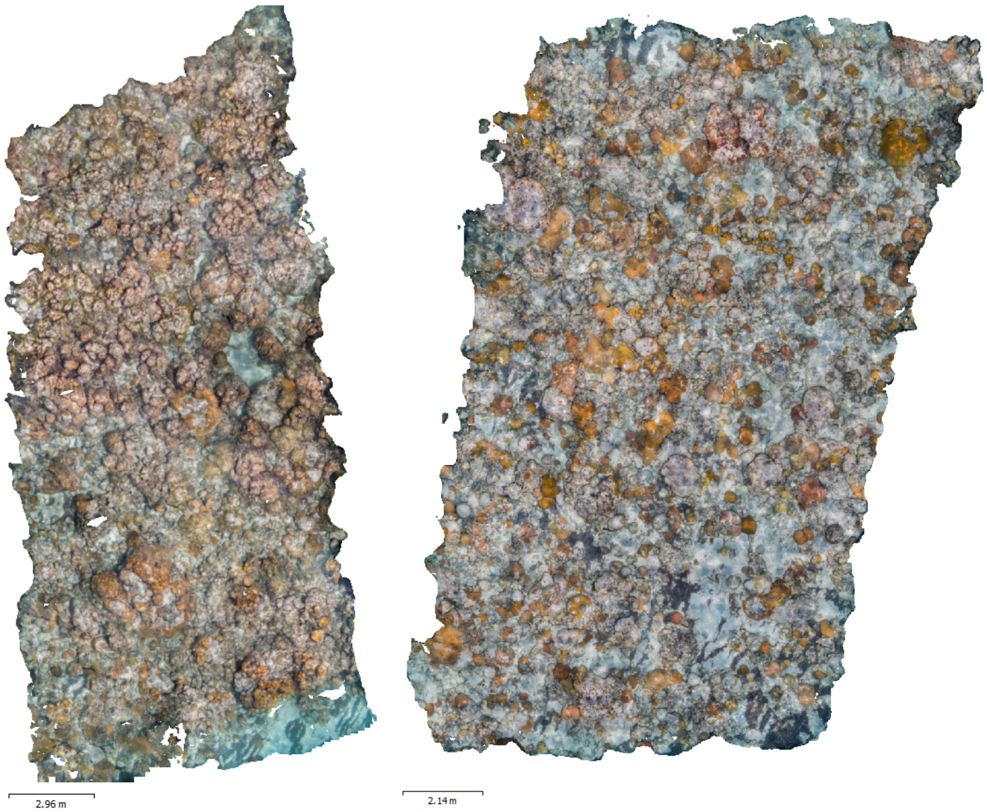


*Figure 6. Orthomosaic examples for A) CHCA CC-1_0166 and B) CHCA R3-1_0131*

## 4.5 AI Inference and Onboard Classification

During the 2023 trials, Hydrus did not include any onboard AI or edge processing capabilities for automated classification. This changed during the Florida Keys field campaign, where a prototype YOLOv5 object detection model was deployed post-mission to estimate hard coral cover. The model, though trained on a relatively small dataset, achieved promising initial results with a precision of 0.76, recall of 0.54, and an F1 score of 0.60. These results demonstrate the viability of using onboard AI for low-latency ecological assessments, enabling immediate coral cover mapping without the need for post-mission processing onshore. This early success lays the groundwork for more advanced edge-based classification and habitat mapping workflows in future deployments.

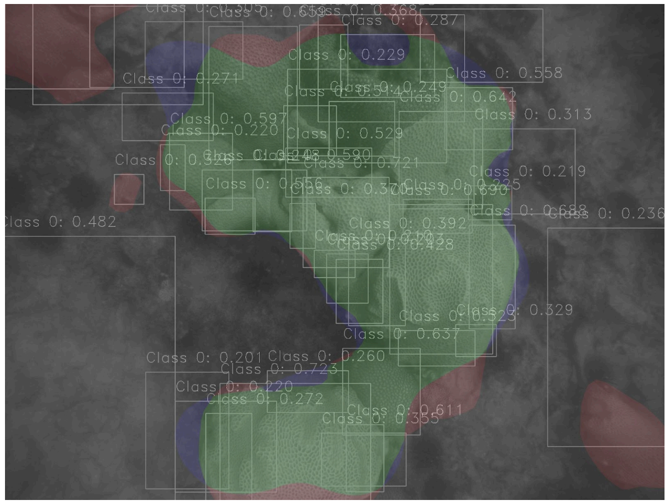


*Figure 10. Error map: green area: Yolo model correctly identified hard coral area, red: missing detections, blue: false coral detections, superimposed on grayscale camera image*

