OCS Study
BOEM 2023-063

Bureau of Ocean Energy Management Environmental Studies Program Shallow-water Geophysical Mapping by Autonomous Vehicle(s): Feasibility Assessment for ASV and AUV

Version: May 8, 2023

U.S. Department of the Interior
Bureau of Ocean Energy Management
Headquarters, Sterling, VA

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List of Abbreviations and Acronyms

Short Form	Long form
%	percent
ADCP	acoustic Doppler current profiler
AI	artificial intelligence
APTIM	Aptim Federal Services, LLC
ASV	autonomous surface vehicle
AUV	autonomous underwater vehicle
BA	Biological Assessment
BOEM	Bureau of Ocean Energy Management
CHIRP	compressed high intensity radiated pulse
CONOPs	Concept of Operations
CSA	CSA Ocean Sciences Inc.
DBM	DBM GEOSURVEY
DOI	Department of the Interior
DVL	Doppler Velocity Log
GNSS	global navigation satellite system
GPS	global positioning system
Hz	hertz
IHA	Incidental Harassment Authorization
IHO	International Hydrographic Organization
INS	inertial navigation system
kHz	kilohertz
Km	kilometer
LARS	Launch and Recovery System
LiDAR	Light Detection and Ranging
m	meters
MBES	multibeam echosounder
Mbps	Megabytes per second
MEC	munitions and explosives of concern
NARW	North Atlantic right whale
nm	nautical mile(s)
NMFS	National Marine Fisheries Service
OCS	Outer Continental Shelf
OFG	Ocean Floor Geophysics
ON&T	Ocean News and Technology
OTH	Over the Horizon
REMUS	Remote Environmental Monitoring Units
ROV	remotely operated vehicle
RTK	real-time kinematic

SB	single beam
SBES	single beam echosounder
SBP	sub-bottom profiler
SCM	Self-Compensating Magnetometer
SMA	seasonal management area
SME	subject matter expert
SSS	side scan sonar
SWAP	Shallow Water Autonomous Prospector
USBL	ultra-short baseline
USCG	United States Coast Guard
USV	unoccupied surface vehicle
THU	total horizontal uncertainty
TVU	total vertical uncertainty

1 Introduction and Objectives

Globally, shorelines are degrading due to an increase in the frequency and intensity of storms, combined with relative sea level rise, while the number and scale of anthropogenic interventions increase (Zhang et al. 2004; Syvitski and Kettner 2011). Sedimentological restoration via beach nourishment and/or habitat restoration has become a reliable mitigation strategy for coastal restoration and resilience building. The success of these restoration efforts depends on locating sufficient volumes of sediment that are suitable for placement on beaches and dunes, and for creating and/or nourishing wetland habitat. Locating potential borrow sites with suitable sediment resources that are extractable at acceptable costs is crucial to the success of restoration goals.

Exploration for offshore sediment can be complex and requires an understanding of geologic processes as well as the use of highly sophisticated acoustic remote sensing geophysical instruments (e.g., side scan sonar, high-resolution seismic reflection profiling, high-resolution multibeam bathymetric survey, etc.) Magnetic anomaly detection using a magnetometer is not used for resources assessment but for detecting infrastructure–like offshore pipelines–and debris, which can limit resource access and thus critical in sediment resource evaluation. In a comprehensive marine sand search, the investigation is typically divided into three sequential phases (e.g., Finkl, Andrews, et al. 2003).

Phase I investigations typically consist of a comprehensive review of the recipient beach and/or project area and previously identified sediment resources offshore of the project area. This desktop study examines previously collected information within the geologic context of the investigation area to identify features having the highest potential of containing project-compatible sand. The results of Phase I are used to define the areas that will be surveyed during Phase II (reconnaissance-level) and Phase III (design-level) investigations. One part of these investigations consists of high-resolution geophysical surveys for marine mineral exploration. This entails collecting data through using a full suite of geophysical instruments (sub-bottom acoustic profiler, side scan sonar, magnetometer, fathometer, and high precision positioning equipment such as global positioning systems and ultra-short baseline (GPS and USBL) systems to assess the general morphology and character of the area.

To determine near surface features, identify key sub-bottom markers, and locate potential project compatible sediment resources in the underlying strata, a high-resolution seismic reflection profile is collected by using a high frequency sub-bottom acoustic profiler. These instruments can operate over a full spectrum of linear frequencies, often in the range of 0.5 to 12 kilohertz (kHz) at a ping rate of 6 to 8 hertz (Hz) during the collection process. The profiler transmits a frequency-modulated pulse that is swept over a full spectrum frequency range and reflects off the varying strata back to the sub-bottom profiler receiver. Along with these traditional Compressed High Intensity Radiated Pulse (CHIRP) sub bottom profiler systems, higher frequency parametric systems are being introduced for sand source and/or marine mining exploration missions. Parametric systems operate at frequencies of 100 kHz with secondary low frequencies ranging from 4 to 15 kHz offering high resolution data of the seafloor and subsurface stratigraphy. To maintain optimal resolution, the tow-fish should be towed no greater than 5 knots and at a depth and location such that any interference or noise from the vessel, sea surface conditions, or the other geophysical instruments is limited while also maximizing acoustic reflection of the seismic pulse. Horizontal accuracy of the towfish can be achieved by using an automated positioning systems to correct for the layback position of the towfish. Acceptable quality data from the profiler can be achieved by maintaining proper speed and altitude, allowing for the instrument to resolve features of interest up to 50 feet (ft) below the seabed and provide high resolution, clear imagery of the subsurface that captures features of interest important to the project goals.

The side scan sonar delivers photo-like images that highlight regions of greater acoustic reflectivity and absorption as well as shadows from objects of bathymetric highs and lows, allowing for identification of hardbottom, sea grass beds, sand dunes, and other habitat and items of historical significance or debris. The side scan sonar is a towed dual channel, dual frequency, sonar system that typically operates in various frequency combinations between 300 and 1,600 kHz to provide continuous planimetric coverage. This equipment often delivers wide band, high energy pulses paired with high resolution and excellent signal to noise ratio using full spectrum CHIRP technology. Acceptable quality data, as defined by Department of Interior (US DOI) standards, for the side scan sonar requires that the tow altitude remains within 10–20 percent (%) of the total range of the instrument and that it can detect a 1 × 1 × 1 meter (m) object on the seafloor with a 95% confidence radius. The key objective of this instrument is to collect high resolution, artifact free seafloor imagery with 100% swath coverage to allow for the identification of benthic habitats, archeological resources, hardbottom, or other areas of interest. Ideal data will produce georeferenced swaths with mosaics at 0.5-m resolution. The side scan sonar is interfaced with a GPS and positioning data from onboard navigation that verifies positioning throughout the survey. The horizontal positioning of the side scan sonar equipment is often layback corrected using the automated hydrographic positioning systems.

The goal of the marine magnetometer is to aid in understanding the survey areas magnetic field, establish exclusion zones, and locate any anomalous objects of interest. The magnetometer runs 110 volts alternating current and can identify buried objects with ferrous (iron) composition, cables, and pipelines and is required for offshore dredging projects that could impact any cultural resources such as shipwreck debris. To achieve key performance objectives and deliver a clean, accurate representation of the magnetic field and any anomalies within the survey, magnetometers should be towed less than 6 m (19.7 feet) above the seafloor, sensitivity should be set to 1 gamma or less, the sampling rate should be greater than 4.0 Hz to deliver sufficient point density, and background noise should not exceed 3 gamma from peak to peak. This will limit any interference from the vessel or other instruments that could impact the quality of the data. To remain within the altitude guidelines, an altimeter or a depth sensor should be attached to and interfaced with the magnetometer.

Configuring marine magnetometers to autonomous underwater vehicles (AUVs) and/or autonomous surface vehicles (ASVs) can be done in a variety of ways. Modular units are necessary for integration with AUVs due to the limited space. A concern with integrating marine magnetometers with AUVs is the effect of the vehicles magnetic signature being in close proximity to the sensor which could affect data during acquisition and post-processing. Units such as the Ocean Floor Geophysics Self-Compensating Magnetometer (SCM) are programmed with a data filter to remove the magnetic signatures from the AUV and its components. Configuration with ASVs is like that of traditional vessels; these units are towed at a defined distance, based on water depth and sensor height off seabed. Operating the sensor behind and below the ASV eliminates any magnetics effects from the acquired data. Positioning of the magnetometer can be accomplished using a calculated layback. For precise positioning of the towed magnetometer, USBLs and a transponder beacon can be used for acoustical positioning.

The goal of the hydrographic data acquisition is to establish bathymetric conditions of the study area using a single beam or multibeam echosounder. This process is performed to map the seafloor topography and identify prominent bathymetric highs and lows within potential borrow areas and to aid in engineering design of borrow areas. The multibeam echosounder often operates at or near a 400 kHz frequency, providing a sounding footprint of around 0.5° × 1.0°. Water depth and bottom conditions will vary affecting the pulse length and ping rate, but they will be sufficient to accurately bottom track and provide full swath coverage across the survey lines. To ensure quality data, a patch test and a beam angle test should be performed to account for misalignments with the reference frame of the vessel and to confirm data integrity and maximum range across the swath. The single beam echosounder often operates at or near a frequency of 200 kHz and can provide 1 cm (0.39 inches [in]) resolution along with 2 cm

(0.79 in) ± 0.1% of depth accuracy. To maintain data quality, a bar check is often performed that verifies transducer measurements and sound velocity corrections. The key objective of the hydrographic instruments is to deliver accurate bathymetric conditions of the survey area that will assist in the characterization of Outer Continental Shelf (OCS) marine minerals.

Interferometric multi-beam and side scan sonar systems are often used on AUVs and ASVs due to their ability of achieving wider swaths in shallow water. These systems, like traditional beam-forming multi-beam and side scan sonar systems, must undergo similar calibration measures prior to data acquisition to ensure data quality. Most systems can collect data that meet or exceed specifications set forth by the International Hydrographic Organization (IHO) and deliver products like that of traditional multi-beam and side scan sonar systems, including seafloor backscatter data.

Over recent years, technological and market advancements have led to AUVs and ASVs being used to conduct deep-water mapping and seabed characterization surveys. Typically, AUVs and ASVs are launched from a vessel or shore and execute a preprogrammed survey pattern (Campbell et al. 2015). Once the survey is complete, they are recovered, and the survey data are downloaded for analysis. Data on water depth, geomorphology, stratigraphy, and structure are collected using a variety of sensing technologies including multibeam echo sounder to provide water column, bathymetric, and seafloor-reflectivity data. Other AUV/ASV survey tools can include still cameras, magnetometers, geochemical sensors, and temperature and salinity sensors (Campbell et al. 2015).

The objective of this Assessment is to provide a market and feasibility assessment, technology overview, and outline of field techniques for using AUVs or ASVs for Phase II and Phase III reconnaissance marine mineral geophysical surveys. The state of these systems is assessed relative to traditional vessel-based, towed-system investigations currently being used and described above. Specifically, this will discuss the feasibility of using various AUV and/or ASV platforms with multiple geophysical sensors to acquire geophysical data, and related analytical and geospatial services, in shallow-water environments (10 to 30 m [33 to 98 ft] water depth) for seafloor morphology, shallow geologic framework, and benthic habitat mapping in support of the delineation and characterization of offshore marine minerals for use in shore protection projects. This information will allow the US Department of the Interior's Bureau of Ocean Energy Management (BOEM) to evaluate the advantages and disadvantages (including cost and productivity trade-offs) of shallow-water geophysical mapping from single or multiple AUV and/or ASV deployment. Specific objectives include:

- A thorough market assessment to address the feasibility of single and multiple AUV and/or ASV geophysical mapping in the shallow-water environment and evaluate trade-offs with existing vessel-based methods.
- An overview of current technology availability, capabilities, and proper applications for shallow water geophysical surveys.
- Identification of parameters based on market research and technology that need to be addressed in a field acquisition plan and develop a sample field acquisition plan.
- Compare AUV and/or ASV instrument performance with traditional vessel-based instrument performance.

Advanced AUVs can be outfitted with various electromechanical and other geophysical sensor payloads (e.g., high-frequency CHIRP sonar, multibeam sonar, side scan (traditional and synthetic aperture) sonar, experimental magnetometer; high-definition video) critical to seafloor mapping applications (Wynn et al. 2014). AUVs have been deployed for the study of geologic framework (less than 100 to 200 m [328 to 656 ft] sub-seafloor), seafloor morphology and morphodynamics, benthic habitats, shipwrecks, and seafloor hazards, including unexploded ordnance and pipelines (Smale et al. 2012; Campbell et al. 2015; Trembanis et al. 2021).

AUV use in deep-water, beneath ice, and other extreme environments is routine and considered optimal since vehicles fly at a low altitude over the seabed and collect data at improved resolution. However, use in shallow-water environments is more challenging because of dynamic conditions, such as vehicle draft, endurance (i.e., payload vs. power requirements), and navigation in the presence of surface waves and strong coastal currents, variable ensonification swath in varying water depths, and risk of collision and entanglement. Crucial to the utility and success of these systems is also the ability to provide near real-time data recovery, data processing, and data quality control and management.

In comparison, today's ASVs are becoming larger, more stable and possess the ability to go further for longer periods while using power hungry geophysical sensors for data collection. These advantages make them quite effective for nearshore sand source applications. ASVs also have an advantage in the marine autonomy field.

With the automotive and transportation industry being consumed with pushing the boundaries of technology to make terrestrial vehicles not only safe for passengers riding in them but for bystanders utilizing the same roadways. Light Detection and Ranging (LiDAR) sensors, machine vision technology for Advanced Drive Assistance Systems, and high-speed connectivity to vehicle platforms are rapidly developing and allowing ASV manufacturers to incorporate similar, if not the same technology into their platforms.

New advances in on-board, artificial intelligence have the potential to improve the range, reliability, and flexibility of AUVs or ASVs for shallow-water applications. That is especially true if multiple AUVs and/or ASVs can be deployed in concert on pre-programmed courses and potentially recovered every 24 hours of deployment in the case of high-endurance vehicles. Promising technology is also coming online for high-bandwidth transmission of data directly from AUVs and/or ASVs to mothership (common term for the primary vessel), and from mothership to shore-based facilities, or from AUVs and/or ASVs direct to cloud infrastructure; that allows for near real-time data review and survey optimization.

2 Existing Data Synthesis and Review of OCS Minerals, Minerals Use, and Associated Physical, Environmental, and Archeological Data

2.1 Existing Information Review

2.1.1 Methods

The APTIM Team conducted a review of the relevant literature including peer-reviewed publications, gray literature, trade journals, and freely available processed data that are relevant to the BOEM scenario for characterization of seafloor morphology, geologic framework, and benthic habitats using ASV, AUV, and conventional vessel platforms.

The APTIM Team used its Library Services capacity for this review under the direction of CSA Ocean Sciences Inc.'s (CSA's) Director of Library Services. The multi-faceted process briefly described below quickly resulted in a comprehensive listing of relevant documents, the basis for development of a database necessary for a review of technology, and a comparative analysis. First, identification of relevant source material was based on a search of numerous bibliographic and library sources. An extensive search for all relevant scientific and technical information was conducted using four major sources, described below:

- Proquest Dialog (https://dialog.proquest.com/professional/commandline)
- OCLC WorldCat (http://www.oclc.org/us/en/worldcat/default.htm)
- Internet search engines to locate relevant websites such as conference proceedings and archives (e.g., https://www.google.com, https://www.bing.com, https://search.yahoo.com)
- Digital Repositories, including industry-related sites and web-wide open term searches

Databases that were searched include those listed below, including the respective timeframes for their holdings and in consideration of any time limits (e.g., given the non-linear evolution of platform and sensor technology, recent entries [last five years] were targeted; however, entries expanded beyond five years due to limited numbers of published information). Importantly, to help capture up to date ASV and AUV technology, this database also includes industry magazine content and underwater engineering information from many databases. The search scope was constrained to focus on relevant sources that included:

- Marine engineering, naval architecture, ocean, and underwater technology
- Abstracts in new technology and engineering
- Mechanical and transportation engineering abstracts
- Petroleum exploration geology, geophysics, and geochemistry

Finally, in concert with the Team's Subject Matter Experts' (SMEs) broad industry and academic network both developing and using ASV and/or AUV technology, Internet search engines were used to find relevant websites and the digital document repositories, which served as excellent sources of gray literature and conference papers, including web-wide key word searches, and maintained sites. While appearing less sophisticated than Proquest Dialog and OCLC WorldCat that were used in the search process, this approach was highly productive, especially with the leadership of CSA's Director of Library Services in communication with the SMEs.

