

Demonstrated Performance of Economical, Man-Portable AUVs in Multi-Vehicle Coastal Surveys

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Abstract- Autonomous underwater vehicles (AUVs) have the demonstrated technical capability to support environmental characterization for commercial, research, and military applications. The track record of AUVs in this mission area over the past decade has resulted in a growing confidence in the reliability and performance of AUVs, and with this confidence comes a rapid increase in the expected breadth and complexity of applications. The historical approach to developing these new capabilities has been grounded in hardware and sensor integration. This approach addresses the immediate need to meet a specific requirement, but it does not address the long term solution for coordinating operations of increasingly complex AUVs in rapid response scenarios. The chasm between technical capability and effective performance will continue to widen until dedicated work addresses a concept of operations and the ability to delegate command and control to the lowest level through increased vehicle autonomy. Critical gains in operational effect can be realized in military applications through this approach and greatly expand the role of forward-deployed tactical teams performing Rapid Environmental Assessment without dedicated special team resources.

Recognized Environmental Picture 10A (REP10A) offers an opportunity to evaluate a unique CONOPS for military survey operations in shallow coastal waters. Low-cost commercial AUVs are employed for coordinated operations in shore- and ship-launched scenarios to address on-scene, evolving search and survey operations without the logistical and support requirements of special teams normally associated with this tasking. Lightweight AUVs can be launched/recovered by a single operator in a one-to-many coordinated survey that streamlines time, maximizes the synoptic nature of the measurements, and reduces mission risk. On-scene products are generated from the AUVs upon completion of the mission, and data is provided to central access points to support environmental modeling. The Naval Undersea Warfare Center, Faculdade de Engenharia - Universidade do Porto, Marinha Portuguesa, and OceanServer Technology, Inc. are the primary participants bringing in-water resources to REP10A. Technical support and products are provided by the Naval Research Laboratory – Stennis Space Center, Naval Oceanographic Office, NATO Undersea Research Centre, University of Massachusetts – Dartmouth, and YSI, Inc. Primary goals of REP10A are evaluation of CONOPS, on-scene products, and reach-back support products. A focus on lightweight AUV-based multibeam swath bathymetry, side scan sonar performance, 3-D water characterization, AUV autonomy, validation of remotely sensed bathymetry, and initialization/steering of near-shore circulation and structure models is maintained during the test.

I. INTRODUCTION

Autonomous Underwater Vehicles are finding increasing use in commercial and military applications, and the capabilities are expanding rapidly as the demand for specialized functions and extensions to traditional missions steadily rises. In some cases, the design is driven to large AUVs to support sophisticated sensor suites and endurance objectives. Typical costs for these units exceed \$1M USD per unit, and specialized teams with substantial logistical support requirements accompany the AUVs for mission planning, execution, and data preparation. Mid-size AUVs represent a substantial reduction in initial and operating costs, and speed, endurance, and sensor capabilities remain effective for a host of applications. However, the smallest class of AUVs, those capable of single-man transport, has established a significant niche in the user community, and this class is well-suited for specific applications. Speed and endurance are still on the order of 4 kts for 5+ hours, and the economy of purchase cost and operation enables multiple vehicles to cooperatively execute missions.

Many missions can benefit from the application of multiple small AUVs, particularly if the missions are time critical, benefit from synoptic measurements, or have disparate high priority subareas. Rapid Environmental Assessment (REA) missions are examples that can derive significant advantage from this multi-vehicle approach, with reduced smearing of time-variable parameters and flexibility in launch points and survey geometries. Additionally, multiple small AUVs mitigate risk to mission success from single unit failure, allow for collaborative real-time survey changes in response to evolving tactical or environmental conditions, and reduce risk to resources in hostile environments.

Benefits to the user community of this smallest class are also realized from expansion of the manufacturing base. Open production has resulted in a leveraging of commercially available components and software, significantly reducing development costs, and the cost of continuing improvements are spread across a customer network with overlapping requirements. The diverse user community has promoted adoption of modularity, and the demand for varied mission applications has resulted in open, non-proprietary Application Programming Interfaces for vendor-independent introduction of specific unique capabilities.

