# Project 129: Fully Autonomous Subsea Asset Inspection by a Shore-Launched AUV

*Final Report*

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# Acronyms and Abbreviations

| | |
|---|---|
| ANCC | Autonomy, Navigation, Command, and Control |
| AUV | Autonomous Underwater Vehicle |
| FLS | Forward Looking Sonar |
| MBES | Multi Bean Echosounder |
| NOWRDC | National Offshore Wind Research and Development Consortium |
| SBP | Sub Bottom Profiler |
| SCM | Self Compensating Magnetometer |
| SSS | Side Scan Sonar |
| VHF | Very High Frequency |

# Executive Summary

The Dive-LD Geophysical Survey and Inspection vehicle was developed as part of a project to execute pier-launched autonomous subsea surveys and identify anomalies in power transmission cables for offshore windfarms. A key feature of this system is the ability to incorporate Autonomous Navigation, Command, and Control (ANCC) software that can monitor gathered data real-time, identify objects of concern, and execute follow-on missions for reinvestigation at the conclusion of an initial survey. This was developed to enable thorough results and ensure clarity without any operator intervention. This is possible with Anduril and third-party ANCC software.

The Anduril and its subcontractor Metron proved this capability repeatedly throughout the Spectacle project. This final report outlines the development, course of testing, and lessons learned over the past 12 months. Overall, the team proved successful, autonomous operation of the DIVE-LD and execution of sensor-specific missions at the direction of two independent ANCC software suites. Not only does this unlock considerable potential in low-environmental impact surveying options (without impacting quality), it also presents an important stepping stone to further development in autonomous decision making, extended operations, and unattended operation.

# 1 The Product

The Dive-LD is a dual-use, large displacement, autonomous underwater vehicle (AUV) capable of integrating numerous sensors and payloads depending on the use case. The vehicle's architecture is free flooded, which allows the vehicle to fill its internal voids with sea water once submerged. Syntactic foam lines the hull to provide buoyancy and all electronics bottles, batteries, and payloads are sealed and pressure tolerant, depth rated to 6000 meters. The vehicle structure is comprised of an aluminum A-Frame that can be separated around the batteries allowing for a quick swap of charged batteries if continuous operations are desired.

Table 1 outlines the sensors utilized on the DIVE-LD. The sensor systems and their placement were carefully considered for overall balance to maintain designed center of gravity. Figures 1 and 2 show the internal and external arrangement of said sensors within the DIVE-LD.

| Sensor | Manufacturer | Model |
|---|---|---|
| **Side Scan Sonar (SS)** | Edgetech | 2205<br>Tri-Frequency (230/540/850 kHz) |
| **Sub-Bottom Profiler (SBP)** | Edgetech | 2205<br>(DW 2-16) |
| **Multibeam Echosounder (MBES)** | Teledyne Reson | T-50 |
| **Digital Stills Camera** | Voyis | Observer & Nova Pro |
| **Forward Looking Sonar (FLS)** | Norbit | Compact FLS |
| **Magnetometer** | Ocean Floor Geophysics | Self-Compensating Magnetometer (SCM) |