Following review, all selected and remaining citations were entered into Clarivate EndNote® bibliographic management software. Any required missing information will be determined and entered; Adobe® Portable Document Format (PDF) references will be attached to the citations during this step. A bibliography can be exported from bibliographic software to create a Microsoft® Word document.

However, because much of the recent, relevant information may not have found its way into journals, gray literature, and conferences, there was substantive reliance on the SME associated with this task, who has decades of experience in the technology of marine operations on and under the ocean surface to help locate relevant information. Their active knowledge of the available technology, the vendors, and the units they provide along with the sensor packages that can be used will provide BOEM with the critical current industry knowledge needed to find and interpret the information review. Additionally, the APTIM Team used its unique working knowledge of the trade and collaborated with Technology Systems Corporation (TSC), who publishes Ocean News and Technology (ON&T), a long-standing industry magazine that provides a nexus with emerging ocean technologies, to identify and catalog emerging AUV and ASV capacities (e.g., https://www.oceannews.com/featured-stories/the-advent-of-commercial-asvs). In the last two years, ON&T has featured over 30 articles on AUVs and 50 on ASVs.

2.1.2 Findings

The APTIM Team reviewed and synthesized existing data, information, and/or studies regarding the use of AUV and/or ASV for collecting shallow-water geophysical data related to BOEM's focus on geophysical data related to seafloor morphology, shallow geologic framework, and benthic habitats. This included literature reviews, recovery and digitization of archival data, and data compilation. As a result of this effort, the APTIM Team identified 24 pieces of literature that reference autonomous operations relating to sand source/mineral surveying. Dohner et al. (2020) is a recent article published in a peer-reviewed journal that validates the use of combined AUV and/or ASV technologies for mapping shallow, turbid coastal waters. Numerous additional references validate the use of ASVs in shallow water mapping (e.g., Bergeron et al. 2007, Stanghellini et al. 2020, Wynn et al. 2014). AUVs have been a viable tool for seafloor surveys for decades, as described in Bingham et al. 2002, Campbell et al. 2015, and Pierdomenico et al. 2015. AUVs used for effective sub-bottom surveys are described in Campbell et al. 2013 and George and Cauquil 2007. Raineault et al. 2012 describes how acoustics can deliver shallow water mapping. Ziegwied 2017 describes how combined ASVs and AUVs can improve surveys.

These articles and publications, including others reviewed, are provided in the list below with brief summaries.

- **ON&T 2022.** The acceptance of ASV technology has resulted in the identification of new applications for their use. Companies are recognizing the long-term potential for the ASV market and are preparing for long-term involvement with the systems. In the last three years, ASVs have acquired momentum that is putting them on a path to becoming a major ocean technology market. By the end of 2025, ASVs will be commonly used for ocean data collection. This Market Summary and Forecast provides a list of ASVs and their manufacturers that was used to inform our search for this report.
- **Trembanis et al. 2021.** The coastal environment is one of the most dynamic environments on Earth. Coastal mapping and monitoring are therefore most important for research and understanding of coastal systems worldwide document and understanding changes to the coastal system are increasingly motivated by the proximity and density of coastal infrastructure and the exposure of people and property to loss and damage. The state of the science of coastal mapping and monitoring has developed rapidly over the last several decades due to advances in both geophysical remote sensing and most recently with the development and growing maturity of

autonomous surveying platforms. This chapter introduces and reviews a variety of sensors and platforms that are now commonly utilized in the field of coastal mapping and monitoring.

- **Dohner et al. 2020.** The shallow, turbid water of the Delaware Bay Estuary is the second most navigated waterway in the U.S. after the Mississippi River and experiences tropical and extratropical cyclones from June through April bringing high winds, storm surges, precipitation, and coastal change. Mapping coastal areas within the Delaware Bay is particularly difficult due to inherent environmental factors such as low underwater visibility (less than 1 m [3.3 feet]), rapid tidal current (greater than 1 m/s [3.3 feet/s]), changeable weather, and strong mid-latitude winds. This study used four sonar systems, two occupied vessels, two autonomous vessels, three real time kinematic GPS (RTK GPS), two unoccupied autonomous aerial systems, and satellite imagery to quantify subaerial and subaqueous volume and feature changes following storm events.
- **Stanghellini et al. 2020.** Although Shallow Water Autonomous Prospector (SWAP) vehicles can host different types of sensors, these vehicles were specifically designed for geophysical surveys, (i.e., for the acquisition of bathymetric and stratigraphic data through single and multibeam echosounders [MBES], side scan sonars [SSS], and seismic-reflection systems). The development of the OpenSWAP vehicles was focused from the very beginning considering implementation of two embedded geophysical sensors: (1) a single beam echosounder (SBES), to perform bathymetric (repeated) surveys, and (2) a chirped sub-bottom profiler (SBP), allowing for the acquisition of high-resolution stratigraphic data.
- **Verumar Philippines 2020.** Autonomous marine systems, ASVs and AUVs, bring increased health and safety, reduce human error risks in operations and in principle should become more cost-effective as uptake of technology increases and new supplier options enter the sector. This white paper provides an overview of the application for fisheries management, including platform, launch/recovery, sensors, equipment, and data.
- **Carton et al. 2019.** Munitions and explosives of concern (MEC) in U.S. waters can present a risk to the development and operation of offshore wind energy resources. Therefore, BOEM requires offshore wind energy developers to evaluate the risk MEC poses to the development, operation, and maintenance of offshore wind energy generation and transmission systems. This article describes an MEC risk management framework consisting of the following steps: (1) MEC hazard assessment, (2) MEC risk assessment, (3) MEC risk validation, and (4) MEC risk mitigation. The MEC hazard assessment involves historical research to identify MEC potentially present in the development area. The MEC risk assessment evaluates the development activities and provides a relative MEC risk ranking for those activities. The developer determines the acceptability of these risks, and any potentially unacceptable MEC risks undergo risk validation through field surveys. The developer then considers the tolerability of the validated risks and develops and implements an appropriate MEC risk mitigation strategy based on actual site conditions. A risk framework provides a structured method to plan and operationalize the identification, evaluation, and mitigation of MEC risk throughout the development, operation, and maintenance life cycle of an offshore wind energy generation and transmission project.
- **NOAA 2019.** Overview of various autonomous systems (AUV and ASV) including key lessons learned in 2019.
- **Offshore Energy 2017.** The survey route included various water depths and strong currents, while facing difficult wind and sea conditions in the Bering Sea offshore Alaska. The project was mobilized immediately following a 9,000 km (4,860 nm) nautical charting survey by Terrasond, of which 4,750 km (2,565 nm) (53%) was executed by a Global C Worker 5 ASV. The cable route survey required a new payload including a hull mounted multibeam sonar, a SBP, and a towed SSS with 250 m (820 feet) of armored sonar cable. The payload swap on the ASV was integrated, calibrated, and demonstrated in the field in less than 48 hours. A total of 1,220 km

(659 nm) of cable route survey lines were then successfully executed by the ASV C-Worker 5 system.

- **Ziegwied 2017.** This paper reviews the Autonomous Surface/Sub-surface Survey System (ASSSS) research program's vehicle (ASV and AUV systems) architecture, positioning, navigation, communication, and endurance.
- **Pierdomenico et al. 2015.** Mapping of physical benthic habitats at the head of Hudson Canyon was performed by means of integrated analysis of acoustic data, video surveys and seafloor sampling. Acoustic mapping, performed using AUV-mounted multibeam sonar, provided ultra-high resolution bathymetric and backscatter imagery for the identification of geomorphological features and the characterization of surficial sediments. A Kongsberg EM2000 (200 kHz) multibeam sonar, mounted on a NIUST "Eagle Ray" AUV was used for this operation.
- **Wynn et al. 2014.** AUVs have a wide range of applications in marine geoscience and are increasingly being used in the scientific, military, commercial, and policy sectors. This paper reviews applications in marine geoscience, particularly in deep water environments and provides a review of future AUV applications including new drivers for their use, new vehicles, sensors, and approaches.
- **Campbell et al. 2013.** This paper describes the acquisition, processing, and application of deep water sub-bottom profiler data acquired using an AUV survey vehicle and processed as a micro-3D seismic data volume (AUV3Dm data). AUV3Dm data precisely defines foundation zone conditions in 3-D space without gaps. The AUV3Dm methodology consists of doing a very detailed 3D seismic survey (4-m [13-feet] line spacing) over a very small area (i.e., approximately 390 m × 500 m [1,280 feet × 1,640 ft]) using a high-frequency seismic (SBP) source (typically 2 kHz to 12 kHz). The AUV used for the survey was a Kongsberg Hugin 3000. MBES, SSS, and SBP were used.
- **Raineault et al. 2012.** Accurate benthic habitat maps are critical for resource management in coastal waters with competing uses. A 900 kHz Marine Sonics Ltd. SSS and 500 kHz Geoswath (Kongsberg) phase-measuring bathymetric sonar (PMBS) were mounted on a Teledyne Gavia AUV.
- **Wynn et al. 2012.** This report investigates the potential benefits of increased use of propeller driven AUVs and buoyancy-driven Gliders for mapping and monitoring of United Kingdom (UK) waters, with specific reference to the developing Marine Protected Area (MPA) network.
- **Yoerger et al. 2007.** This paper reports the development and at-sea deployment of a set of algorithms that have enabled an AUV to conduct near-bottom surveys in the deep sea. Algorithms for long baseline acoustic positioning, terrain-following, and automated nested surveys are reported.
- **Nicholson and Ricketts 2008.** BM GEOSURVEY is the marine survey arm of De Beers Marine, the world's largest marine precious mineral mining company. DBM GEOSURVEY (DBM) has pioneered the development of geophysical survey systems over the past 20 years to improve mineral resource development and support DBM's mining activities. The Maridan 600 AUV was used starting in 2000. This article reviews the development of methods and systems for surveying the seafloor for offshore diamond mining and exploration.
- **Bergeron et al. 2007.** This article describes a case study where recent advances in seafloor mapping tools have permitted detailed mapping over large areas in water depths of less than one meter using a U.S. Geological Survey (USGS) 7.6 m (25 feet) ASV.
- **George and Cauquil 2007.** The efficiency and navigation accuracy at which SBP data (2 to 8 kHz) can be acquired with deep-water AUVs allow for the acquisition and creation of a high resolution (4-m [13 feet] bins) seismic cube. Kongsberg Hugin 3000 using an EdgeTech 2 to 16 kHz CHIRP SBP.
- **Moline et al. 2007.** To better characterize and improve our understanding of coastal waters, there has been an increasing emphasis on autonomous systems that can sample the ocean on relevant

scales. AUVs with active propulsion are especially well suited for studies of the coastal ocean because they can provide systematic and near-synoptic spatial observations. With this capability, science users are beginning to integrate sensor suits for a broad range of specific and often novel applications. Here, the mature Remote Environmental Monitoring Units (REMUS) AUV system is configured with multi-spectral radiometers to delineate benthic habitat in Sequim Bay, WA.

- **McPhail 2002.** This paper examines the advantages and disadvantages of the use of AUVs as platforms for Ocean Margin surveys, compared to conventional towed instruments, drawing on examples of AUVs currently being used throughout the world. It illustrates the development and use of a scientific AUV, Autosub, during the past four years. How has it developed to overcome technological problems, such as launch and recovery, and achieving greater depth and range, and how have the engineers coped with the integration of many different types of sensors. It discusses some reasons why AUVs are not more generally used for ocean surveys.
- **Bingham et al. 2002.** BP has been contracting commercial services using a survey class AUV to collect SSS, swath bathymetry and SBP data at proposed oilfield development locations in the U.S. Gulf of Mexico and the UK sector of the North Sea. In the deep-water Gulf of Mexico, the surveys were conducted at proposed field facilities locations and along proposed pipeline routes in water depths ranging from 500 to 2,300 m (1,640 to 7,546 feet). In the North Sea surveys were conducted on the continental shelf in water depths between 80 and 120 m (263 and 394 feet). This paper reviews the expectations of AUV technology before these surveys, contrasts the expectations with actual experiences during the surveys, and indicates desired directions for future AUV technology development. The review of AUV capabilities confirmed the potential of the technology in two areas: as a replacement for conventional ship-born hydrographic survey tasks and as a replacement for conventional tethered ROV tasks. Two significant limiting factors were identified: limitations in battery power restricted either endurance or the sensors that the vehicle could carry. Second, vehicle navigation and control. While all the navigation components, in particular inertial systems, were available and all the sensors were in existence, they had not been integrated into a commercial autonomous vehicle before. But with existing technology, the concept of a “survey-class” AUV seemed feasible. As a result, an outline specification of requirements was drafted and promulgated within the industry. Kongsberg Hugin 3000 AUV and Maridan 600 AUV were used in the study.
- **Wernli 2000.** This paper reviews the markets for commercial, military, and scientific uses of AUVs and specifically describes projects and various vehicles employed.

It is important to note, for the purpose of this study, little, to date, has been published regarding performing sand source surveys with autonomy. Though broader literature exists in the realm of deep-water seafloor, cable and pipeline route surveys, there is a peer-reviewed gap around sand search activities specifically. There would be room for a funded research and development program explicitly to close the knowledge gap pertaining to this type of work.

2.2 Existing Technology Review

2.2.1 Methods

The APTIM Team created a Microsoft® Excel spreadsheet (i.e., the Asset Database; Appendix A) that facilitated the comparative analysis of the many platforms and sensors to understand their strengths, limitations, and costs. The APTIM Team organized the information into the database to capture the key characteristics of ASVs and AUVs. Key characteristics entered the database included but were not limited to size, payload capacity, power requirements, data storage capacity, speed, duration, portability, available coms (e.g., acoustic modem, RF, cell, satellite), manufacturer, International Traffic in Arms Regulation (ITAR/Commerce Controlled status, foreign or U.S. sourced, availability, cost, service support, and overall quality. SME qualitative assessments as well as other attributes as defined by the Team in consultation with BOEM, including those for vessel system comparisons, were also included in the database.

The attribute list of the vehicles was developed in consultation with the SME of the overall team. The data structure allowed comparisons not only within vehicle class but among vehicles, to inform later choice of vehicle for task and scenario.

The selection of initial vessel platforms for comparison was limited due to available resources. The SME, in consultation with BOEM, evaluated the vessel platform capabilities relevant to sand source surveys. Based on the APTIM Team's current knowledge of the industry, there are more ASV than AUV models. The AUV and ASV selection results are presented below in Table 2-1. Appendix B provides more details and specifications on the selected AUVs and ASVs and was generated from the Asset Database (Appendix A). Various equipment associated with the ASVs and AUVs were also analyzed and are listed in Table 2-2. Appendix C was also generated from the Asset Database (Appendix A) and details specifications for the equipment.

2.2.2 Findings

This section provides a discussion on the assessment and key characteristics of the seven ASVs and the three AUVs selected by the APTIM Team (Table 2-1) and provides a discussion of various pieces of associated equipment that were reviewed in the analysis (Table 2-2).

For cost comparison purposes, the APTIM Team developed a relative cost scale for the various AUV and ASV platforms denoted by $, $$ and $$$ symbols. These symbols mean the following:

$ = >$250,000 to <$500,000

$$ = >$500,000 to <$1,000,000

$$$ = >$1,000,000

These costs are relative and represent general cost assumptions at the time of publication. The costs of these platforms can vary significantly and are subject to market fluctuations.