II. BACKGROUND

The many advantages of economical, man-portable AUVs have attracted the attention of the US Navy for specific mission areas. The Naval Undersea Warfare Center Division, Newport (NUWC) purchased three Iver 2 AUVs in FY2007 from OceanServer Technology, Inc. in Fall River, MA as R&D platforms to investigate Command and Control (C2) software development supporting collaborative behaviors and survey optimization for oceanographic characterization, areas of investigation applicable to multi-vehicle AUV operations. The economy, operability, and flexibility for code integration through open, non-proprietary APIs provided a significant draw for this purchase. The platforms proved to be very effective for rapid prototyping and evaluation of code, particularly for C2 routines introduced through a secondary CPU using a Back Seat Driver (BSD) paradigm. The BSD utilized the Mission Oriented Operating Suite (MOOS) and Interval Programming (IvP) helm to introduce and regulate multiple, potentially conflicting, objective-oriented behaviors with weighted priorities.

While the R&D aspects of the Iver2 AUVs were extremely useful, the potential for operational support with a new CONOPS suited to the commercialization of this AUV technology was also of interest. The advantages of employing economical, man-portable AUVs in multi-vehicle REA survey missions by forward deployed tactical forces provided significant appeal. The Littoral Battlespace Sensing, Fusion, and Integration (LBSF&I) acquisition program under the Oceanographer of the Navy targeted REA and Intelligence Preparation of the Battlespace (IPB) missions, and this AUV technology was well suited to rapid characterization of the environment in shallow coastal waters, with response times largely unfettered by logistical support. Initial procurements centered on the purchase of ocean gliders (LBS-G), however, and the rapid response supported by organic assets deployed by tactical units was pushed to a later procurement phase of LBSF&I.

Significant interest was voiced by operational commands whose need for on-scene environmental data was a high priority, and whose requirements were often rapidly evolving. The Naval Special Warfare (NSW) and Navy Expeditionary Combat Command (NECC) had search and survey missions which were particularly well suited to the Concept of Operations supported by economical man-portable AUVs. In 2007, Naval Special Warfare Group 4 (NSWG 4) arranged for the procurement of four Iver 2 AUVs for evaluation in an operational setting. The AUVs were bought as a commercial “off-the-shelf” product with no modifications of software or hardware to better address unique military requirements. After a brief familiarization period, the Iver 2 AUVs were deployed with Special Boat Team (SBT) 22 in the SW Asia theater and put to work in local search and survey missions. Operations and maintenance on the AUVs were performed by an Aerographer’s Mate embedded in SBT 22. Personnel from the Riverine Squadrons and SEAL Team 5 were trained locally on Iver 2 operations, and they utilized these assets in their independent operations.

Over the next year of Iver 2 AUV operations and field evaluation, NSW Group 4 worked with SBT 22 personnel to assemble a list of capabilities and system improvements required to achieve full benefit in tactical utilization of the Iver 2 AUVs and support consideration as a future acquisition item. This list included new sensors for integration, as well as changes to existing software. Specifically, the list comprised:

- a. integration of the Imagenex Delta T multibeam sonar currently utilized in the US Navy Expeditionary Multibeam Kit (EMK)
- b. integration of Iridium communications hardware with provision for two-way Short Burst Data communication
- c. integration of a DVL/ADCP system for navigation accuracy and current profiling
- d. integration of an improved temperature/conductivity sensor
- e. development of Command and Control software to promote survey optimization and enhance vehicle safety
- f. the ability to develop on-scene products using software applications already familiar to the user community (Falconview, CARIS, and OceanServer Technology, Inc. VectorMap)

Note that the integration of these components would not affect the suite of sensors and capabilities already provided in the baseline Iver 2 AUVs, such as dual-frequency side-scan sonar, existing navigation, communication components, etc.

The Office of Naval Research (ONR) TechSolutions program office reviewed a proposal from NSWG 4 to have OceanServer Technology, Inc. perform the integration of existing commercial components on the Iver 2 AUV, and to task the Naval Undersea Warfare Center Division, Newport with project oversight, C2 software development and integration, and Iridium communications design. The ONR TechSolutions program office awarded funding to the project for late 4th quarter FY09 and FY10. The delivery of three Lightweight NSW AUVs in SEP 2010 will complete the project. Preliminary evaluation of the Lightweight NSW AUVs was completed during the mid-project demonstration in March, 2010, and a more complete operational test of the three Iver 2 AUVs was scheduled in association with the NATO Undersea Research Centre (NURC) exercise Recognized Environmental Picture 2010 (REP 10).