**Table 1. DIVE-LD Geophysical Survey and Inspection Sensors**

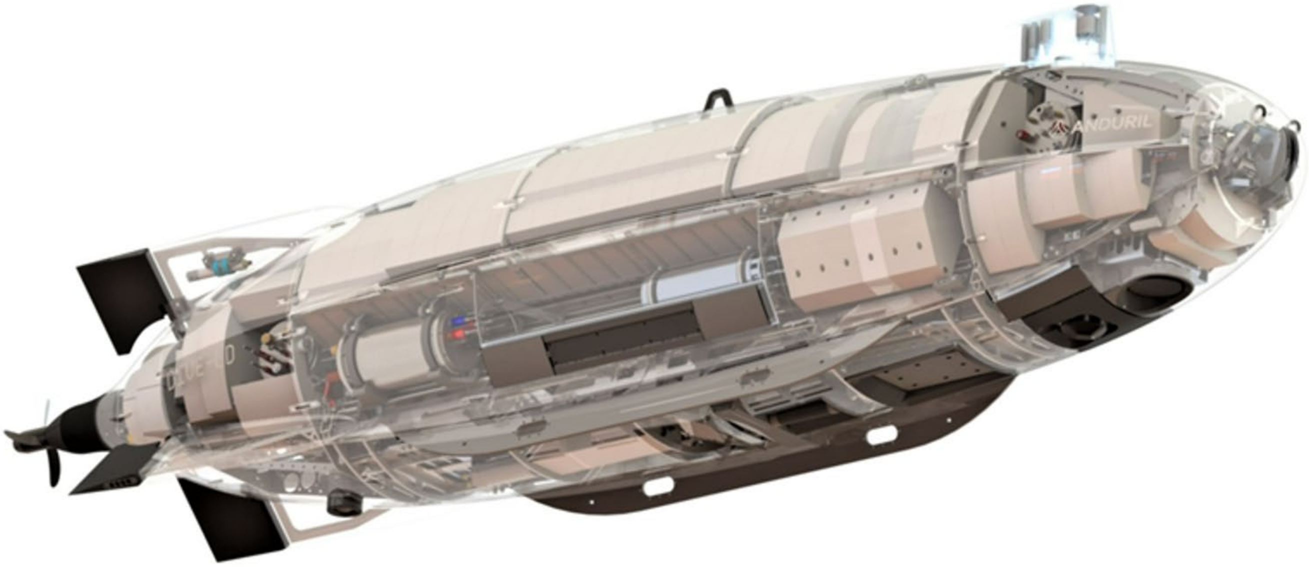


Figure 1. DIVE-LD Geophysical Survey Build

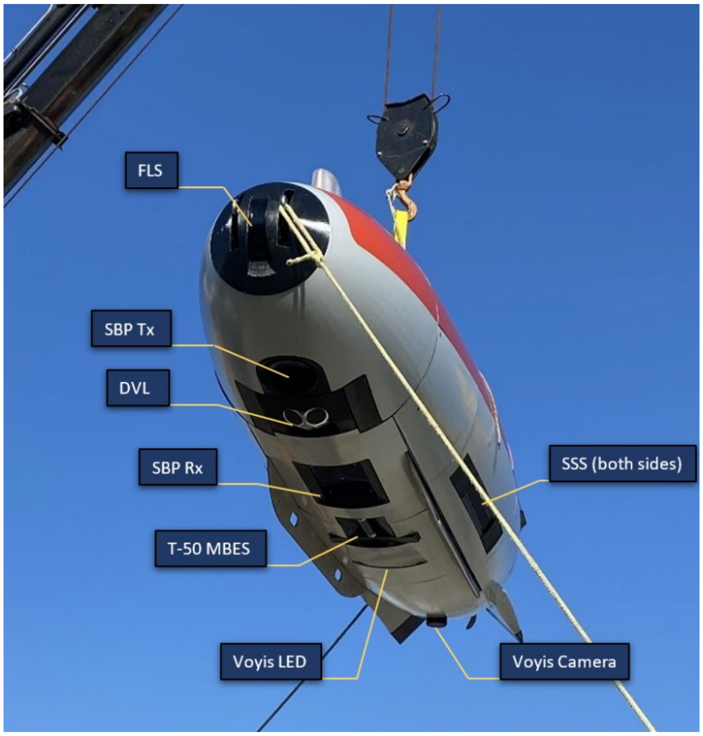


Figure 2.  DIVE-LD Geophysical Survey Sensors

This project was an important affirmation of the selection of the sensors and configurations of the final product. Initial concerns of payload interference and sufficient control were quieted through the thorough mechanical trialing, payload integration, and (most importantly) through in-situ testing results. Nevertheless, areas of improvement were identified. Mechanically, this included updating the material of the fairings (less interference with internal sensors), rearranging payloads to integrate two additional batteries (extended operational life with no impact on performance) and replacing the frame due to slowly failing old welds (frame lifetime was better defined). For performance, our operators were able to clearly identify what parameters resulted in the clearest data, and how to post-process results efficiently and accurately. In the future, engineers will develop an automated method to overlay results from different sensors from the same survey area to create a compelling, multi-faceted image (Figure 3) for our customers.