Table 2-1. List of ASVs andAUVs Analyzed in this Feasibility, Field Techniques, and Best Practices Analysis

Manufacturer ASVs	Model ASVs
iXblue	DriX
L3Harris	C-Worker 4
Seafloor Systems	Hydro-Cat 180
SeaRobotics	5.7 m
Marine Advanced Robotics Inc.	WAM-V 8
XOCEAN	XO-450
Maritime Robotics	Mariner

Manufacturer AUVs	Model AUVs
Teledyne	Gavia
L3Harris	Iver4
Hydroid	REMUS-300
Manufacturer AUVs	Model AUVs

2.2.2.1 Autonomous Surface Vehicles

2.2.2.1.1 iXblue DriX

The DriX is a novel ASV that places much of the vehicle below water. It is optimized for hydrographic survey and provides a novel submerged tow-body and launch and recovery system. It is less modular, requiring careful specification upfront. A larger and more expensive ASV, the DriX is aimed at the commercial offshore energy market. This ASV can operate in open ocean conditions over extended periods of time.

Cost: $$$

Advantages: Open water performance, tow body for payload versatility, significant field experiences.

Considerations: Cost, configurability, launch and recovery, payload constraints.

2.2.2.1.2 L3Harris C-Worker 4

The C-Worker 4 is a conventional design offering the benefit of significant field experience across the C-Worker family. This ASV offers reasonable modularity and good open water performance. It provides a balance between coastal and open ocean capabilities. This ASV can engage extended operations in the near to mid-shore region.

Cost: $$

Advantages: Affordable, flexible, capable of use in near-shore conditions.

Considerations: Sea state limitations, launch and recovery.

2.2.2.1.3 Seafloor Systems Hydro-Cat 180

The Hydro-Cat 180 is a classic catamaran design optimized for stability in survey applications. It is robust and modular. As with most catamaran designs it performs well until conditions overcome its passive stability. This ASV is well-suited for nearshore work on a day basis.

Cost: $

Advantages: Affordable, flexible, suitable for shore-based operations.

Considerations: Sea state limitations, endurance, payload constraints.

2.2.2.1.4 SeaRobotics 5.7 m

The SeaRobotics 5.7 m is a typical catamaran design. It is functionally quite like the Hydro-Cat 180 and mostly differentiated on price and configuration. As with the Hydro-Cat 180 it is well-suited for nearshore work on a day basis.

Cost: $

Advantages: Affordable, flexible, suitable for shore-based operations.

Considerations: Sea state limitations, endurance, payload constraints. The unmanned surface vehicle (USV) 2600 (4 m [13.1 ft]) model is similar.

2.2.2.1.5 Marine Advanced Robotics Inc. WAM-V 8

The WAM-V design is a novel variation of catamarans. It provides for improved stability and seakeeping in adverse sea states. This makes it a good choice for survey applications. The system can support diverse payloads but may face physical limitations in mounting numerous sensors. The system has significant field experience. This ASV is well-suited for nearshore work on a day basis.

Cost: $$

Advantages: Design supports rough sea operations, well suited for survey, significant field experience.

Considerations: Maintenance and support over long-term, smaller space for multiple payloads. The WAM-V 16 model is similar.

2.2.2.1.6 XOCEAN XO-450

The XO-450 is an ASV optimized for survey operations. It provides stability, payload support, and operational concepts suitable for near-shore and open-water operations. The design has significant field experience and is well proven.

Cost: $$

Advantages: Proven performance in survey, trailer-based concept of operations suitable for near-shore day operations, suitable for diverse payloads.

Considerations: Service model may make alternative payload configurations difficult to deploy.

2.2.2.1.7 Maritime Robotics Mariner

The Marine Robotics Mariner is a typical ASV powered by internal combustion. It offers water jet or thruster propulsion for versatility. The use of a moonpool for payloads likewise supports diversity in payloads. The Mariner has not been as widely used as comparable systems in its class, such as those from XOCEAN, but it is a reputable design from an established manufacturer.

Cost: $$

Advantages: The provision of an optional winch for deeper deployment of select payload sensors is a distinguishing feature of the Mariner ASV.

Considerations: That same winch could present a reliability challenge if it becomes fouled during operations.

2.2.2.2 Autonomous Underwater Vehicles

2.2.2.2.1 Teledyne Gavia

The Gavia is a medium-sized AUV notable for its modularity. Different sensor, battery, and operational modules can be mixed and matched to make the Gavia vehicle adapt to various applications. This also makes it easy to mobilize and ship to project sites. There are many Gavia units in use worldwide and they have significant experience in geophysical survey applications.

Cost: $$

Advantages: Modularity, field proven, diverse payloads available.

Considerations: New payloads can take a long time to come to market as modules.

2.2.2.2.2 L3Harris Iver4

The Iver4 is a small to medium AUV derived from the earlier (smaller) Iver series. It is a newer design without significant field experience, but its predecessors are widely used. Iver systems have been typically employed for search, usually with side scan sonar, rather than geophysical survey. Due to its low cost the Iver platform has been used extensively for innovation and development of novel applications and payloads.

Cost: $ to $$

Advantages: Good size and/or performance compared to price, benefits from lessons learned in hundreds of prior Iver AUVs.

Considerations: Not well established as a geophysical platform, Iver4 is unproven.

2.2.2.2.3 Hydroid REMUS-300

The REMUS-300 is, like Iver4, a new design derived from a long history of AUVs from the same vendor. The REMUS 100 is one of the most widely used search AUVs, especially for mine-hunting. As with Iver4 this system is not widely used for geophysical work, but technical underpinnings are available. The REMUS-300 is of strong interest to U.S. Navy buyers so should be well supported for many years to come.

Cost: $$

Advantages: Derived from a very successful family of AUVs, strong U.S. Navy interests.

Considerations: Not well established as a geophysical platform, REMUS-300 is unproven.

2.2.2.3 Equipment

For cost comparison purposes, the APTIM Team developed a relative cost scale for the various equipment and sensors for use on these platforms denoted by $, $$, and $$$ symbols. These symbols mean the following:

$ = >$30,000 to <$75,000

$$ = >$75,000 to <$150,000

$$$ = >$150,000 to <$250,000

These costs are relative and represent general cost assumptions at the time of publication. The costs of these platforms can vary significantly and are subject to market fluctuations.

Table 2-2. List of Equipment Analyzed in this Feasibility, Field Techniques, and Best Practices Analysis

Manufacturer	Model	Type
Teledyne Marine	EchoTrac E20	Single beam echosounder
EdgeTech	2200	Side scan sonar
EdgeTech	2200	Sub-bottom profiler
EdgeTech	2205	Side scan sonar
EdgeTech	2205	Sub-bottom profiler
Teledyne	ParaSound	Sub-bottom profiler
EdgeTech	SB-424	Sub-bottom profiler
EdgeTech	SB-216S	Sub-bottom profiler
EdgeTech	SB-512i	Sub-bottom profiler
Innomar	Standard-USV	Parametric Sub-bottom profiler
Tritech	Seaking Parametric SBP	Parametric Sub-bottom profiler
Kongsberg Marine	M3 (500m)	Multibeam echosounder
Kongsberg Marine	EM2040	Multibeam echosounder
Norbit	Winghead i67	Multibeam echosounder
R2Sonic	2020	Multibeam echosounder
R2Sonic	2024	Multibeam echosounder
Teledyne Marine	T-20p	Multibeam echosounder
Ocean Floor Geophysics	SCM	Magnetometer
Geometrics	G-882	Magnetometer
Marine Magnetics	Explorer v.AUV	Magnetometer
Sonardyne	AvTrak 6 (Directional) 8220-3111	Ultra-short baseline positioning system
Teledyne Marine	Pathfinder	Doppler velocity log
Teledyne Marine	Tasman	Doppler velocity log
iXblue	Phins SubSea	Inertial navigation system
Applanix	POS MV WaveMaster-II	Global navigation satellite system/inertial navigation system

2.2.2.3.1 Teledyne Marine EchoTrac E20 SBES

The EchoTrac E20 SBES is designed for easy mobilization, is compact, robust, and applicable in many types of environments. This system offers dual frequency (low and high) channels that can be used for shallow and deep operations with low overall mobilization effort. The ability to interface various SBESs with this unit improves its versatility.

Cost: $$

Advantages: Ease of mobilization, integration of various SBES transducers.

Considerations: Supports SBES transducers only.

2.2.2.3.2 EdgeTech 2200 SSS/SBP

The EdgeTech 2200 modular sonar system comprises an SSS and SBP system designed to be installed on AUVs and ROVs. Each of the sensors in this system offer multi frequency capabilities allowing for a range of working depths and resolution capabilities.

Cost: $$

Advantages: AUV and/or ROV mounting capability, addition of magnetometer, increased working depths.

Considerations: Power consumption.

2.2.2.3.3 EdgeTech 2205 SSS/SBP

The EdgeTech 2205 is like the EdgeTech 2200 as both are modular systems with the addition of bathymetric capabilities. This system can be configured with various pressure housings, rated for 3,000 and 6,000 m (9,842.5 to 19,685 feet). Each component of this system has multiple frequency configurations including the optional bathymetry addition.

Cost: $$

Advantages: UUV (unoccupied underwater vehicle)/ASV/ROV/remotely operated towed vehicle mounting capabilities, bathymetric option available.

Considerations: Power consumption.

2.2.2.3.4 Teledyne Marine ParaSound SBP

The Teledyne Marine Parasound SBP delivers high quality and high-resolution data in terms of sediment profiling, water column imaging and single-beam echo sounding. With increased working and penetration depths, this system can be utilized for various sub-seafloor mapping initiatives.

Cost: $$

Advantages: Increased working depths and penetration depths.

Considerations: Hull mounting capability only, power consumption.

2.2.2.3.5 EdgeTech SB-424 SBP

The EdgeTech SB-424 belongs to a family of towed sub bottom profiler systems; this system, specifically, operates using a higher frequency than its counterparts. Operating in higher frequency capacities yields a higher resolution data set with a typical sediment penetration between 2 and 40 m (6.56 to 131.2 feet), depending on sediment types.

Cost: $$

Advantages: Lower relative overall weight, high resolution, frequency modulated compressed CHIRP type.

Considerations: Towed system only, limited frequency range.

2.2.2.3.6 EdgeTech SB-216S

The EdgeTech SB-216S is the intermediary in the single beam (SB) family. This system operates in a lower frequency and pulse length than the SB-424 giving this system greater sediment penetration between 6 and 80 m (19.7 to 262.5 feet) depending on sediment type.

Cost: $$

Advantages: Greater sediment penetration, frequency modulated CHIRP pulse type.

Considerations: Increased relative weight, towed system.

2.2.2.3.7 EdgeTech SB-512i

The EdgeTech 512i is the largest system in the EdgeTech SB family operating at lower frequencies than the SB-216S and SB-424. This system offers a wider range of operating frequencies and pulse types resulting in penetration depths of up to 250 m (820 feet) depending on sediment types.

Cost: $$

Advantages: Wider range of frequencies and/or pulse types, greater sediment penetration.

Considerations: Increased weight, towed system.

2.2.2.3.8 Innomar Standard-USV Parametric Sonar

The Standard-USV is explicitly designed for AUV and/or ASV applications. The high ping rate, a small footprint, and the possibility of transmitting sound pulses over a wide frequency range ensure sub-bottom data with excellent resolution and excellent sediment penetration. Electronic beam stabilization across (roll) or along track (pitch) compensates for wave-induced vehicle movements.

Cost: $$$

Advantages: Uses two different frequencies which are emitted at the same time, unlike CHIRP Technology. Produces a lower frequency signal with a narrow bandwidth providing a more focused view.

Considerations: High cost vs. CHIRP technology and less readily available in the US market.

2.2.2.3.9 Tritech Seaking Parametric SBP

This product is designed specifically for AUV and/or ASVs and ROVs. The system allows the operator to view the raw 200 kHz seabed profile and the 10–30 kHz sub-bottom layers produced by the parametric pulse.

Cost: $$

Advantages: Tritech's SeaKing range of sonars and sensors allows for the Parametric SBP to be used in conjunction with other SeaKing sensors over one communication link. All products in the SeaKing family (or third-party products within the ARCNET communications link), can be run simultaneously, using the same processor and display, such as Tritech's Surface Control Unit (SCU) or a customer-supplied PC or laptop.

Considerations: There is a requirement for additional hardware pieces, such as a junction bottle and surface control unit (SCU). This adds other complexities to design and installation into ASV/AUVs

2.2.2.3.10 Kongsberg Marine M3 (500 m)

The Kongsberg M3 MBES is a compact sonar system that incorporates the transmit and receive acoustic arrays in a small, single housing. This system offers high frequency capabilities with a wide range of working depths and operating modes.

Cost: $$

Advantages: International Hydrographic Organization (IHO)-compliant, light weight, mounting options.

Considerations: Limited swath angles.

2.2.2.3.11 Kongsberg EM2040

The Kongsberg EM2040 MBES sonar is a robust system that that offers highly accurate bathymetry along with water column data acquisition. This multifrequency enabled system has a depth rating of up to 6,000 m (19,685 feet).

Cost: $$

Advantages: IHO-complaint, water column logging, backscatter logging, multiple frequencies, pulse lengths, and detection modes.

Considerations: Increased weight, power consumption.

2.2.2.3.12 Norbit Winghead i67

The Norbit i67 MBES sonar is the first curved array system in this class of geophysical equipment. This system has an integrated Global Navigation Satellite System /inertial navigation system (GNSS)/INS positioning system aiding in quick mobilization times. This high-resolution sensor has the capability to be mounted on a wide variety of survey vessels.

Cost: $$

Advantages: IHO-compliant, integrated GNSS/INS, backscatter and water column logging, wide swath angles.

Considerations: Used with proprietary data acquisition software, surface vessel mounting only.

2.2.2.3.13 R2Sonic 2020

The R2Sonic 2020 MBES is a smaller unit in comparison to the remaining MBES sensors R2Sonic units making it ideal for mounting on small surface platforms as well as small AUVs. The 2020 can operate with up to five various frequencies simultaneously while having the ability to collect backscatter and water column data.

Cost: $$

Advantages: IHO-compliant, small and compact, low power consumption, dual head configuration available.

Considerations: Lower resolution beamwidths than counterparts.

2.2.2.3.14 R2Sonic 2024

The R2Sonic 2024 MBES is a more advanced and robust sensor than the 2020 counterpart. This system has higher resolution beamwidths in all dimensions while keeping the ability to be mounted on smaller ASVs. This sensor also can operate at various frequencies simultaneously and log various types of geophysical data.

Cost: $$

Advantages: Higher resolution, wider swath angles.

Considerations: Surface vessel mounting only, increased weight, and power consumption.

2.2.2.3.15 Teledyne Marine T-20p

The T-20p is a portable MBES system, contained in a titanium housing, which can be configured for a wide range of vessels and projects. This highly configurable, lightweight system is easily packed and transported while preserving the ability to log various types of geophysical data such as backscatter and water column data.

Cost: $$

Advantages: Lightweight, frequency modulated pulse option, fast mobilization.

Considerations: Limited mounting options, limited depth rating.

2.2.2.3.16 Ocean Floor Geophysics (OFG) Self Compensating (SCM) Magnetometer

The Ocean Floor Geophysics (OFG) Self Compensating Magnetometer (SCM) is a versatile system that can be mounted on a variety of survey vessels including ASVs and AUVs. This system has a depth rating of up to 6,000 m (19,685 feet) and can operate with low power consumption. Compensated data can be achieved in real-time by using OFG's proprietary software.

Cost: N/A not for sale on open market, proprietary technology.

Advantages: User friendly, real-time compensation, applies to a variety of survey types.

Considerations: Proprietary software needed for operations.

2.2.2.3.17 Geometrics G-882 Magnetometer

The Geometrics G882 magnetometer is applicable to many types of marine surveys ranging from archaeological to unexploded ordnance detection. The high sensitivity incorporated in this towed system makes the G882 ideal for detecting ferrous objects of all sizes.

Cost: $$

Advantages: High sensitivity and sample rate, lightweight, Time Varied Gain (TVG) configuration.

Considerations: Limited mounting options, proprietary software needed.