III. RECOGNIZED ENVIRONMENTAL PICTURE 2010 (REP 10)

Recognized Environmental Picture 2010 (REP 10) was organized and scheduled under NURC leadership to sequentially address operational and tactical oceanographic objectives in two locations: 1. the Gulf of Cadiz near the western entrance to the Gibraltar Strait (REP 10A) and 2. the western Alboran Sea (REP 10B). The Gulf of Cadiz would support operational evaluation of low-powered AUVs in shallow water or near shore operations, augmenting the deep water assets for environmental characterization and providing an REA capability for shallow water and amphibious operations. The operational test of the Iver 2 AUVs would be embedded in REP10A scenarios and mission design. Rescheduling and relocation of REP 10A due to changes in ship schedules led to a hosting of the exercise by Marinha Portuguesa near Sesimbra, PO. Faculdade de Engenharia - Universidade do Porto provided the liaison for international participants, and NURC maintained endorsement. The Naval Special Warfare Group 4, Naval Undersea Warfare Center Division-Newport, OceanServer Technology, Inc., and YSI, Inc. had personnel and equipment on site, and UMASS Dartmouth and the Naval Research Laboratory supported the exercise with data processing, management, review, and modeling.

REP 10 A was conducted primarily from the Marinha Portuguesa ship NRP Bacamarte (Figure 1) during 8 days in roughly 50 m water depth west of Troia, PO. The ship provided underway opportunities and anchored for a portion of the time to support launch and recovery of some of the larger AUVs and USVs participating from the Marinha Portuguesa AUV squadron and the Faculdade de Engenharia - Universidade do Porto research group. Approximately one dozen mine shapes and decoys were seeded in the OPAREA as targets for AUV sonar missions. Rigid Hull Inflatable Boats (RHIBs) and a Marinha Portuguesa Dive Squadron were assigned to NRP Bacamarte during the exercise to support evolutions.



Fig. 1 (a-c) The NRP Bacamarte. Of Marinha Portuguesa provided services as served as a transport and launch platform for AUVs during REP 10A. The AUVs were launched while underway at 5 kts from the vessel quarter using a canvas sling. Approximately 2 minutes were available between sequential launch points to prepare and deploy the AUVs. Shore launch of multiple vehicles was easily accomplished in 0.5 m of water depth using a delayed launch, with a total launch sequence of < 2 minutes.

Operational demonstration in REP 10A of the Iver 2 AUVs developed for NSWG 4 with funding from the ONR TechSolutions program office will be characterized in four areas: Capability, Operability, Reliability, and On-Scene Products.

Capability Capability will be evaluated in terms of both component and system performance. Integrated sensor and communication components must perform without degradation relative to independent operation. (Note Iridium integration was not completed for this operational test, and this will be the sole component of the project specification not evaluated with REP 10A data.) Platform characteristics will be assessed to ensure that navigation and maneuvering meet the objectives detailed in the performance specification, and C2 software performance will be evaluated in the REP 10A scenarios to determine robustness in varying conditions. Because the exercise was extended to 23 JUL, a full evaluation of capability at the component and system level remains to be completed. Preliminary review of the data sets have revealed both successes and individual, non-recurring component-level faults that are being investigated for correction.

Operability Operability of the system proved excellent in REP10A, and reinforced experiences from the mid-project demonstration. It was evaluated in terms of mission planning and review, AUV launch/recovery, and field maintenance/repair.

Mission planning and review were conducted using the OceanServer Technology, Inc. VectorMap software. Selection of imagery or electronic charts from a very broad choice of formats and sources provided a multi-layer geo-referenced backdrop for mission planning using standard windows-based interfaces for waypoint selection and trackline design. A host of supporting tools assists the operator in automatically assigning track spacing relative to water depth, selected coverage, and many other parameters associated with the multi-beam or side-scan sonar performance. A selection of standard survey/behavior profiles is available to further automate the mission design task, or to relocate, modify, and copy missions for sequential or multi-vehicle operations. Data logs from the AUVs were readily draped over the assigned mission tracklines for review, and selectable data pop-ups follow cursor movement on the actual trackline to provide additional detail. Opening the ASCII log files in EXCEL or similar tools for manipulating and charting tabulated data allowed a quick evaluation of performance over the mission. Mission design and graphical review, and chart/data based log file evaluations, were essentially performed in minutes by operators with no previous training or exposure to the applications.