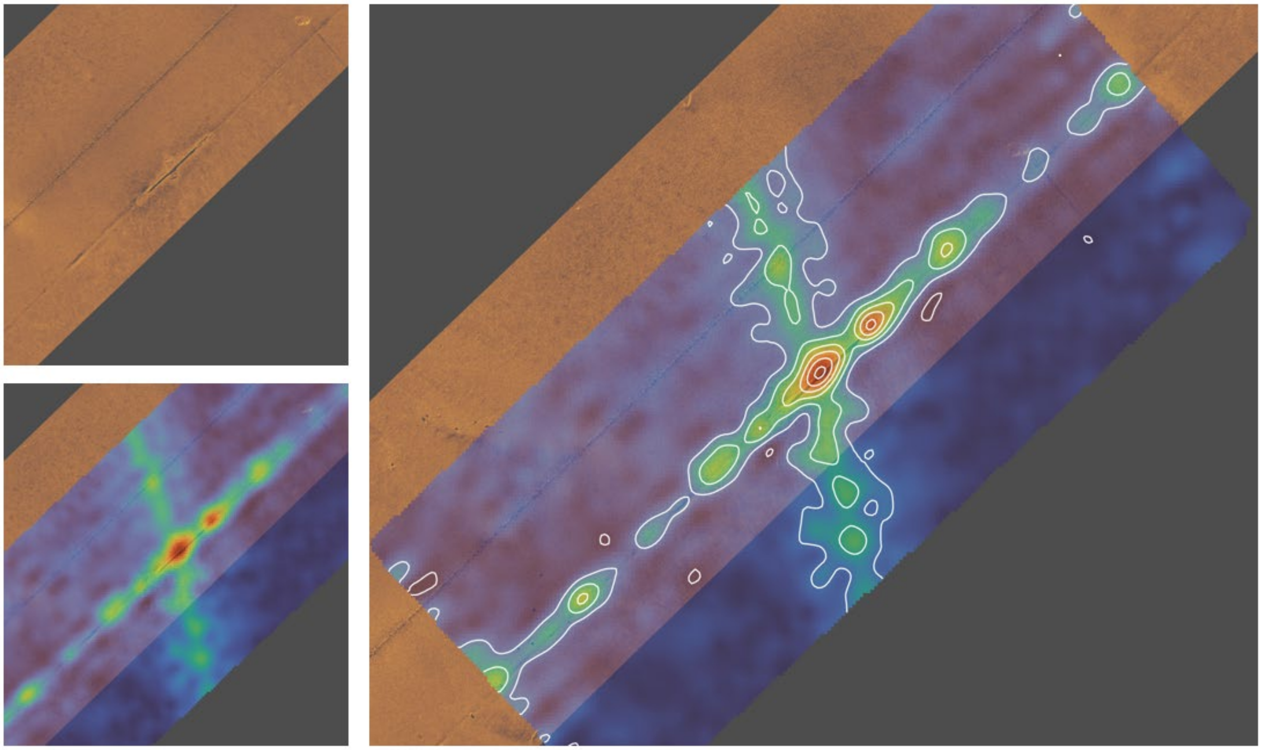


**Figure 3. Side Scan Sonar (Top Left), Magnetometer (Bottom Left), and Combined Image (Right) of Overlapping Cable**

# 2 Results

The objective of this project was to prove an AUV was capable executing an autonomous inspection launched from a pier, along with autonomous reinspection of key anomalies identified in its initial assessment. Ultimately, the Anduril team was successful in proving each facet of this concept over the course of the year while learning important lessons along the way (see Section 3 below). Pier launch was proven and safely managed with manual control (required in a high-traffic area), followed by a transition to fully autonomous transit and survey over the Point Judith to Block Island power cable. Autonomy was trained over months of data collection and trial, and ultimately proven successfully with both Anduril and third-party software, which was reported throughout the project for sponsor and advisory board oversight and reported confidentially for the sponsors in report *D3.2 - ANCC Checkout Report*. Reinspection was adjusted to be conducted with VHF Side Scan Sonar vice the Voyis camera, as the shallowness of the Rhode Island waters yielded significant turbidity, making any optical photos taken impossible to utilize.