2.2.2.3.18 Marine Magnetics Explorer v.AUV

The Explorer v.AUV magnetometer is unique in its design and capabilities. This fully reengineered total-field magnetometer is lightweight and neutrally buoyant so it can be easily towed behind an AUV without the sensor floating or sinking from the AUVs trajectory. The magnetometer also requires low operating power causing less drain on internal AUV batteries.

Cost: $$

Advantages: No warmup required, AUV compatible, increased depth ratings.

Considerations: Overall weight may be an issue for towing.

2.2.2.3.19 Sonardyne AvTrak 6

The AvTrak 6 transceiver provides comprehensive tracking data for a wide variety of devices. This system is designed to be integrated with AUV systems to provides tracking and telemetry to a surface vessel or other AUV systems. The AvTrak 6 also includes an emergency relocation mode.

Cost: $$

Advantages: Compatible with USBL units, low power consumption, internal back-up battery.

Considerations: Portions of mechanical construction are plastic.

2.2.2.3.20 Teledyne Marine Pathfinder DVL

The Teledyne Pathfinder Doppler Velocity Log (DVL) is a compact unit that provides sub-sea navigation to a range of vehicles from small ROVs to larger AUVs. The phased array transducer provides highly accurate positioning data and, with the addition of new proprietary algorithms, tracking even if the seafloor is out of range of the transducer.

Cost: $$

Advantages: Acoustic Doppler current profiler (ADCP) option, INS compatible, 300/600 kHz frequency options, and depth ratings available.

Considerations: Additional power consumption.

2.2.2.3.21 Teledyne Marine Tasman DVL

Like the Teledyne Pathfinder DVL, the Tasman DVL is another phased array DVL with the added capability of interchangeable transducers that can be replaced in the field along with a low latency trigger to avoid any acoustic interference from other sensors.

Cost: $$

Advantages: Interchangeable transducers, wide range of tracking.

Considerations: ADCP option added as upgrade.

2.2.2.3.22 iXblue Phins SubSea

The Phins SubSea INS system provides highly accurate inertial measurements for use in applications such as precise AUV and towfish navigation. With a depth rating of 6,000 m (19,685 feet) and a titanium housing, this unit is ideal for ROV and/AUV integration.

Cost: $$

Advantages: Aiding sensor integration, fast mobilization, shock and vibration proof.

Considerations: Power consumption, increased weight.

2.2.2.3.23 Applanix POS MV Wavemaster-II

The Applanix POS MV Wavemaster-II is a highly accurate GNSS system that integrates inertial measurements with GNSS Azimuth Measurement System (GAMS) heading to produce the most accurate navigation and attitude data for all integrated sensors. Accuracies can be increased to centimeter level values by incorporating a correction service such as Fugro Marinestar, RTK services, and through post processing navigation and attitude data with observed ephemeris data.

Cost: $$

Advantages: Multiple sensor integration, high relative accuracy during GNSS outages.

Considerations: Topside unit only.

2.2.2.3.24 Hemisphere V200

Like the Applanix POS MV, the Hemisphere Vector V200 GNSS system offers centimeter level navigation data with the support of multiple satellite systems such as GPS, GLONASS, Galileo, QZSS, and BeiDou. With integrated sensors, this system has a quick mobilization time and can accommodate a wide range of sensors.

Cost: $$

Advantages: Sub-meter navigation and attitude accuracies, quick mobilization.

Considerations: Proprietary correction service used for increased accuracies.

2.3 Feasibility Study

2.3.1 Instrument Comparison–AUV and/or ASV to Ship-based

In the realm of marine technology, specifically geophysical equipment manufacturers, there is not a wide pool to select product from. Therefore, most manufactures that develop conventional “ship-based” technology also support the autonomous vehicle market. Many survey instruments used aboard ships may be identical to those used aboard AUVs and ASVs (e.g., INS, towed SSS, MBES). When there are differences, these are dictated by limitations of the vessel and mission. Specifically, by:

- Size
    - Autonomous vessels are always smaller than traditional ships.

    - Small form factor is important on ASVs and crucial on AUVs because space abord these small vessels is at a premium. The cylindrical shape of a typical AUV body further limits the space that onboard sensors may occupy.
- Speed
    - There are no significant differences in speed between traditional survey vessels and autonomous vessels and, in some cases, AUVs can survey at higher speeds due to the altitude relative to the seafloor.
- Data Storage and Offloading
    - Advanced AUVs and ASVs can be outfitted with similar storage space as crewed vessels.
    - Less advanced systems can be outfitted with removeable external hard drives, up to 2 terabytes.
    - The offloading of data can be conducted through various methods, such as physically removing external hard drives, connecting to the vessel's onboard computer, and connecting to the vessel's onboard computer remotely.
    - Telemetry of real-time data collected by ASVs to a nearby vessel or shore-based data repository may be accomplished through additional investments in equipment and technology, specifically through line-of-sight, cellular or satellite telemetry systems. These telemetry systems remain unreliable, dependent on weather, a local base station, cellular network connectivity, and/or satellite connectivity, and may prove cost prohibitive depending on survey budgets. Data telemetry is not an option for AUV.
- Power
    - Autonomous vessels operate with significantly lower power budgets than ships.
    - Instruments aboard autonomous vessels are designed to make efficient use of power.
- Heat
    - AUVs in certain missions are designed to have a limited thermal signature. Instruments that can operate without giving off excessive heat are preferable in these applications. One example is a Fiber Optic Gyro (low-heat output) as opposed to a Ring Laser Gyro (high-heat output).
- Multiple Assets
    - Self-organizing Wide area Autonomous vehicle Real-time Marshalling (SWARM) assets working in unison can cover wide swaths of area.
- Noise
    - AUVs in certain missions are designed to have a limited acoustic signature. This is a product of the survey instrumentation more than it is the sound of the vessel itself. Therefore, the same limitations will be forced upon AUV and/or ASV platforms as with conventional survey vessels. During transit ASVs and AUVs will be much quieter given their smaller size and typical electric propulsion.
    - Autonomous vehicles offer less room to distance acoustic sensors from sources of onboard noise (e.g., propulsion units). As a result, sonar systems with superior noise filtering capabilities are preferable for autonomous vessels. Sensors that produce minimal noise are preferable about autonomous vessels.
- Pressure
    - Not an issue on ASVs.

Power consumption of sensors relative to power sources aboard AUVs and ASVs is a major consideration. However, this is not the case aboard ships. Efficient sensors are preferable aboard autonomous vessels and allow for longer missions as some sensors draw too much power to be utilized on autonomous vessels (e.g., seismic gear). There is added engineering costs to automate sensors that would otherwise be operated by shipboard personnel. As autonomous bathymetric survey is increasingly utilized, most sensor manufacturers offer products for use on AUVs and ASVs. Availability for typical bathymetry instruments is plentiful; however, finding space aboard and configuring a sensor layout may be more of a consideration aboard autonomous vessels than ships.

2.3.2 Data Product Comparison–AUV and/or ASV to Ship-Based

AUV and ASV completed data products show no differences when in comparison to ship-based data products. The processing software for ship-based and autonomous-based systems are the same; thus, end products will be familiar to users regardless of the platform. Furthermore, there is no difference in data product resolution when comparing data derived from an autonomous vehicle and a ship. Quantitative analysis will show little to no difference in data uncertainty, Total Vertical Uncertainty (TVU) and Total Horizontal Uncertainty (THU), when comparing data products from AUVs and ASVs to those from traditional survey vessels. Demands of AUVs in the offshore industry has increased as their data products have proven to meet or exceed accuracy and resolution requirements. AUVs often provide a higher resolution, and positionally stable, data product when compared to traditional vessel mounted equipment.

To ensure geospatial precision, AUVs utilize multiple aiding systems (DVLs, USBLs, acoustic modems) in addition to an INS to compensate for lack of real-time GPS. Because they are smaller than ships, a tighter motion sensor helps to ensure good resolution in data products derived from sensors mounted aboard ASVs. Additionally, autonomous vessels operated in remote areas may not be able to deliver a complete data product as rapidly as data products from a ship as some crewed vessels conduct data processing during operations. However emerging automated processing tools are under development.

AUVs may not be able to provide real-time data due to bandwidth restrictions of underwater communications. For example, it is common practice to observe "snippets" of bathymetric data in real time from AUVs to ensure that everything is functioning properly, but the complete data set/product is not delivered until the AUV reaches the surface. An ASV may be similarly limited by its communication bandwidth through the air; a large multibeam sonar data set may take some time to reach an end user via a satellite connection, and that feature will add additional, potentially prohibitive data telemetry costs to the planned survey. As such, developing proper quality assurance, control, and surveillance protocols (as described later under Section 3.2) is key to selecting an operating platform, and factors into the overall feasibility of which system is chosen for any survey. If real-time data surveillance and quality control is required for a dataset, the traditional toward sensor manned survey vessel may be the best option, as data can be reviewed, and quality assessed, in real time allowing for adjustments to ensure and improve quality during survey operations. AUVs will not allow for this detailed, real-time data monitoring, and ASVs will not unless the specific project is able to invest in a sufficient data telemetry system, which adds additional cost and equipment.

2.3.3 Rate of Technology Advancement

We are currently living in what is commonly referred to as the Fourth Industrial Revolution, more commonly known as the Digital Age. The development of technology has been advancing and evolving in ways unimaginable in the 1970s. Some of the first business computer systems required an entire building to hold the hardware to operate them. Today a mobile phone can hold more data, access it faster, and communicate it, virtually, anywhere on the planet with a suitable communication network.

New technology has allowed the development of processor chips that can perform billions of operations per second (gigahertz). This has resulted in small, very fast, large memory capacity devices which can deal with large amounts of data very rapidly. Modern hardware and advanced software combined with advanced communications technology, allow autonomous solutions to be controlled from anywhere on the planet. Similarly, cloud computing allows the capability to upload acquired data collected by the systems for remote processing. The advancement in technology growth is being driven by the increasing awareness of these capabilities by potential AUV and/or ASV customers. As capabilities become feasible the number of customers, systems, and system developers grow along with it.

The development of autonomous solutions has continued at a very significant pace over the last few years with more AUVs and ASVs entering operation all the time. Enabling technologies such as software, energy storage, processors, and advanced manufacturing have become more available and capable and this has reduced the barriers to entry, increasing competition and innovation. The number of manufacturers is increasing as is the geographic scope of suppliers. Today, viable AUVs and ASVs are commercially available from dozens of manufactures across North America, Europe, and Asia. They come in a variety of sizes and shapes and have a very diverse set of operational capabilities which all place their own unique demands on those who own and operate them.

The largest and most sophisticated AUVs and ASVs are expensive, typically over $5M, and are sold in modest volumes, at fewer than a dozen per year. These highest-performance offerings have not seen a significant change in pricing, but their relative performance has improved. Higher resolution sensors and longer endurances are coming online for the top performing systems. The end users of these systems have come to trust them for high-value operations and are working to deploy them in larger numbers. Examples of these AUVs would be the Kongsberg Hugin, a market leader for deep ocean surveys, and the SAAB Seaeye Sabertooth another industry leader in the seabed and infrastructure inspection market. Likewise, an ASV in the high-range category would be the Sea-Kit which offers several large USV models that provide survey and interventional, ROV capabilities at prices ranging from $2 to 5M

A different trend can be seen in the most compact systems. As the size of the systems decrease, the price rapidly declines, as well. The smallest AUVs and ASVs are on the verge of becoming commodities with many different vendors competing aggressively. In this smaller category a basic system, including some sensors, can be obtained for under $100,000. Often these smaller systems come in certain fixed configurations designed to increase reliability and reduce costs. This sector of the market is moving from competition on performance to more commercial considerations including price, service, and scope of payloads. Compact AUV examples are the Hydroid REMUS 100 ranging in price from $250,000 to $400,000, which is the leader in compact AUVs for defense applications and is widely used by the scientific community. SEABER, based in France and valued around $100,000, is an emerging offering aimed at scientific and commercial end users. Compact ASV systems, such as the Sea Robotics 1.8 m Surveyor, ranges between $100,000 to $250,000 and is a typical example of a compact survey solutions specifically for shallow protected areas.

In the middle of the market, medium sized AUVs and ASVs offer the most flexibility. Some of these systems are modular, allowing customers to add new payloads, or spare batteries, after their initial purchase. This category is also seeing a trend toward "as a service" business models, especially in ASVs. Many of the vehicle manufacturers have noted that as the cost of the capital assets declines the opportunity for profits moves to the service arena. Some of the most interesting ASVs on the market today are available only in a service mode and cannot be purchased outright. Medium Range AUVs like the Hydroid REMUS 300, which costs approximately $750,000, is a new offering in the medium class and is based on the well-known REMUS 100 line. The L3H Iver 3 can be purchased for $350,000 to 500,000 and is a strong offering in both defense and commercial and/or scientific markets. For Medium Range ASVs, the L3H C worker 4 is a well-regarded system for commercial applications but is usually deployed in an "as a service" model meaning not for commercial sale. XOCEAN manufactures the XO-450, also a well- regarded system for commercial applications usually deployed in an "as a service" model.

AUV and ASV development is accelerating. The price-performance curve of basic systems is rapidly trending toward commoditization. At the same time sophisticated systems are coming to offer hybrid operations including the potential to perform both survey and intervention from one system. The combined operation of ASVs and AUVs has been demonstrated and will become a typical-use case over the next few years. This will enable more real-time supervisory control of AUVs, analogous to what is seen with ASVs today. Improving "artificial intelligence" will make it easier for a limited number of human operators to support an ever-increasing number of deployed ASV and/or AUV systems. New sensors will increase the productivity of the vehicles while new energy storage systems will increase overall endurance. Improved connectivity, especially through satellite systems such as Starlink, will expand the potential for remote operations around the globe. Improved sensors and onboard intelligence will broaden the operating regime for ASVs to include more congested waters with other stakeholders such as fishing and cargo vessels. The number of AUV and/or ASV units in operation is likely to grow at a geometric rate over the next decade. Solutions available in 2022 will be commercially out of date in 6 to 8 years and outclassed by new offerings in four to six years.

Energy storage on ASVs and AUVs is evolving slowly. For ASVs internal combustion engines/generators are well understood but present some challenges to autonomous operation and maintenance. Though for energy density, fuel-based solutions remain most prevalent. As with the transition to electric automobiles electrification of vessels is occurring. In crewed vessels, this is being seen in near shore needs, such as ferries or tugs. These larger hulls can accommodate less dense battery chemistries that provide better economics. However, most ASVs, like leading electric vehicle automobile providers, strive for highest energy density possible. Considering the relative volume in the sector, ASVs are not pioneering new chemistries, but benefit from developments in other fields. Early developments in lithium-ion chemistries from the electronics industry are giving way to solutions from the electric vehicle market. Select ASVs are experimenting with the lithium iron phosphate (LIP) batteries also used in some automotive cases.

Until new or different battery chemistries are invented or perfected, the amount of power that can be stored aboard will remain a major limiting factor to the capabilities of AUVs. These uncrewed vessels will have to cease operations to find power either at the surface or at sub-sea docking stations. This limitation is costly to the time and financial budget of any survey; however, ASVs have a slight advantage in that they can be aided by alternate power sources such as onboard solar panels or foils beneath the boat that harness energy from the sea. These alternate power sources regenerate batteries and prolong the run time of an ASV, but at present, a ASV with a standard sensor suite for hydrographic surveying draws more power than can be generated during survey operations and must cease survey operations while batteries are replaced or recharged. The pace of energy storage in ASVs and AUVs will be driven by external innovations. However, innovations are being implemented at an increasing rate, such as a hydrogen fuel cell system that will be used in the commercial industry for increased vessel endurance during mission operations.

Along with innovations for autonomous power systems, similar innovations are being created for the equipment they carry. A constant consideration in the autonomous industry is power consumption of the equipment, especially with regards to AUVs because they do not have an ability to readily re-supply power sources. Manufacturers are designing equipment for much lower power consumption rates than those onboard crewed survey vessels. A particular challenge is with SBP, which require more power than other geophysical equipment; however, manufacturers have been integrating them with AUVs and ASVs currently on the market with positive results such as the Teledyne Gavia AUV and the iXblue DriX ASV. These SBP units have a typical power consumption in the range of 30 to 40 watts versus the kilowatt average of traditional systems.