Iver 2 AUV launches were performed from the ship while underway on 7 of the 8 scheduled exercise days. The launches were performed at 5 kts at designated drop zones as the NRP Bacamarte steamed on a course that allowed sequential launches on the perimeter of assigned survey areas. With drop zones 300 m apart, the launch times were staggered by 2 minutes. A canvas sling from Brooke Ocean Technology was used to lower the AUVs for launch with approximately 2 m freeboard. The launches were easily accomplished with the <25 kg AUVs by either 1 or 2 individuals without event. The AUVs assumed station-keeping at designated coordinates at the completion of the mission. When the coordinates were within WiFi range of the ship, the AUVs were piloted using manual control and recovered via the manual sling, bow door, or alongside access. For remote stations, a RHIB was deployed for recovery. No deck machinery or auxiliary equipment other than the canvas sling was required for launch or recovery from the ship. On 3 of the 8 exercise days, Iver 2 AUVs were launched from the shore. Vehicles were set on a delayed launch, then carried to shallow water (0.5 m) and released to acquire the mission start point. On two of the days, the NRP Bacamarte was brought to the beach, the bow door was lowered, and the AUVs were carried ashore for launch. Total time for the launch from the time the bow door was on the beach until multiple AUVs were underway to the mission start point was approximately 2 minutes. All scheduled shore and ship launches over the exercise period were successfully executed without event.

Components and assemblies were replaced in the field during the exercise as a result of both external and internal causes. External causes included collision of a surface craft with a surfaced AUV and dropping the AUV on the steel deck. In the former case, the fin and bent servo shaft were replaced with a hex wrench in < 10 minutes, and in the second case, the fin was replaced with a single hex wrench in < 2 minutes. Other servicing of the AUV fleet during the exercise period included swap-out of a tail section, replacement of a bushing and O-ring set in a module joint, and swap-out of some suspect sensors. Each of the tasks was performed in < 30 minutes with a screw driver and set of hex wrenches. The modularity of the system and simplicity of design support very well a CONOPS of AUVs deployed with tactical units without special support teams or equipment. Note that shunts in the tail section are removed in < 10 minutes to individualize battery cells and maintain the power supply at <95 W-hr per unit, allowing for unrestricted commercial air shipment without DOT Class 9 requirements.

Reliability Reliability will be evaluated in terms of component and system performance, and by mission completion statistics. Minor component faults associated with both software and hardware were evidenced sporadically in the first week which affected a subset of data collection and mission execution by individual units. No common faults occurred across all the AUV units, and only 1 repeatable fault surfaced among 1 of the units after servicing. In every mission throughout the exercise period, the missions were engaged correctly after launch, and in all but two of the missions across the 8-day period, the vehicles returned

properly to the assigned recovery point for stationkeeping. Some of these returns were completed via a Safety Return Path designated by the operator for use in the event of a mission abort. Mission aborts were triggered properly by designated safety thresholds. One of the AUVs was apparently hit while on the surface by one of many fishing boats in the area and only recovered some days later when notified by the “finder”. A more complete statistical analysis of component, system, and mission reliability will be presented when evaluation of the logs is complete.

On-Scene Products The primary objective of AUV operations for the NSW and NECC user communities is a suite of on-scene tactical products showing the results of the local search and survey missions. A secondary objective is the forwarding of the data to Reach Back Cells or other activities for model and integrated product support. One focus in REP 10A was the simplified production of near real-time graphical products in the field without specialized personnel, support, or additional software applications. This will represent a significant improvement from the challenging approach adopted in early evaluations, where crude interpolation routines used to generate bathymetric products from sparse single-ping data provided the only graphical product in addition to the side scan sonar imagery. The on-scene environmental product suite comprises:

- multi-beam sonar swath bathymetry (CARIS)
- side-scan sonar image scrolling and geo-referenced mosaic products (IMAGENEX and OceanServer Technology, Inc. VectorMap)
- temperature and conductivity, areal variability at selected depths (CARIS)
- surface/middle/bottom ocean currents, areal variability with selectable depth bins (CARIS and OceanServer Technology, Inc. VectorMap)
- mission geometry and vehicle track made good (OceanServer Technology, Inc. VectorMap)

Figures 2-6 depict some of the on-scene products available from the Iver 2 AUV data.