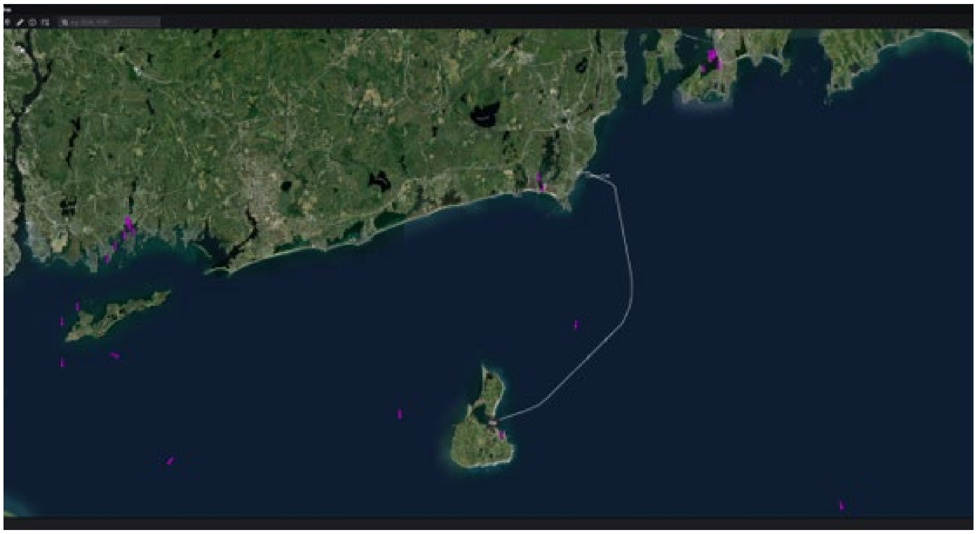


**Figure 4. Mission Control View of Test Area**

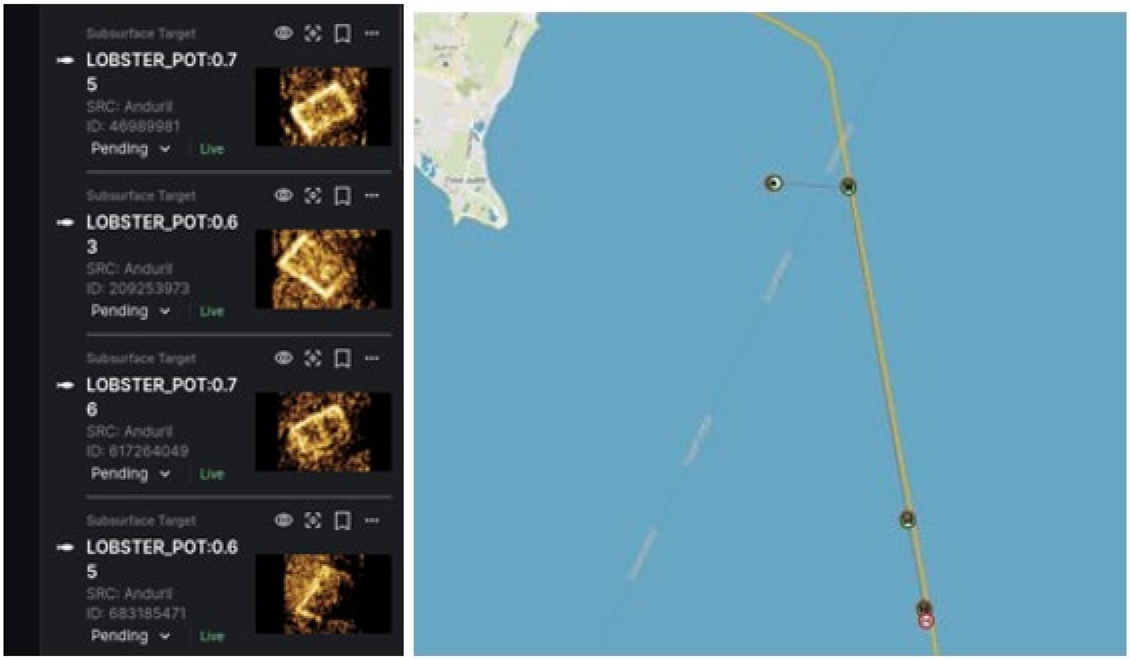


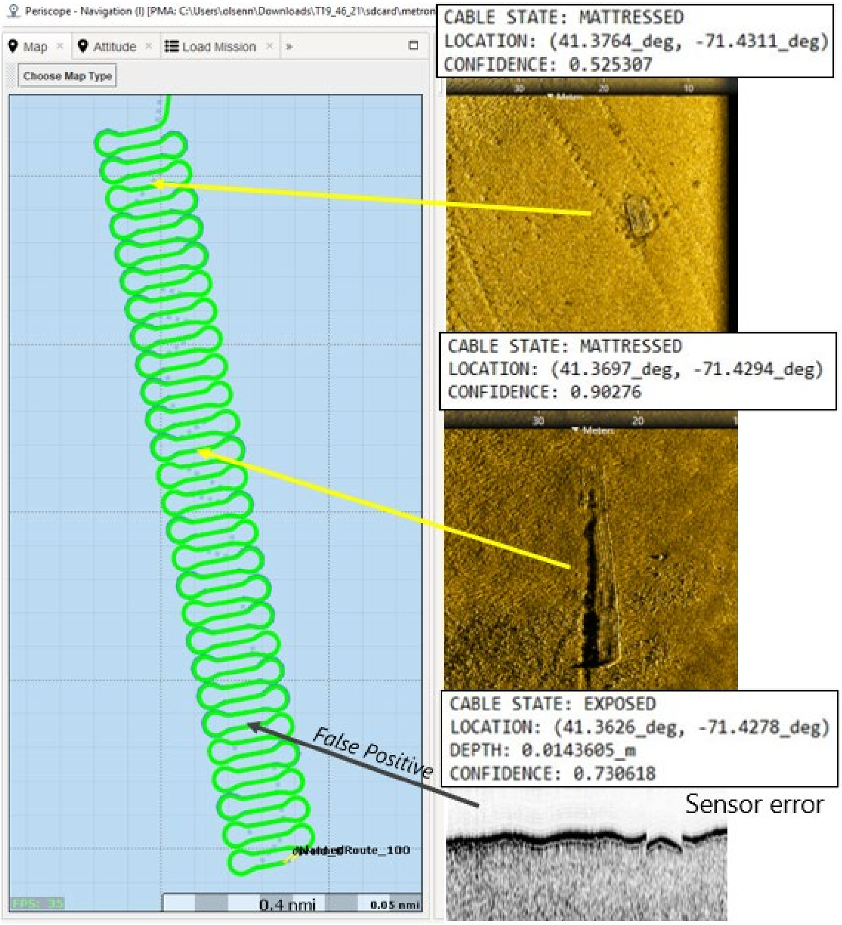
**Figure 5.Dive Spotter Anomalies Detected**

A mission was planned over known (and unknown) anomalies along the Point Judith to Block Island subsea cable. By design, the DIVE-LD should flag areas of concern in-situ, aggregate those areas of concern into a recommended reinspection path, and then conduct that reinspection. This was successfully executed with both SSS and SBP sensors and Anduril and Metron software respectively (Figure 5, Figure 6, Figure 7).