A persistent challenge in ocean technology is the lack of radio-frequency spectrum below water. Without this capability, ubiquitous in air, undersea robotics do not benefit from GPS, cellular telemetry, or Wi-Fi. While physics allows radio-frequency waves to penetrate seawater, they can only reach very short ranges. In select cases Wi-Fi and/or Bluetooth techniques have been used when two devices are in contact. Without radio frequency underseas systems make use of acoustics. Many different systems have been developed to provide both positioning and telemetry undersea. They all face the same physics constraining them to lower resolution and/or bandwidth at longer ranges. Thus, state-of-the-art acoustic telemetry, which can reach up to 10 km (6.21 miles) in practical use, is more akin to text messaging than video streaming. Though some acoustic telemetry providers are experimenting with higher bandwidth it is accepted that real-time control of an ASV at some distance, usually over 1 km (0.62 mile), is not feasible. This is not anticipated to change in any meaningful way over the coming years.

AUVs and ASVs have adopted differing approaches to onboard processing driven by the relative lack of telemetry to underseas systems. Because ASVs often benefit from Wi-Fi or high-bandwidth cellular links, they tend to provide more real-time operator control and limit onboard processing. This is particularly true for operational sensors, such as cameras. Though some efforts are emerging to use machine learning and edge processing to obstacle avoidance. In contrast, payload sensors, such as a multi beam sonar on a ASV or a side scan sonar on an AUV, are usually logged for later review with minimal onboard processing. Instead “snippets” of data are typically returned for operators to review to assure systems are functioning properly. One area where onboard processing has become common is automatic target recognition (ATR) usually for navy mine hunting. In such systems an onboard processor is “taught” to recognize threats and then can either react during a survey to alert operators or conduct extra imaging passes of high interest targets. This approach has benefited from significant defense investment. More recently the technique is being transitioned to pipeline following behaviors for commercial ASVs. In both cases the availability of significant “training data” is important to making such onboard processing feasible. Prior to this technology, the autonomous vessel would remain deployed for the duration of the survey and upon completion, a technician would need to process the entire data set to find the intended target.

The combined operation of “fleets” of AUVs and/or ASVs has often been discussed. Notable demonstrations have included coordinated operations of dozens of ASVs for precise control and placement of seismic receiver arrays. Other demonstrations have seen ASVs on the surface direct the actions of AUVs operating beneath them. As an example of cooperative operations, an ASV could be running survey lines in tandem with a traditional crewed boat. In this example, the ASV is in contact with the boat and can maintain an exact offset that allows for highly accurate line spacing. An example of collaborative operations would be a survey carried out by two ASVs. Through constant communication and data sharing, if one ASV detects greater depths on the edge of its survey line plan, the other ASV can adjust line spacing in real time to ensure complete sonar coverage of the survey area, often referred to as “collaborative autonomy.” Both examples are commonplace in commercial surveying and are made available by mainstream, commercial-off-the-shelf survey software. Both capabilities can be used by multiple uncrewed assets simultaneously on the same mission.

Glider AUVs, which are widely used for physical oceanography over long distances and durations, are often operated in coordination with each other and other assets. These systems, as well as some long-endurance ASV deployments, often benefit from commuter-controlled planning and tasking. Thus, a single operator can oversee a sizable number of systems at sea. Typically, this approach is not seen in simple “day-jobs” conducted near shore but a dedicated operations team.

A human vessel captain perceives and processes a plethora of information using four of the five senses (taste is not used). If one sees debris on the water, they will take action to steer clear. If they smell smoke from the engine compartment it can be quickly addressed. Feeling the waves increase to an uncomfortable or unsafe level, the captain can turn for home port. Hearing a buoy bell or another vessels motor in limited visibility conditions allows for heightened awareness by the crew. Autonomous vessels must replicate a human captain’s ability to detect and react in real-time. In addition, ASVs must navigate congested waterways and analyze variances in sea conditions. This is a monumental task.

To add sensory tools to the autonomous vessels, engineers use various technologies such as RADAR or LiDAR and cameras for distance control to replicate what human eyes and ears perceive. Based on the vessels level of autonomy, it may have 20 to 40 sensors that collect massive amounts of data in real time at the rate of gigabits and terabits per second. An autonomous platform must react to the information in real time. To do that, the vehicles must have powerful computing. But there is such a large quantity of data that no computer could process it in real time without artificial intelligence (AI). That is why AI is such a key factor for autonomous vehicle technology. Combining AI with computing power is what makes autonomous vessels a viable technology.

ASVs are beginning to increase levels of autonomy is in obstacle avoidance. Inspired by the capability of autonomous driving systems in automobiles engineers are exploring the utility of cameras and/or LiDAR to assist ASVs in navigating their surroundings. These efforts are very rudimentary and not yet delivering significant performance. While automobiles operate in a structured environment, ASVs face especially complex conditions. LiDAR is typically a short-range device and not well suited to the motions of a vessel. Cameras have shown greater promise with both longer functional range and the ability to discriminate select targets. For example, identifying a boat as opposed to a buoy has proven feasible. However, such results remain challenged as wind, wave, and spray can obstruct views easily. The most promising tools for ASV obstacle avoidance are simple depth finding sonars, which can prevent running aground, and automated identification system (AIS) receivers which can provide information on surrounding vessel. These tools have been well integrated into ASVs and are generally reliable.

In summary, autonomous systems in the survey market are here to stay and will continue to develop as a safer alternative to crewed missions especially as technology rapidly improves. The vessels themselves may not be the key driver in the future but the technology that goes into each system will be the key driver.

Specifically for sand source surveys, as it stands today, the costs associated with operating these platforms would far exceed the costs associated with a modestly equipped crewed vessel leaving and returning to the dock each day. The value proposition increases as surveys move further away from the coastlines and deeper into offshore waters where the price point of operating a manned 24-hour ship greatly exceeds a 12-hour survey launch. This is where the autonomy cost margins improve significantly.

The National Oceanic and Atmospheric Administration (NOAA) is actively looking into augmenting USVs into their fleet, replacing typical survey launches. By exchanging a small vessel with a crew of three to four people for a USV brings a greater safety margin for them; however, the larger offshore ship remains nearby. Launching AUV and ASVs from shore or harbors and relying on autonomy to safely perform the mission and return is putting a considerable amount of reliance on artificial intelligence (AI) especially in highly dynamic environments where these sand sources are located. This reliance on AI then becomes more of a cultural and policy issue to address. With time, more confidence in AI will occur; however, in its current state, the industry is not 100% ready for this yet.

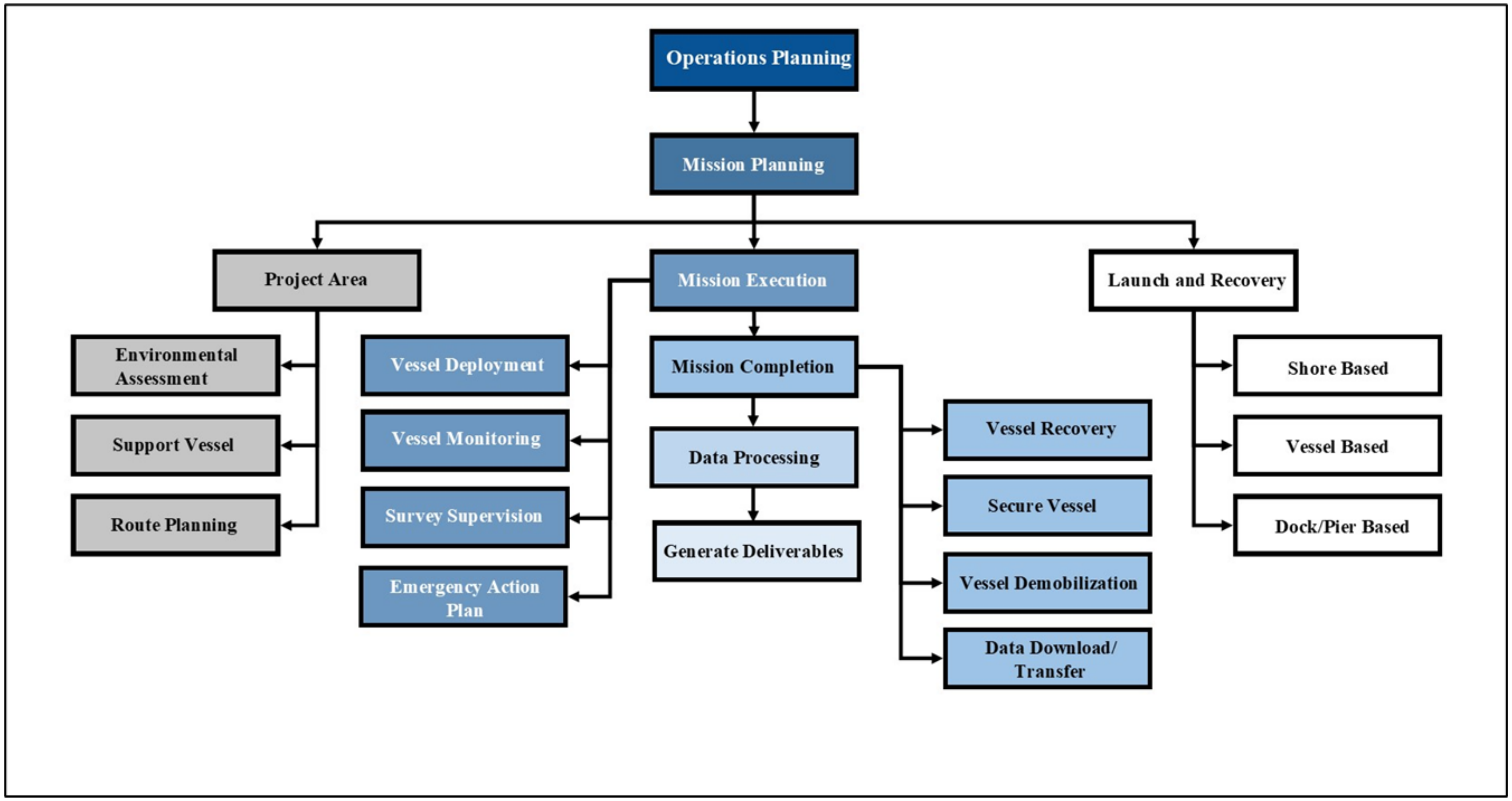
The autonomous community has simply not been tasked to address this specific type of sand source survey mission to date. By performing in-situ field trials of various systems in controlled environments and publishing the results of these tests would go a long way in building that cultural and policy void that exists and vastly improving the confidence in the technology.

3 Data Acquisition Protocols and Guidelines

3.1 ASV and/or AUV Deployment and Operations Procedures

ASV and/or AUV deployment methodologies continue to develop, as each mission provides manufacturers and vehicle owners with valuable lessons learned to better improve operations for future use. Three primary deployment and recovery methods will be discussed herein: Beach/Shore, Vessel/Mothership, and launch from a Pier/Dock/Boat Ramp. Both ASV and AUV operations involve an approximate 30-minute initialization period upon vehicle power-up, during which time the ASV and AUV automatically proceed through a start-up sequence. These sequences allow the vehicle to power-up and check the functionality of all onboard sensors and confirm the necessary communications between sensors and the vehicle control module. Autonomous behaviors onboard the platforms conduct all the self-checks and initiate the alignment procedure for the onboard fiber-optic gyro-based INS. Once the INS alignment is complete, the autonomous systems can be sent on the pre-planned mission. Figure 3-1 provides a flowchart illustrating the various steps and considerations when using ASVs/AUVs for data acquisition.

Figure 3-1. Process Flow Chart for Using Autonomous Vehicles for Data Acquisition



How the ASV and/or AUV is controlled, operated, and/or overseen by its human operators is a key constraint. Typically, the system is programmed with a mission and then “let loose” to execute that mission. Often these missions are a series of waypoints marking out a “mow the lawn” pattern of motions designed to move the system over an area of interest to collect data. During the operation of these surveys, the systems use their onboard sensors and processors to “autonomously” react to changes in the environment such as water depth or surrounding vessels. For the most part, human operators are tasked with designing a proper survey pattern and then monitoring the operation in case of anomalies. To fulfill this role, it is important that operators have some form of communication with the system (usually radio based in air and acoustic underwater) and are positioned in an appropriate location to understand the operating environment. Usually, AUV operations are “easier” in that there are few concerns about interacting with other vessels. ASVs have been refined and tested over many years and demonstrations have included remote (sometimes very distant) operators safely managing ASVs at sea. This is now routine practice for many commercial and military operators. During the survey mission, data files or log files are recorded either in an onboard computer, flash drive, hard disc drive (HDD), or telemetered by a communications server process (ASVs only, all AUVs store data onboard until recovery). Typically, an AUV and/or ASV has a server process that handles communications with each survey instrument onboard. The server process has the option to log all data received from these instruments or to telemeter the data via satellite connectivity or through radio transmissions. Regardless of the method, there are normally redundant means to capture data being collected for preservation in the event of unforeseen issues.

Operational efficiency is rapidly advancing in the data storage and management systems as satellite connectivity improves. Cloud-based computing also opens the realm for collaborative visualization between field and on-shore personnel. Examples of data advancements are artificial intelligence, machine-learning, and sensor optimization on the fly (e.g. Havenstrøm et al., 2021). A full synthesis of the advances of machine learning and deep learning techniques to ASV/AUV operations and data optimization is beyond the scope of this study.

3.1.1 Beach Deployment and Recovery

3.1.1.1 ASV

The beach launch through the surf zone deployment method is the least favorable of the three scenarios listed above. The size and weight of most ASV systems capable of achieving sand source surveys preclude them from being launched in this manner. The WAM-V with its rubber pontoons is lighter than other systems detailed in this report, resulting in various deployment capabilities. Likewise, the Gavia and Remus-3000 are light enough for a two-person team to carry them into the water for deployment.

With beach operations, the ASV is moved into the water across the land-sea interface. It is typically carried across sandy beaches but also conceivably across marshes or other shore types. Usually, this method involves operators physically carrying the devices, though small carts have also been used. The significant challenge here is that humans moving near the water presents hazards, and this technique is best suited to small, light, systems. This method of deployment will require the ASV to be powered on and systems tested to ensure functionality before deployment. The ASV operator can maneuver the vessel through the surf zone manually or autonomously.

Access to beaches for deployment normally requires vehicles pulling trailers which in some areas require permits to be issued or permission from local government entities. Weather conditions also have an important role due to wave heights and unstable shifting sands.

Recovering an ASV from the shore is completed by reversing the deployment operations. The ASV is maneuvered close to shore, either manually or autonomously. Operators can use common station keeping and/or standby abilities for the ASV during recovery. Before vessel recovery, all propulsion systems must be powered off to avoid injury during this process. The vessel can be transported from the surf zone to shore and placed in a Launch and Recovery System (LARS), such as a small trailer or cart, if available, and demobilized.

Challenges for this method of deployment and recovery include sea state, shore conditions, recreational or commercial activities, and weather. Proper planning, vessel selection, and execution ensure personnel safety and timely mission completion.

3.1.1.2 AUV

The beach deployment method is the least favorable of the three scenarios listed above. The size and weight of most AUV systems capable of achieving sand source surveys preclude them from being launched in this manner. The deployment of an AUV from the beach follows procedures like that of an ASV. The vessel is carried, or transported via cart, through the land and sea interface and powered on to test propulsion systems and initiate the positioning system. When deployed, the AUV can be set in shallow water and proceed with its mission. This method of deployment will necessitate the AUV surfacing frequently during the mission to update the positioning system in lieu of an USBL. Alternatively, an AUV can be employed with an integrated USBL system to offer position references as well as health and status information to the AUV and operators. Attitude and Heading Reference Systems and INS provide accurate and reliable navigation information in all conditions, including GNSS-denied environments. Without aided INS, the AUV will begin to drift off course over time.