In addition to the formal graphical products, C2 behaviors develop log files that help to visually determine designated bathymetry contours and mixed layer depth from displays. EXCEL files can be used to develop intuitive views of environmental data over the mission without a graphical geo-reference.

All log files containing AUV sensor and platform data were posted daily to an FTP site maintained by UMASS Dartmouth Advanced Technology and Manufacturing Center (ATMC). ATMC personnel reviewed the posted data and created daily products using the same SW applications that AUV operators in the field were using for locally generating products. The logs and products were available for other agencies approved for FTP site access, such as the Naval Research Laboratory (NRL) and the NATO Undersea Research Centre (NURC). NRL used the temperature, conductivity, and ocean current measured locally by the AUVs to validate the regional forecast models for oceanographic conditions (RELO-NCOM, DELFT 3D), including vertical structure, areal variability, currents at selected depths (0, 10, 20 m), local wind and sea state, and sound speed. The data will also be used to evaluate methodologies to integrate AUV data directly into the standard forecast models, and to support initialization and re-baselining processes. NURC used the AUV data to ground truth and calibrate shallow water bathymetric products derived from remotely sensed data. Commercial satellites Quickbird and GeoEye provided high resolution images and information on atmosphere radiances in 4 bands (red-green-blue and near infrared) to support product generation.

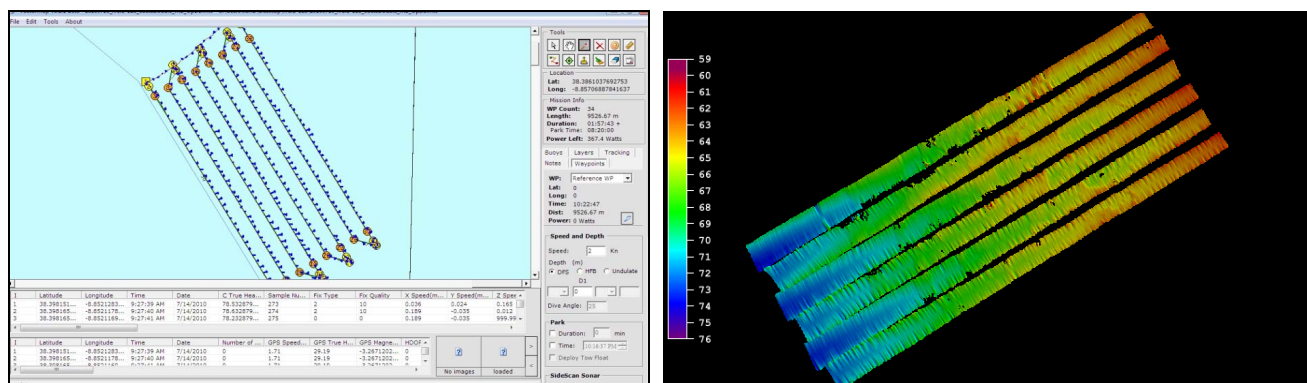


Fig. 2 (a-b) VectorMap software from OceanServer Technology, Inc. provides graphical window-based mission planning and review capability. In the data review mode, AUV tracklines can be superimposed on missions, and full log file review of 1 Hz data can be associated with position on the chart. Data parameters, such as current vectors, can also be superimposed on the chart/image and AUV trackline for rapid evaluation of survey results. Multibeam sonar data (uncorrected) and mosaiced side-scan sonar imagery also can be displayed in VectorMap on-scene.