The potential benefits to the offshore wind industry estimated at the start of this project remain in place, but now have considerably more context for what is feasible, what elements remain difficult for even AUVs to overcome, and what development focus could address them. While the technology is capable of gathering accurate, usable data with impressive autonomy, the safe operational environment and communication avenues for the DIVE-LD are more limited. Sea state impacts the stability of the DIVE-LD on the surface and its ability to communicate via satellite with operators near or far. Navigational accuracy requires periodic surfacing (if a supporting surface asset is not present), and each instance of surfacing introduces operational risk. Furthermore, the ability to direct, change, or intervene with the DIVE-LD is constrained to nearby, line-of-sight communication methods. An operator must be within a narrow range of the vehicle to result in any course change – improving long-distance, over-the-horizon bi-directional communications will dramatically improve the operational benefits the DIVE-LD can bring to this application set. Improvements in stability, navigational accuracy (support options), and long-distance comms are the focus for the next year at Anduril based on the results of this project.

Figure 6. DIVE LD Reinspection Paths

Finally, the ability to execute this format of mission using third party autonomy, navigation, command, and control (ANCC) software is an important result. Figure 7 below shows an example of Metron ANCC software conducting a Sub Bottom Profiler (SBP) initial search and the anomalies it discovered along the way. The integration of this software was challenging, and both teams learned extended trial periods at sea were required to discover and ultimately resolve bugs present, errors which largely were caused by misalignment of code. However the end result  was an important milestone for Anduril Maritime and the flexibility of the solution it provides for end-customers in the offshore wind industry. For example, if a client has a software and data synthesis suite that it requires to be utilized, this software can easily be integrated into the DIVE-LD while maintaining Anduril's given mission control and hardware lineup. This provides market depth and a wider application of this technology both within the offshore wind industry and other commercial markets.



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DEPTH: 0.0143605_m
CONFIDENCE: 0.730618
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**Figure 7. SBP Anomalies Detected**

# 3 Lessons Learned

This project was a critical step in honing the sophistication and reliability of not only the DIVE-LD and her software (technical lessons learned), but also of the personnel supporting that operation on a day-to-day basis (operational lessons learned).

## 3.1 Technical

One of the most critical lessons our team learned was the importance of quality and complete bathymetry data. The expected seabed topography and depth changes are pre-loaded into mission plans for a set of tasks for the DIVE-LD to complete. These are updated and verified based on where the execution is to take place. If updated versions or accurate locations are not verified, the mission planner will have a false understanding of the anticipated changes to seabed topography, and as a result may direct an unsafe transit behavior. While the DIVE-LD has mechanisms to remove itself from dangerous situations (flying too close to the bottom, for example) these are intended as emergency backup procedures. The mission planner is expected to direct transit routes at safe depths given an existing setting. This is not possible, however, if you have an inaccurate or incomplete understanding of the planning environment!

This was learned the hard way during Test Event 2, when unverified bathymetry data led the mission planner to direct the return transit of the DIVE-LD to pier at a depth too close to the seafloor. A sudden change in depth from a small sea mount resulted in the DIVE-LD briefly skimming the sandy surface. While damage was wholly negligible, this remained an important sanity check – the date and completeness of bathymetry data is now a required verification step for each transit event.

Second, building a sophisticated software-based, autonomous decision structure within a 3m long AUV was an arduous process that introduced step changes in autonomous behaviors in parallel with important improvements in baseline software code. In the early months of the project, these updates were made as needed, with little documentation on what was changed, why, and what secondary impacts those changes may have on other aspects of the vehicle. As a result, if a problem arose it was extraordinarily difficult to discern the source of a behavior or code error. This resulted in agonizingly complex and time-intensive troubleshooting. A simple procedural fix (locking mission software prior to updating autonomy software) allowed improved clarity and much easier root cause identification when a software bug inevitably arose. The challenges that arose revealed a tangential lesson – as we rapidly integrate new features into the DIVE

LD, close attention must be paid to how these amass and impact its internal computer. Understanding where additional features tip from improvement to obstacle will be critical as this product matures.

Finally, the Anduril team learned the value of data quantity when building an autonomous decision tree. The data collected does not have to be perfect; in fact, having a range of resolution of the same object will improve the robot's ability to correctly identify those objects in varying environments (with varying clarity). The more reference points the robot has to fall back on, the more likely it will 1) find something anomalous and 2) accurately label it. At this stage in development, all data is helpful data!