Depending on the distance of the survey area in relation to shore, or the AUV and/or deployment location, an advanced system may need to be chosen with "Over-the-Horizon" capabilities. This will allow control and communications of the vessel throughout the journey, regardless of distance offshore. More advanced communications systems use satellite communications and telemetry for control and oversight whereas typical ASV operations are limited to line-of-sight with respect to the vessel and operator.

AUV recovery from shore is accomplished similarly, in part, to ASV recovery operations. Upon completion of the mission, the AUV can be maneuvered close to shore manually or autonomously. The vessel will need to be surfaced for this operation to provide accurate and timely positions to the operator. As the vessel returns to shore, the system will be programmed to a standby mode and propulsion systems powered off to avoid potential injuries. The vessel can be carried out of the surf zone and placed in a LARS, if available, or carried to the appropriate location for demobilization.

The Gavia AUV for example can deploy in the surf zone with two operators launching the vehicle. The AUV is wheeled into the surf zone with an aluminum cart (upon which the AUV rests). Upon reaching approximately 70 cm in depth, the vehicle, which is 0.5% to 1.0% buoyant, is floated off the cart and held manually by one operator. The second operator executes a preplanned mission that directs the AUV to transit through the surf zone and to the desired survey lawnmower location. Recovery of the AUV occurs in the reverse process.

Missions can include any combination of transit waypoints and/or survey lawnmower patterns for the collection of data. Transits, and survey lawnmower execution, can occur while surfaced or submerged, but transit is most efficient (and safest) when submerged. In the absence of position updates from USBL acoustic position systems, the AUV must periodically return to the surface during submerged survey operations to acquire an updated GPS fix that constrains the drift error that is inherent with the inertial navigation system. The frequency of GPS position fixes is determined by mission planners during mission design to meet navigation accuracy requirements.

The challenges apparent to ASV beach deployment and recovery apply to AUV operations and procedures. Access to beaches for deployment typically requires vehicles pulling trailers, which in some areas require permits to be issued or permission from local government entities. Weather windows also play an important role due to wave heights and unstable shifting sands. Upending an AUV fully equipped to perform sand source surveys could be disastrous for the mission and cause extreme damage to the electronics. In addition, AUVs, while fully sealed for pressure, can also find themselves quickly in turmoil if caught sideways in the wave and pushed back onto shore.

3.1.1.3 Procedures for Deploying/Recovering from Beach through the Surf Zone[1]

- Personnel needed – 2 to 3
    - 1 vessel operator and/or supervisor
    - 1 safety observer
    - 1 survey personnel to help move vehicle
- Shore Deployment and/or Recovery
    - Mobilize ASV and/or AUV, integrate sensors
    - Unload vessel in area close to survey area, if possible
    - Check beach conditions (sea state, traffic, fishing gear, marine life)
    - ASV and/or AUV pre-check, sensor start, sensor pre-check
    - Program mission from onboard computer
    - Deploy vessel to wading depth
    - Once deployed, complete mission, verifying data collection
    - Retrieve vessel at wading depth in surf zone
    - Power off propulsion system and sensors
    - Bring vehicle onshore, retrieve data and secure in/on transport vehicle

3.1.2 Vessel and/or Mothership Deployment and Recovery

3.1.2.1 ASV

ASVs can be deployed from a number of vessels/motherships with the appropriate equipment and deck layout. Depending on the ASV selected, including size and overall weight, equipment such as davits, cranes, or A-frames may be required for launch and recovery procedures. Before deployment, the system is powered on and propulsion systems are tested. Deployments can be conducted by personnel lowering the ASV to the water surface manually, if the design of the vessel and/or mothership allows, or by specialized equipment. The core challenges here are both typical crewed vessel constraints (cost, weather, safety) and the demand for increased size of vessel/mothership as ASV size increases. Once deployed, the ASV can be maneuvered to the project area manually or autonomously and proceed with the mission.

At the completion of the mission, the ASV can be maneuvered back to the main vessel and placed in a standby mode. Before recovery, lines or cables are attached to lift points and propulsion systems are powered off to avoid potential injury. The recovery process is completed by reversing the deployment procedures.

Common challenges with this method of ASV deployment and recovery are similar to traditional crewed survey vessels including sea state, weather, and vessel configurations. Vessel and/or mothership launches do have benefits for the operator by allowing for simultaneous operations to occur. While the ASV is

[1] Developed by CSA.

performing operations in one area, the vessel and/or mothership can perform other scopes of a project thereby doubling up on operations.

The Drix for example is a versatile USV designed to be operated either Over the Horizon (OTH) or within Line of Sight. iXblue provides dedicated LARS to support launch and recovery operations, including the Drix Deployment System and Universal Deployment System. The LARS can be configured as one or two lifting points. They are designed to be operated either from a crane or davit depending on the selected configuration. The Drix can also be towed from a vessel as small as a rigid-hulled inflatable boat.

3.1.2.2 AUV

AUVs have an advantage with vessel/mothership deployment and recovery as this method results in a wider range of vessels that can be chosen for AUV operations. Vessels with equipment such as powered davits, low gunwales, and swim platforms are ideal for deploying and recovering smaller AUV systems. Cranes, A-frames, or large davits are required for operations with larger AUV systems. Pre-deployment procedures are like the ASV procedures, the vessel is powered on, inertial systems initiated, and propulsion systems are tested. Once deployed, the AUV can begin the programmed mission and transmit positional data to the operator via USBL, DVL, and INS systems onboard without the need for frequent resurfacing.

As the mission is completed, the AUV will resurface and return to the crewed vessel or maintain its position for recovery. Before recovery, lines or cables are attached to lift points and propulsion systems are powered off to avoid potential injury. Like vessel based ASV recoveries, the AUV recovery process is completed in reverse of the deployment procedures.

Any number of vessels of opportunity (from a 5 m skiff to a 70 m offshore survey vessel) can be used for at-sea launch and recovery of the smaller AUVs. No specialized equipment beyond a swim platform, low-freeboard gunwale, or a powered davit (with appropriate working load rating) are required to support launch and recovery operations. An advantage to working from a vessel of opportunity is that transit time to/from the survey footprint can be minimized. Supervision of the AUV can be performed by the operators or by an ASV.

Deploying large AUVs from other vessels/motherships is common and usually employs specialized tools like ramps, A-frames, davits, and in some cases custom “garages” to capture the system and improve reliability and safety of launch and recovery. The core challenges here are both typical crewed vessel constraints (cost, weather, safety) and the demand for increased size of vessel as AUV/ASV size increases.

Common challenges with vessel based AUV deployment and recovery is sea state, weather, and vessel configurations.

3.1.2.3 Procedures for Deploying/Recovering from Vessel/Mothership[2]

- Personnel needed – 3 to 6
  - 1 davit, crane, and/or winch operator
  - 1 safety observer
  - 2 deckhand and/or line handler
  - 2 vessel operators and/or supervisors
- Small boat launch/recovery
  - Mobilize ASV and/or AUV, load onto vessel (manual loading, winch and/or davit)
  - Transit to survey area
  - ASV and/or AUV pre-check, sensor start, sensor pre-check
  - Program mission from onboard computer
  - Deploy ASV and/or AUV by hand/winch
  - Once deployed, begin mission, verifying data collection
  - Once the mission is complete and ASV and/or AUV is near vessel, secure using rope/pole
  - Connect to winch, power off propulsion system
  - Bring aboard and secure
  - Power off sensors
  - Connect to ASV and/or AUV, download/process data
- Ship-based launch and/or recovery
  - Mobilize ASV and/or AUV, load onto vessel
  - Transit to survey area
  - Position ship or boat in or near survey area
  - ASV and/or AUV pre-check, power on sensors and sensor pre-check
  - Program mission from onboard computer
  - Attach A-frame, crane, or davit to ASV and/or AUV lift points
  - Once deployed, begin mission, verifying data collection
  - At end of mission, maneuver vessel close to ASV and/or AVU and recover with poles/lines at attached lifting gear to lift points
  - Lift on deck
  - Secure ASV and/or AUV
  - Connect ASV and/or AUV to onboard computer or remove portable hard drive to for data download
- Some ASV systems use proprietary Launch and Recovery Systems
  - Systems include
  - iXblue DriX

3.1.3 Pier, /Dock, and/or Boat Ramp Deployment and Recovery

3.1.3.1 ASV

Deploying an ASV from a pier, dock, and/or boat ramp, depending on overall size and weight of the ASV, will require the crew to carry the ASV to the water, transport via LARS or road trailer, or use machinery such as cranes or davits. Other infrastructure such as boat ramps or floating docks can support this method of deployment and recovery for larger ASVs. Beforedeployment, the ASV is powered on and

[2] Developed by CSA.

tested by the operators. Once deployed, the ASV can begin transiting to the survey area. Depending on local activity, a support vessel may be required to provide safe navigation to the survey area.

Pier, dock, and/or boat ramp recovery procedures are like shore operations. As the ASV arrives at the recovery site, the system is programmed to a standby or station mode while any recovery equipment can be mobilized.

Common challenges associated with pier, dock, and/or boat ramp deployment and recovery procedures include distance from the survey area, wind speed, sea state surrounding the launch structure, lifting and swinging equipment, as well as supporting structure and equipment. Additional vessels may be needed to escort the ASV in or around heavily trafficked areas such as ports, harbors, or anchorages.

With advances in ASVs and communications, OTH operations are becoming a common accommodation with advanced ASV systems. These operations require intricate telemetry equipment such as satellite, iridium, Wi-Fi, and cellular receivers. OTH capabilities have allowed for remote operation of ASVs, as well as AUVs, transiting across congested and complex waterways autonomously with oversight from a trained operator.

Starlink, a satellite internet constellation operated by SpaceX, is now providing satellite Internet access coverage to over 40 countries. It also aims for global mobile phone service after 2023. SpaceX started launching Starlink satellites in 2019 and Starlink has since developed a maritime version that provides high-speed, low-latency internet access while at sea. This technology is currently being trialed by several of the ASV manufacturers chosen in this Task Order.

3.1.3.2 AUV

Pier, dock. and/or boat ramp deployments with an AUV system can be conducted manually, by hand, with most small models; however, the larger AUVs will require the use of equipment such as cranes or davits. This procedure will require a support vessel in cases where the AUV must transit through congested waterways such as ports, harbors, and anchorages where the support vessel can provide safe navigation, position updates, and status updates. Before deployment, the AUV will be powered on and tested, the programmed mission will utilize waypoint navigation to the survey area. The operator, located on the support vessel, can monitor conditions while enroute.

Pier, dock, and/or boat ramp recovery procedures for AUVs will require the AUV to resurface and use preprogrammed waypoint navigation to return to the launch area. Upon arrival, the AUV can be out in standby mode and propulsion systems powered down. If lines or cables are required for recovery, the support vessel can attach to lift points. Once attached, the vessel can be recovered and demobilized.

Challenges presented in this method of deployment and recovery include distance to the survey area, local vessel traffic, weather, sea state, availability of support vessels, and seafloor topography. Proper planning, vessel selection, and execution ensure personnel safety and timely mission completion.

Inshore launches, from a dock inside of a port/harbor, can also be executed. The AUV is launched by hand and the pre-planned mission incorporates transit waypoints for the AUV to safe navigation and transit from the harbor to the survey area. Mission design requires that the AUV has enough onboard battery to complete the survey activity and the return transit (or plans must be made to recover the AUV at sea from a support vessel). As in the case of shore-based launch and recovery, the AUV operations require that acoustic communications with the AUV are maintained from either a manned support vessel or from an ASV.

3.1.3.3 Pier, Dock, and/or Boat Ramp Launch and/or Recovery and Recovery with Autonomous Operations[3]

- Personnel needed – 3 to 4
  - 1 crane and/or lift operator
  - 2 deckhand/ and/or line handler
  - 1 vehicle operator and/or supervisor
- Dockside Launch via road trailer
  - Mobilize ASV and/or AUV and trailer to boat ramp
  - ASV and/or AUV Pre-check
  - Back ASV and/or AUV into water
  - While ASV and/or AUV is alongside dock, power on sensors for pre-check
  - Program mission from onboard computer
  - Launch escort vessel to lead ASV and/or AUV to open water
  - ASV operator on escort vessel to maneuver ASV and/or AUV to open water
  - Once on site, begin mission, verifying data collection
  - Once the mission is complete, retrieve ASV/AUV with pole/lines
  - Lift on deck and secure
  - Connect to onboard computer/remove hard drive and review/process data
- Pier and/or Quayside launch via crane and/or davit
  - Maneuver ASV and/or AUV to pier side
  - ASV and/or AUV pre-checks
  - Sensor warm-up and pre-checks
  - Connect to ASV and/or AUV to program mission
  - Attached lifting gear to lift points
  - Deploy ASV and/or AUV
  - Coordinate with escort vessel to release ASV and/or AUV from lifting gear
  - ASV operator to maneuver into open water or utilize obstacle avoidance capabilities.
  - Once on site, begin mission, verifying data collection
  - Once the mission is complete, retrieve ASV/AUV or maneuver back to pier/quayside
  - Coordinate with crane operator, attached lifting gear to ASV/AUV to lift points
  - Lift and secure on shore
  - Connect to ASV and/or AUV and review and/or process data
- Some systems have capabilities of complete autonomy and obstacle avoidance or use Operations Centers for real time piloting to eliminate the necessity of escort vessels
  - Systems include
    - iXblue Drix
    - XOCEAN XO-450

3.1.4 Concurrent Equipment Operation

There are many sensors embarked on ASV and/or AUV systems. These systems can be operated concurrently during mission operations using the onboard computer systems and often include SBES, traditional and interferometric MBES, SSS, magnetometer, SBP, ADCP, GNSS and INS, DVL, USBL, and video monitoring systems. Some acoustic systems may interfere with each other, but manufacturers understand these issues and design sophisticated timing sequences to resolve this problem. It will be the duty of the ASV and/or AUV operator and/or mission supervisor to determine optimal ASV and/or AUV

[3] Developed by CSA.

and survey settings to best utilize the equipment. Various instruments can be integrated with ASVs and AUVs and can be categorized by operational, meteorological and oceanographic, and hydrographic survey instruments.

All sensors are controlled by the ASV and/or AUV operator through remote desktop connections to the onboard computer systems. The onboard computers host all necessary software for ASV and/or AUV control, sensor operation, mission planning, data storage, and processing software.

Operational sensors can be integrated with an ASV to further understand their operating environments. These systems include onboard cameras to provide live video feeds to the operator, automated identification systems for information regarding nearby vessels, radar systems utilized in settings with obscured visibility, telemetry systems to provide control of the ASV by the operator, and navigation/positioning systems for use in on-line survey and autonomous operations.

AUVs have a similar ability for operational systems integration; however, are limited to the number of additional systems available for integration due to relative vessel size, payload capabilities and communications. AUVs can be equipped with live feed cameras, navigation and positioning sensors, and telemetry systems to provide environmental information to the operator.

SWARM applications for autonomous vessels are currently in use, acting as the primary vehicles for data collection or as force multipliers in conjunction with crewed survey vessels. NOAA has adopted this methodology for some of their hydrographic platforms. These systems can be a combination of ASVs, AUVs, or both. ASVs can be equipped with USBL systems and provide precise positioning to AUVs. Mission planning for simultaneous operations will take into account considerations such as working area, telemetry, applied sensors, and vessel duration.

With the integration of autonomous vessels to offshore operations, crewed survey vessels have the ability to complete various tasks within the operational range of the ASV and/or AUV. These tasks can include geotechnical sampling, benthic sampling, or similar activities.