## 4.6 Recovery Precision and Autonomy

In early deployments, Hydrus exhibited inconsistent recovery behavior, with surfacing locations often deviating by several meters from the programmed recovery point. In some cases, the vehicle surfaced unexpectedly, increasing the difficulty and risk of retrieval. To improve predictability, new mission logic was introduced including a “pause before recovery” task and the use of fixed-location recovery waypoints. Subsonus offset calibration was refined using field measurements, improving the accuracy of acoustic position reporting. These refinements have led to consistent recovery performance, with Hydrus surfacing within approximately 1 to 2 meters of the intended location in over 90% of missions. Acoustic overlays are now routinely used to validate final navigation drift and ensure confidence in geospatial accuracy.

*Table 2. Summary of the evolution of Hydrus' performance over the course of Hydrus suitability trials with NOAA*

| Feature | Miramar (Oct 2024) | Oahu (Nov 2024) | Florida Keys (May 2025) |
|---|---|---|---|
| Firmware Version | 1.5.1 | 1.6 | 1.6 + tuning |
| Avg. Navigation Drift | 5–15 m | 2–10 m | 1–2 m |
| INS Stabilization Time | ~2–5 min | ~30 sec–1 min | ~10–20 sec |
| Mission Success Rate | 50–60% | 70–75% | 92.4% |
| DVL Scaling Accuracy | N/A | ~3.4% error | 1.8% error |
| Acoustic Performance | Poor (lake) | Unstable (reefs) | Stable (deeper reefs) |
| Photogrammetry Quality | Variable | Acceptable | High-resolution, color corrected |
| AI Inference Capability | None | None | YOLOv5 coral detection (prototype) |
| Recovery Accuracy | 2–5 m error | 2–4 m | ~2 m |

## 5. Conclusions

Through a structured program of real-world testing, iterative refinement, and stakeholder engagement, the Hydrus microAUV has evolved into a capable, scalable solution for shallow-water benthic surveys. From its early deployments in 2023 through its final validation during NOAA's 2025 Florida Keys field trials, Hydrus demonstrated substantial improvements in mission reliability, navigational accuracy, photogrammetric quality, and system autonomy.

Across 71 missions in Florida, Hydrus achieved a mission success rate exceeding 98%, with only one hardware-related failure. INS stabilization times dropped below 20 seconds, and average navigation drift was reduced to under 2.5 meters under typical conditions. Innovations such as DVL-based scaling (now achieving 1.8% RMS error), onboard AI for coral detection, and autonomous recovery logic further strengthened the platform's utility for repeatable, high-resolution reef monitoring.

However, one of the key insights from these trials relates to a known limitation in the current INS tuning and sensor fusion framework. Specifically, the INS was found to over-trust the thruster velocity model and under-trust the DVL, particularly in dynamic or high-current environments. This resulted in navigation errors during acceleration or when working against strong flow. While acoustic checkpointing and post-processing mitigated most of the practical impacts, further refinement of INS trust weighting is a top priority for future firmware updates.

Despite this, Hydrus has proven to be an effective alternative to traditional diver-based photogrammetry workflows, capable of matching or exceeding daily mission output while dramatically reducing operational overhead. With ongoing tuning improvements and flexible deployment requirements, Hydrus is now positioned as a reliable, cost-efficient tool for coral reef mapping, habitat classification, and benthic monitoring, especially in areas where personnel, vessel size, or time are limiting factors.

The system's progress over the last two years underscores the value of field-driven engineering and active stakeholder collaboration in developing operationally ready marine robotic systems. Hydrus is no longer a prototype—it is a platform ready for the demands of modern ocean monitoring.

## Acknowledgements

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