## 3.2 Operational

Humbly, this was the first long-term commercial project executed by our operational team. As a result, significant process maturation was realized over the year that this project was executed. An important (albeit dry) component of that was standardizing internal documentation and reporting for routine operations at sea. This includes, but is not limited to: standardized underway checklists, pre-dive checklists and system verification, log structure and reporting requirements, standard operating procedures, post mission analysis, and internal data handover. While there remains room to grow, establishing these structures was a critical step for the maritime business to realize its ability to scale and responsibly execute follow-on work.

Furthermore, within the year of operation with NOWRDC, the Anduril team experienced their first high-tempo operational schedule over a fall and winter in New England. This setting proved extremely challenging for the extended at-sea operations needed to develop reliable vehicle behavior and collect data; this also required substantial improvement in forward-looking logistical planning and coordination. Weather windows were limited, and the team needed to be able to quickly take advantage of opportunities to work within them.

**Figure 8. Manual control of DIVE-LD from support vessel.**

This constraint forced the team to streamline decision making. First, operational safety limits were defined for work at sea. What wind or seas prevent the vehicle from communicating with operators? What sea state could result in loss of vehicle control? At what wind speed or wave height is it no longer possible for the support vessel to recover the DIVE-LD? Answering these questions helped define what qualified as a safe weather window. In parallel, program managers ensured personnel and material resources were available while the engineering team ensured a clear-cut test plan that maximized time on the water (and included contingencies). While slow at first, this ultimately developed into a very natural weekly cadence of weather look-ahead, test plan adaptation, and resource assignment that remains in place today.

# 4 Benefits & Next Steps

As stated in Section 2, the benefits assumed at the beginning of this project remain front of mind and entirely achievable. We have proven that geophysical surveys can be conducted autonomously and yield accurate information without any operator intervention and beginning with a launch from a pier, minimizing big-deck vessel requirements. The fewer vessels present in the overall development picture, the lower the environmental and safety risk profile. This includes minimizing spills, fuel burn, and interference with wildlife.

The lower vessel profile also significantly reduces operational costs and logistics, a lesson the Anduril team learned quite thoroughly over the past year. Day rates for vessels are expensive, and the supply grows thinner by the day offshore wind demand whittles away potential alternatives. Removing the support vessel from the picture saves those dollars for wiser use elsewhere, reduces operational risks, and dramatically simplifies the overall operational picture to a pier, a crane, and a handful of operators.

This gets even more exciting as one introduces extended endurance and more sophisticated communication technology to the picture. Currently, mission re-direction and troubleshooting can only occur when the vehicle is in line-of-sight. Operators can receive one-way communications from the DIVE-LD that give a basic update on location and status via Iridium satellites. The next pivotal milestone for Anduril and the DIVE-LD is developing two-way communications that are usable beyond the line of sight, with operators ashore and the vehicle >30km away. This significantly reduces risk and increases situational awareness as mission length extends. Empowering shore-based operators to get detailed status updates from the vehicle and re-direct to new missions (or instruct it to return to port for troubleshooting) will be another step-change in productivity and simplicity for this AUV.

Finally, the other development milestone the Anduril team and industry will focus on is real-time data quality processing. Currently, the DIVE-LD is capable of understanding when its sensors are operating correctly. However, it cannot tell if the data it collects meets a given set of quality standards; this can only be inferred once the vehicle is out of the water and data is uploaded and analyzed by a trained engineer.

In the near future, Anduril's focus is to develop and train software that can detect data quality and direct reinspection of poor-quality areas prior to returning to port. The autonomy and in-situ reinspection capabilities trained through this project are an important stepping stone to this capability. Ensuring that time spent collecting data always resulted in high-quality data would dramatically reduce costs and logistical hurdles for a given survey. The fewer times one has to send out a vehicle/vessel to inspect a site, the less money and risk is added to a picture. Having a quality verification built into the robot will ensure that number is kept to an absolute minimum, which in turn will compound the environmental and cost benefits described above.

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