The use of multiple assets to perform sand source surveys such as two or more ASVs and AUVs to cover a larger area more expeditiously is certainly possible. While a novel concept and certainly achievable through software programming during mission planning phases, the practicality quickly diminishes as costs will far outweigh the time savings. (See Table 3-1)

Table 3-1. ASV and/or AUV Platform Summary Including Operations, Endurance, Estimated Day Rate Operational Cost, and Sea State Operating Scale

ASV	Model	Concept of Operations	Endurance	Payload Flex	Cost Factor	Operating Scale–Beaufort Sea State
ixblue	DriX	Dock/Vessel	1 day	Low	$$$	6
L3H	C-Worker 4	Dock	1 day	Medium	$$	NP
Seafloor Systems	Hydro-Cat 180	Dock	~1 day	Medium	$	3
SeaRobotics	5.7 m	Dock	~1day	Medium	$	3
Marine Advanced Robotics Inc.	WAM-V 8	Dock	~1 day	High	$$	NP
XOCEAN	XO-450	Dock	1 day	Low	$$	NP
Maritime Robotics	Mariner	Dock	1 day	Medium	$$	NP
AUV						
Teledyne	Gavia	Beach/Dock/Vessel	~1 day	High	$$	N/A
L3H	Iver4	Beach/Dock/ Vessel	<1 day	Medium	$$	N/A

ASV	Model	Concept of Operations	Endurance	Payload Flex	Cost Factor	Operating Scale–Beaufort Sea State
Hydroid	REMUS-300	Beach/Dock/ Vessel	<1 day	Low	$$	N/A

ASV = autonomous surface vehicle; AUV = autonomous underwater vehicle; NP = Not Published; N/A = Not Applicable
$ = $1,000 - $2,999
$$ = $3,000 - $4,999
$$$ = $5,000+

Currently, and depending on the unit chosen, the cost of purchasing, leasing, renting, and/or operating multiple AUVs and ASVs along with their ancillary equipment and integration software can quickly surmount that of hiring, occupying, and operating traditional survey vessels. As an example, to deploy a swarm of five ASV or AUVs, the operator will need to locate five identical vehicles. Depending on your operational requirements and location, the operator will prefer to use a vehicle capable of operating in varying sea states and have a flexible enough payload to be able to operate as near a full suite (side scan sonar, magnetometer, sub-bottom profiler, and swath bathymetry) geophysical/hydrographic payload as possible, requiring the purchase or lease of five full-suite systems. At this point, the operator is potentially looking at vehicle rental costs upwards of $20,000 per day (five vehicles at $4,000 each per day for example), and sensor costs of upwards of $17,500 per day (five full-suite sensor packages for an estimated $3,500 per day.) These costs do not reflect the costs incurred by hiring additional vessel operators and/or support vessels.

The high valuation of the rental costs for autonomous systems are directly attributed to lack of available assets on the open market. Rental companies such as Ashtead Technology, Unique Systems, Seatronics, Echo81, and Subsea Technology and Rental, some of the larger rental companies for example, may have a few identical systems in their global fleet and likely not possessing the software required for swarm operation.

As the market evolves, new units will be added into the rental markets; however, which unit becomes harder as new manufactures of autonomous platforms are created, or existing ones develop new models to outperform their competitor's. Autonomous systems also require heavy maintenance and training, rental companies often shy from owning technology like this because it becomes not commercially viable versus other sources of income requiring less hands-on time from technicians.

A sufficiently-sized and adequately-occupied vessel (for vessel-deployed systems), or a sufficiently equipped and occupied shore base with AUV and/or ASV lifting and refitting capabilities either at the beach or a nearby port, will be required to maintain the retrieval and/or deployment schedule required of the five vehicles approximately once each day for each vehicle, with sufficient battery and data storage spares to be able to swap power and storage media for a rapid redeployment in order to maintain survey operations nearly around the clock.

While the five-vehicle swarm may be able to cover significantly more ground than a traditional single survey vessel deployment, the current vessel or shore base logistics requirements for retrieval/deployment, staffing, vehicle/sensor power and equipment needs for multiple autonomous systems deployment, retrieval and maintenance will likely exceed the cost of traditional vessel-based survey operations, as significant costs savings cannot be realized due to the deployment and/or retrieval logistics and the power and data transfer needs of numerous autonomous systems as opposed to real-time data collection using towed equipment on survey vessels, which can largely be completed around the clock, and without daily interruptions to sensor deployment and data collection.

Simultaneous operations using an ASV and AUV to conduct operations do occur. The AUV riding on the surface has access to GNSS satellite constellations. The coordinates are acoustically transmitted from the surface to the AUV on the seabed providing guidance to the onboard INS. This prevents drift over long duration surveys. Again, for sand source surveys this is not typically something that is cost-effective to do nor practical in such small survey areas.

Hydrographic sensors most installed on ASVs and AUVs include MBES, SSS, SBP, magnetometer and GNSS/INS systems. With the advancement of ASV and AUV overall size and technology, the ability to integrate multiple sensors for simultaneous operations has increased greatly. ASVs and AUVs can be integrated with the same equipment being used on traditional, crewed survey vessels resulting in seamless data processing and interpretation procedures. These sensors will provide seafloor data pertinent to sand source surveys in imagery, three-dimensional point clouds, and subsurface cross sections to identify key factors such as natural and anthropogenic/archaeological features, sediment layers, and benthic habitats.

The Gavia AUV for instance utilizes an L1/L2 GNSS receiver for surface GPS fixes for navigation. When submerged, the AUV relies upon an Ixblue C5 PHINS INS, aided by a DVL. The navigation drift while submerged is 0.25% of distance traveled (or better). Periodic GPS fixes or USBL position updates constrain the drift. Post-processing of the raw L1/L2 GPS data and the inertial navigation data is performed to improve overall navigation quality, such that IHO Order 1A survey standards can be achieved (it may be possible to approach Special Order standards; however, these methods are still being tested).

Survey instrument payload for the Gavia AUV is flexible, but the AUV can be configured to simultaneously collect four modes of geophysical survey data. These consist of:

- MBES: Reson T20 MBES
- SSS: Edgetech 2205B Interferometric Dual-frequency side scan sonar (600 kHz/1600 kHz or 600 kHz/900 kHz)
- SBP: Benthos CHIRP III Sub-Bottom Profiler (14 to 30 kHz, adapted into the current Gavia Sub-bottom Profiling Module)
- Magnetometer: Ocean Floor Geophysics Self-Compensating Magnetometer (onboard) or Marine Magnetics Explorer Magnetometer (towed)
- Similar setups are consistent with the Iver4 and Remus 300 AUVs

All instruments can be operated to collect data concurrently. However, optimal survey altitudes and track line spacing may require multiple AUV and/or ASVs to be deployed in a single survey area. For example, unexploded ordnance (UXO) and/or MEC surveys may require narrow survey line spacing and presentation of the AUV near the seafloor (<4 m [13.1 feet] altitude). This is not necessarily optimal for wide area MBES and SSS collection. However, survey altitudes of 5 to 8 m (16.4 to 26.2 feet) are ideal to optimize all four geophysical survey data collection modes.

The Drix underwater payloads, for example, are normally installed in a gondola located two meters below the water line. The gondola design can be customized as per clients' specific requirements. A gondola will typically accommodate a MBES, a SBP and a USBL system. A common configuration would include Kongsberg 2040 MKII as MBES, iXblue Echoes 3500 T1 as SBP and GAPS EMX as USBL. This configuration is given as an illustration. iXblue provides interfaces with the most common survey equipment whether from Teledyne, Norbit, Innomar, etc.

iXblue has also designed FlipiX, a remotely operated towed vehicle designed to be operated concurrently with the Drix as towing vessel. FlipiX when combined with the Drix provides a comprehensive solution to perform hydrographic, geophysical and UXO operation in a single run. FlipiX is designed to convey

SSS and Magnetometers. To note, operation of the FlipiX requires a support craft to connect the towed array of SSS and Magnetometers.

Other ASVs such as Hydrocat, Sea Robotics 5.7 m and the WAM-V have options for small winches to tow SSS and magnetometer sensors closer to the seabed. These winches are deployed from a control station via telemetry to the vessel.

3.2 AUV and/or ASV Unique Field Survey Factors

While high-resolution geophysical surveys in relative shallow water for sand and other minerals on the OCS are similar, there are multiple variables that must be considered when designing a project, selecting the proper survey equipment and developing the proper quality assurance and quality control requirements. Each unique project needs to develop a Field Data Acquisition Plan (FDAP) as well as a Quality Assurance and Surveillance Plan (QASP) outlining operational goals, quality concerns, regional and/or local logistical and planning considerations and unique field survey factors that may impact survey operations and the vehicles, vessels, and sensors selected for any specific survey.

An FDAP will help define operational goals, identify the line plan, data coverage needs, and potential impacts related to environmental factors, seasonal weather and/or oceanographic issues, and other operational factors. After the development of the FDAP, a detailed QASP will be developed to define data quality expectations and implement a surveillance plan for assuring that the survey is meeting these expectations. The QASP will define potential data quality impacts (like a thermocline, for instance), and the strengths and limitations of the chosen platform(s) to define a clear surveillance protocol to monitor data quality (like the collection and evaluation of real-time data from a towed platform, telemetered data from an ASV platform or incremental collection of remote AUV data with predefined retrieval, review and surveillance timelines) to ensure all sensors are collecting quality data that meets project goals.

The FDAP details and QASP goals will need to be considered independently with each project when selecting the proper vessel and/or vehicle, deployment/retrieval protocols and survey sensors. The following subsections attempt to describe some of these unique field survey factors that would need to be addressed on a project-by-project basis.

3.2.1 Unique Field Survey Factors

The same concerns that shape crewed surveys apply to ASV and/or AUV operations. For example, weather conditions and other uses of the region (e.g., jet skis, scuba diving, fishing) are all equally relevant to ASV and/or AUV work. Some considerations that are specific to these new tools include:

Water depth and/or topography–AUVs collect excellent data by traveling close to the seafloor. While they can adapt to changing water depths, they are not well suited to very complex topography such as coral reefs, walls, or ledges.

Ambient uses–if an area is widely fished this presents a challenge to both ASVs and AUVs. Likewise, very dynamic and busy waterways are not well suited to ASVs.

3.2.1.1 Environmental Considerations

Concerns shaping crewed survey vessels also shape ASV and AUV operations including environmental considerations such as weather, sea state, and visibility. These factors will affect ASV deployment and recovery operations, other surface support vessels as well as telemetry strength. Surface conditions can also affect incoming data from all sensors onboard such as wave height increasing the heave of the vessel, affecting navigation and mapping sensors.

Water depth and topography are a key consideration when programming and executing a survey mission with an ASV and an AUV. For shallow water geophysical surveys, operational water depths are determined by the draft of the selected ASV and operational limits of the integrated sensors. While most AUV systems have the capability to adapt to changing water depths, highly dynamic seafloors can pose threats to the safety of the AUV. Areas of interest for sand source surveys have low relief; however, seafloor features such as boulders, bedrock outcrops, and reefs all pose considerations for AUV operations. AUVs can be equipped with sensors to allow for the capability of object avoidance using forward-facing sonars and cameras, mitigating risks in these areas. The class of AUVs for sand source surveys have a shallow operational capability compared to some of the larger assets. Manufacturers vary the depth rating based on the market they are designed for. For the units in Table 3-1, a maximum of ~1,500 m (4,921 feet). Full-size AUV platforms are now achieving operations in water upwards of 4,000 m (13,123.4 feet).

Surface and subsurface currents will also affect the operation and data quality of both ASV and AUV systems. This will cause the vessel to consume more power to complete the mission and attain the appropriate on-line heading during data acquisition. These considerations will be applied appropriately during mission planning.

One of the advantages to AUVs is that the AUVs are decoupled from sea state conditions and can maintain a stable survey behavior independent of sea state. The five critical environmental constraints are:

- **Sea State and Surf Zone Conditions:** this impacts the safety during launch and recovery operations, and it also impacts the data quality of MBES data because of the heave signal that the passing waves introduce to the MBES transducer draft. Post-processing techniques attempt to manage this issue, but it is always cause for concern.
- **Currents:** Current magnitude and direction can impact ASV and/or AUV transit, power consumption, and stability while on-line for surveys. Currents of two knots or less are preferred. Further impacts caused by currents are mitigated by mission design parameters to best accommodate currents that are anticipated in survey areas.
- **Kelp, Seaweed, Fishing Gear.:** Kelp, seaweed, and fishing gear pose entanglement hazards to AUVs. Areas with dense kelp or seaweed tend to be avoided. Eelgrass beds tend to be acceptable, because the AUV will fly at a constant altitude above the beds which are attached to the seafloor, so they pose minimal risk. Fishing gear can pose greater entanglement risks to both AUVs and ASVs due to their location throughout the water column. Surface buoys can become tangled in ASV propulsion systems where AUVs can become entangled in nets, lines, etc.
- **Rough and/or complex seafloor morphology:** Large and/or high boulders, bedrock outcrops, shipwrecks, and coral reefs can pose impact or entrapment hazards to AUVs that are executing missions with constant altitude behaviors designed into the missions. Object avoidance capabilities (such as those enabled on the REMUS-300 AUV) mitigate risks of impact, and self-egress behaviors are also designed into the vehicle to free itself from some entrapment scenarios.
- **Oceanography:** AUV operations are not altered during a mission; the presence of thermoclines and pycnoclines may pose data quality risks during acquisition for AUVs due to the restriction of real-time monitoring; however, these vessels are equipped with sound velocity sensors that can log data continuously for post-processing applications to rectify these phenomena. Further, as mentioned above, additional consideration must be given in FDAP and QASP plans for addressing and surveilling these concerns, with real-time systems (AUV and towed) providing more flexible options for quality surveillance than AUVs, which require deployment, data collection, and retrieval before being able to determine data quality issues and QASP compliance.

3.2.1.2 Operational Considerations

Operational considerations for ASV and AUV operations include vessel control and oversight, vessel traffic, vessel configuration, energy management, and vessel navigation references.

How the ASV and/or AUV is controlled by operators is a key constraint. Typically, the system is programmed with a mission and then deployed to execute. Often these missions are a series of waypoints marking out a pattern of motions designed to move the system over an area of interest to collect data in a pattern designed to meet all requirements and specifications. During the operation of these surveys the systems use their onboard sensors and processors to autonomously react to changes in the environment such as water depth or surrounding vessels. Operators are tasked with designing a proper survey pattern and then monitoring the operation in case of anomalies. To fulfill this role, it is important that operators have some form of communication with the system (usually radio based in air and acoustic underwater) and are positioned in an appropriate location to understand the operating environment. Usually, AUV operations are "easier" in that there are few concerns about interacting with other vessels. ASVs have been refined and tested over many years and demonstrations have included remote (sometimes very distant) operators safely managing ASVs at sea. This is now routine practice for many commercial and military operators.

Another consideration in the planned use case is designing a survey plan that optimizes the operation. This effort is identical to that conducted by current crewed vessels and is usually driven by the specifications of the desired sensors. For example, laying out survey lines to account for differing swath width of mapping sensors and to account for prevailing wind and waves (to minimize vessel disturbance) are well understood practices. These apply to ASV and/or AUV missions, as well.

Energy management for ASVs and AUVs is essential for operational considerations. Some systems may carry more than enough onboard energy to complete any planned survey mission. Others may need to make accommodations for energy recharge. ASVs may need to pause a mission to replace depleted batteries or refuel an internal combustion engine, while AUVs would need to return to the operator to recharge the internal batteries or replace depleted batteries. While this is a necessary consideration it is not a fundamental obstacle to the types of surveys anticipated.

Navigation references must be defined based upon the vessel being used and are essential to achieving acceptable positional accuracies. ASVs use the same surface positioning tools, typically GPS, as crewed vessels. But AUVs need different tools to measure their position both relative to the seafloor and to the relevant geographic reference frame. These tools typically include DVL for speed over ground measurement, inertial measurement units to track AUV body motion and acoustic systems that can provide measurements to known points, either the vessel or seafloor. The most common acoustic solutions are 1) USBL systems that measure range and bearing between a surface point (usually vessel) and the AUV and 2) long baseline systems that measure AUV position relative to a grid of beacons placed on the seafloor. Long baseline provides greater accuracy but at increased cost in more mobilization and time spent installing and surveying the transponder grid.

Shallow water geophysical surveys should not impact any marine habitats because the AUV can maintain a steady, constant altitude above the seafloor to avoid impact with the bottom and disruption of benthic communities.

In the last few years, valuable experiences in autonomy have been learned. Manufacturers working with regulatory authorities to achieve authorization and approval to operate have increased. In most cases, this experience has been developed from project-by-project requests which in part has led to the education of authorities not familiar with the autonomous marine industry. The principal points of contact are the USCG, Harbor Masters, and Harbor Authorities in the vicinity where operations will occur. Often times a

Notice to Mariners and approved very high frequency radio navigation warnings may also be issued to notify mariners in the vicinity.

Health, Safety and Environment documentation should be developed by the company to plan for all launch and recovery risk assessments, emergency recovery plans and procedures, and a step-by-step guide on mission planning and methodology statements. These documents should be provided to any authority or contract issuer before work begins. Industry best practices start with the cognizance of the sensitivity and responsibility towards autonomous vehicles operating alongside manned vessels.

3.2.1.2.1 Restricted Areas

Area restrictions concerning traditional, crewed survey vessels also apply to ASVs and AUVs. Government-controlled areas, such as military ports and harbors, and high traffic areas pose the same restrictions to autonomous vehicles as crewed vessels; however, these areas are not subject to sand source considerations. Other instances of restriction include areas with ongoing military and government operations where permits or other forms of authorization may be required to conduct geophysical operations. The process for granting authorization depends on Federal and local regulations. The request for authorization is one essential step of the operation planning and will, in many instances, rely on operational risks assessment.

There are no additional restrictions for AUV operations, except that surfaced AUVs are unable to avoid passing vessel traffic. Care must be taken during AUV operations to design missions that avoid high vessel traffic areas, and to supervise AUV operations that are in the vicinity of potential vessel traffic. Also, during surf zone launch and recovery operations, the launch and recovery lanes should avoid swimmers and surfers to prevent injury to bystanders.

3.2.1.2.2 Key Personnel

The USCG's Navigation Safety Advisory Council (NAVSAC), U.K. Maritime, and the European Safety and Regulations for Unmanned Maritime Systems (SARUMS) Group have all published voluntary best practices to provide an initial set of standards, guidance, and information to owners and operators for the safe design, manufacture, testing, operation, and maintenance of autonomous vessels[4].

Currently, there are no formal requirements, including licenses or certificates, for operating ASVs and/or AUVs. Some vessel manufacturers offer system specific training programs for their vessels or training may be provided through organizational programs. However, good practice for AUV and ASV operations include the employment of licensed personnel, such as captains and hydrographers, to oversee operations. Due to the highly technical nature of these types of vessels and their associated equipment, personnel chosen for autonomous operations must be well versed in geophysical surveys and marine operations to assemble, disassemble, test, and troubleshoot all sensors.

Roles and personnel assignments may differ depending on specific operations. One person may take responsibility of more than one role depending upon specific operations such as launch and recovery. Key roles may include but are not limited to, an operations lead, mission supervisor, vessel supervisor, vessel operator, and equipment operator. Other essential personnel may be required to operate various machinery for launch and recovery operations and will be dependent upon the ASV chosen to conduct each mission. No universal credentials are noted, good practice includes a licensed skipper to oversee

[4] See https://maritimesafetyinnovationlab.org/wp-content/uploads/2016/06/navsac-resolution-16-01-unmanned-maritime-systems-ums-best-practices-final-05-may-2016.pdf

ASV operations, but not necessarily be "at controls." Operations demand good marine technicians who can assemble, test, and debug complex ocean technology. Surveys will benefit from staff trained in hydrographic survey techniques. None of the requirements for ASVs are different from current practice with manned vessels and existing staff can easily adapt to this technology.

AUV Operators are trained by the manufacturer and via organizational training programs. There are no specific certifications or licenses for AUV operations. It is wise for companies to have a lead autonomous director on staff, fully trained and experienced autonomous operators, a USCG-licensed Merchant Mariner and Certified Hydrographers in their autonomous department.

3.2.1.2.3 Emergency Operations

Emergency scenarios for ASVs and AUVs include the fouling of thrusters, vessel strikes, loss of propulsion or power, loss of vehicle through sinking, and sensor failure. More advanced autonomous vessels have capabilities that will mitigate these potential risks such as object avoidance and OTH operations. OTH operations are defined as the capability to conduct any mission beyond the line of sight, usually through satellite or cellular data connections. With this capability, operators can supervise vessels during missions and detect anomalies as, or if, they occur.

Advanced systems can program positions for vessel returns and adjust telemetry communication sources in the event of signal loss in case of emergencies as well as self-righting capabilities. AUV systems are equipped with the capability to self-egress in cases of entrapment or fouling; however, this is a low-risk scenario in cases of sand source surveys.

Secondary support vessels will be a necessity for ASV and AUV operations in any event of emergency. Vessels of Opportunity can include USCG (or other governmental) vessels, charted fishing vessels, or small rigid-hulled inflatable boats. The vessels considered for emergency recoveries shall be outfitted to accommodate the necessary recovery procedures for the ASV and AUV including using ROV resources to retrieve subsurface or sunken vehicles, as necessary. These vessels will remain on standby in emergencies if the ASV or AUV is unable to respond to commands from the operator. The standby vessels may also be used to deploy supplemental gear and/or equipment such as the iXblue FlipiX.

3.2.1.3 Other Considerations

As with all selection of geophysical survey equipment whether using a traditional or autonomous platform, there are several additional considerations for assessing the risk as it relates to marine mammals, sea turtles, and fish. These considerations include the noise produced by the survey equipment; strike risk by the survey platform; and entanglement risk by any deployment and recovery systems that might be incorporated in the autonomous systems. These considerations are discussed in the following sections.

3.2.1.3.1 Sound Sources

The sound sources proposed for the survey systems include MBES, SBES, SSS, and SBP in the form of CHIRP and parametric sources. BOEM reviewed these sources in the Biological Assessment (BA) for Data Collection and Site Survey Activities for Renewable Energy on the Atlantic Outer Continental Shelf (Baker and Howson 2021) and in BOEM 2018. The BA analysis determined that the ranges of acoustic disturbance from these sources were 10 m (32.8 feet) or less for sea turtles and marine mammals and no more than 32 m (105 feet) for fish species. Many of these sources were evaluated by an interagency BOEM, USGS, and NSF team and were found to be unlikely to result in takes of marine mammals due to their low sound intensity, high-frequency absorption, and/or limited beamwidth, and therefore are considered de minimis (Ruppel et al. 2022)

Permit and mitigation requirements for lower frequency, high source level CHIRP sources may need to be addressed on a source-specific basis. If mitigation is required, visual observers may be required, or some type of remote sensing/remote monitoring may be required so that actions could be taken if there was a risk to an animal.

3.2.1.3.2 Strike Risk

AUVs operate below the surface at slow speeds. There are no known reports of adverse AUV interactions with sea turtles or marine mammals; therefore, limited strike risk is expected from AUV operations. However, some ASVs are large enough and move at speeds that could pose a risk to marine mammals and sea turtles, particularly juveniles. Although the risk is low, speeds less than 10 knots would be recommended for all ASV operations, including transit periods. It is expected that ASVs would be required to operate under all speed restrictions proposed by NMFS even though they may be under 35 feet (10.7 m) in length. The 10-knot speed restriction would be applicable for a project between November 1–April 15th with extended periods to April 30th in North Carolina waters. Additionally, there is North Atlantic right whale critical habitat along the eastern U.S. from Central Florida to Cape Fear, North Carolina, which does not directly pose additional restriction but would be more highly scrutinized for potential strike risk due to calving.

Sea turtles could be expected year-round in the Gulf of Mexico and along the southeastern states. Although no critical habitat for any of the sea turtle species occurs in the Gulf of Mexico or along the southeastern states, offshore *Sargassum* critical habitat for loggerhead sea turtles is present offshore of the southeastern states. It is expected that slow speeds will reduce the strike risk to negligible for sea turtles.

3.2.1.3.3 Entanglement

The configuration of the AUVs and ASVs with the survey equipment are not expected to have any loose lines or other gear likely to cause an entanglement risk to either marine mammals or sea turtles.

3.2.1.3.4 Marine Habitats

Fundamentally, AUVs and ASVs present the same potential environmental impacts as crewed survey vessels. Submerged aquatic vegetation is a concern for the planning and execution of AUV operations, although this risk of disruption is minimal. AUVs currently on the market can maintain a constant altitude during mission operations independent of sea state conditions.

3.2.1.3.5 Marine Fauna

With regards to marine fauna migration patterns and periods, there are no restrictions present for ASV and AUV operations; however, dense schooling fish can interfere with acoustic sensors. It will be the duty of the ASV and/or AUV operator to monitor incoming data to determine if additional data collection is required. This type of marine behavior can also influence forward-looking sonar and object avoidance capabilities.

The current regulation for seasonal management areas (SMAs) for North Atlantic right whales applies only to vessels greater than 65 feet (19.8 m) in length which would be required to travel at speeds 10 knots or less in designated SMAs off the eastern seaboard. There are additional mandatory reporting requirements for vessels ≥300 gross tons and vessel routing recommendations in some areas (the southeast region off Georgia and Florida has recommended routes to avoid and reduce collisions). Since ASVs and/or AUVs do not fit any of these criteria (all are smaller than the requirements), then SMA rules would not apply–unless there are support or other vessels that fall under the vessel size requirements.

There is currently a proposed rule that would amend the spatial and temporal boundaries of the current SMAs and further include all vessels equal to or larger than 35 feet (10.7 m) in length. All ASVs/AUVs are smaller than this size requirement; however, the proposed rule would apply to support vessels, if approved.

Finally, there are also Dynamic Management Areas and Slow Zones that are established when certain numbers of North Atlantic right whales are detected in those areas. Both are voluntary 10 knot or less speed recommendations (all vessels).

Overall, for the ASVs and AUVs described in Table 2-1, there would be no mandatory restrictions regarding the North Atlantic right whale speed rule and critical habitat, but there are some considerations to take into account (calving area critical habitat, voluntary speed recommendations) as well as larger support vessels (based on length and/or gross tonnage) could fall within restrictions.

3.3 Summary Assessment

The use of AUVs and ASVs for seafloor survey applications is understood and well adopted by the current industry. Placing greater emphasis on deploying new or existing technologies will enable increased efficiency. A variety of vehicle types exist on the open market and are in use with a diverse set of service companies. The relevant sensors for sand assessment such as the instruments listed in Table 2-2 are all available in specific models for autonomous platforms or configurable for integration with them. Associated positioning and control capabilities make ASVs and AUVs suitable for sand source missions. In sum, using AUV and ASV vehicles with appropriate high-resolution geophysical and hydrographic sensors is feasible for shallow water sand search investigations that have been, to date, completed using various combinations of (SBP/SSS/MAG) towed systems in conjunction with hull or side pole mounted sensors off manned survey vessels.

That said, specific project goals, operational requirements, project budgets and timelines, and other limitations (regional and/or local logistical considerations, vessel, vehicle and/or sensor availability, regional/seasonal weather and oceanographic conditions) must be considered on a case-by-case basis to truly determine if an AUV, ASV or traditional vessel based towed survey is the best solution for any given project. The state of the industry at this point supports the use of AUV, ASV and traditional towed-sensor survey vessels depending on these variables. As an example, for a small survey planned to last three to five days in length, in a region with available survey vessels, appropriate port and maritime facilities, qualified survey staff, during calm seasonal weather conditions and with limited transit times, it may be difficult to beat the cost and efficiency of a traditional towed-sensor vessel-based survey. Alternatively, if the survey requires a significant transit from appropriate port and maritime facilities, must cover a large amount of seafloor with a long deployment time, will occur in a remote region on the shallow-water OCS, or must be completed in a short timeline, a swarm of AUV or long-distance ASV vehicles with an appropriate support vessel may be the most efficient and cost-effective selection.

The fundamental challenge is one of devising an appropriate Concept of Operations (CONOPs) suitable to the specific geographic and policy considerations of the various survey regions and specific survey goals. While these issues require careful consideration before embarking on an ASV and/or AUV survey, they are not fundamental obstacles. In the current commercial, scientific, and military survey applications, these tools have delivered favorable economics compared to more traditional crewed vessels. It is likely that similar cost and efficiency improvements will be seen in sand resource assessments, leading to a long-term shift toward AUV and ASV surveys over the current standard of traditional towed sensor survey vessels.

Costs for owning, operating, and maintaining AUV and/or ASV platforms are coming more in line with conventional survey operations. A diverse and healthy fleet of systems to choose from and manufacturers competing for market space are driving this change.

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Appendix A: Asset Database

This Appendix will be delivered as a Microsoft® Excel file under separate cover.

Appendix B: Specifications for Autonomous Surface Vehicles and Autonomous Underwater Vehicles

Table B-1. Specifications for AUVs Analyzed in this Feasibility, Field Techniques, and Best Practices Analysis

Notes:
*indicates capability changes based on AUV configuration.
1Equipment operating depths are based on maximum pressure rating.
"DC = direct current
kWh = kilowatt hours
Li-ion = lithium ion
NiMH = nickel-metal hydride
SSD = solid state drive
TB = terabyte

Appendix C: Specifications for Associated Equipment

Table C-1. Specifications for Equipment Analyzed in the Feasibility Study, Field Techniques, and Best Practices Analysis

Notes:
ASV = autonomous surface vehicle
AUV = autonomous underwater vehicle
DVL = Doppler velocity log
GNSS = Global Navigation Satellite System
Hz = hertz
INS = inertial navigation system
kHz = kilohertz
MBES = multibeam echosounder
mGauss = milligauss
N/A = not applicable
NEMA = National Marine Electronics Association
ns = nanosecond
nT = nanoTesla
PPS = pulse per second
SBES = single beam echosounder
SBP = sub-bottom profiler
SSS = side scan sonar
USBL = ultra-short baseline
V = volt
VAC = volts, alternating current
VDC = volts, direct current
W = watt

Table C-2. Abbreviations and Acronyms

Acronym	Definition
AC	Alternating Current
Cm	Centimeter
cm/s	centimeters per second
COFDM	Coded Orthogonal Frequency-Division Multiplexing
DDS	Drix Deployment System
DVL	Doppler Velocity Log
FM	Frequency Modulated
GB	Gigabyte
GHz	Gigahertz
GNSS	Global Navigation Satellite System
HF	High Frequency
HP	Horsepower
Hz	Hertz
IHO	International Hydrographic Organization
INS	Inertial Navigation System
IP	Internet Protocol
kg	Kilogram
kHz	Kilohertz
kW	Kilowatts
kWh	Kilowatt Hour
LiFePO4	Lithium Iron Phosphate
Li-ion	Lithium Ion
LiPoly	Lithium Polymer
LTE	Long Term Evolution
M	Meter
MBES	Multibeam Echosounder
mm	Millimeter
mm/s	millimeters per second
NiMH	Nickel-Metal Hydride
NMEA	National Marine Electronics Association
nT	nanoTesla
PbAcid	Lead Acid
RAM	Random Access Memory
RDSM	Removable Data Storage Module
RTK	Real-Time Kinematic
SATTCOM	Satellite Communications
SBES	Singlebeam Echosounder
SBP	Sub-Bottom Profiler
SCM	Self-Compensating Magnetometer
SSD	Solid State Drive
SSS	Sidescan Sonar
TB	Terabyte
USBL	Ultra-Short Base Line
V	Volts
VAC	Volts, Alternating Current
VDC	Volts, Direct Current
W	Watts
Wh	Watt Hour
WHOI	Woods Hole Oceanographic Institution

U.S. Department of the Interior (DOI)
The DOI protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

Bureau of Ocean Energy Management (BOEM)
BOEM's mission is to manage development of U.S. Outer Continental Shelf energy and mineral resources in an environmentally and economically responsible way.

BOEM Environmental Studies Program
The mission of the Environmental Studies Program is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments. The proposal, selection, research, review, collaboration, production, and dissemination of each of BOEM's Environmental Studies follows the DOI Code of Scientific and Scholarly Conduct, in support of a culture of scientific and professional integrity, as set out in the DOI Departmental Manual (305 DM 3).