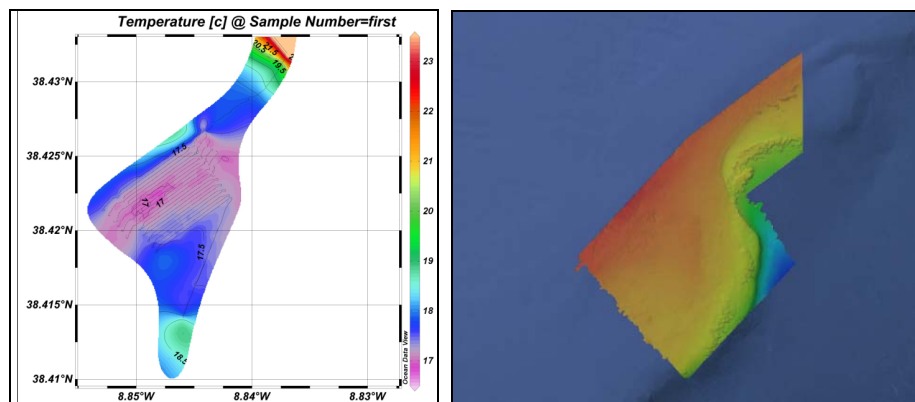


Fig. 3 (a-b) CARIS software allows for interpolation of environmental data for areal displays at selected depth planes. Conductivity, temperature, and bathymetry are developed from the CT sensors on these AUVs. CARIS is also used for generating corrected multibeam sonar bathymetry products. CARIS products can be exported as GEOTIFF files for display on VectorMap.

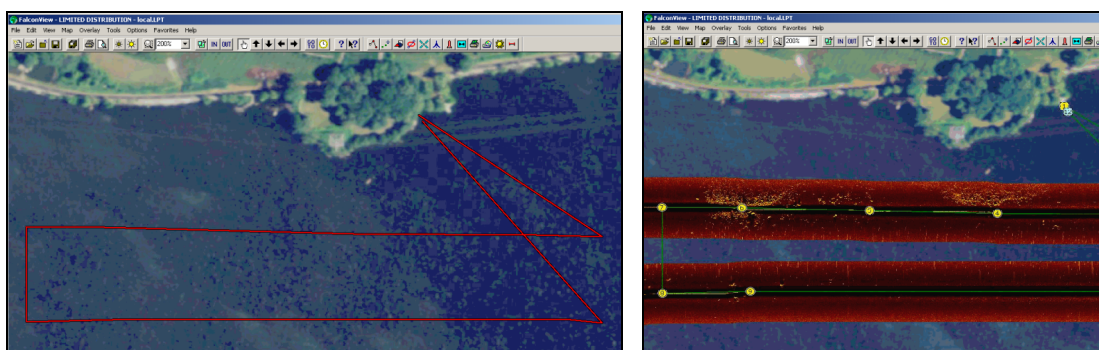


Fig. 4 (a-b) FalconView software used for mission planning and review by Naval Special Warfare personnel can host geo-rectified images from VectorMap and CARIS. Tracklines from mission design and AUV logs are displayed on the background FalconView chart, and multibeam or side scan sonar imagery can be imported to Falconview with the chart or image used in the primary application. FalconView tools function with the imported products.

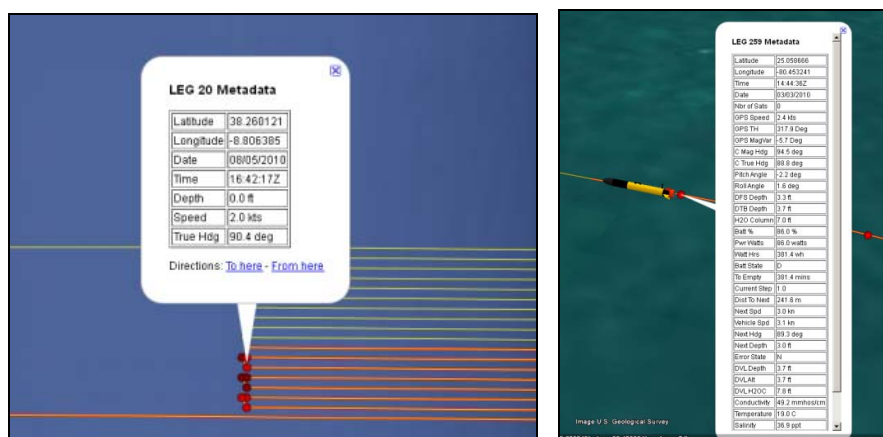


Fig 5 (a-b) VectorMap and CARIS products are also readily saved as .kmz files for use with the latest releases of FalconView or with Google Earth and compatible GIS applications. The saved files maintain the mission waypoint descriptions and AUV data logs to support mission evaluation.

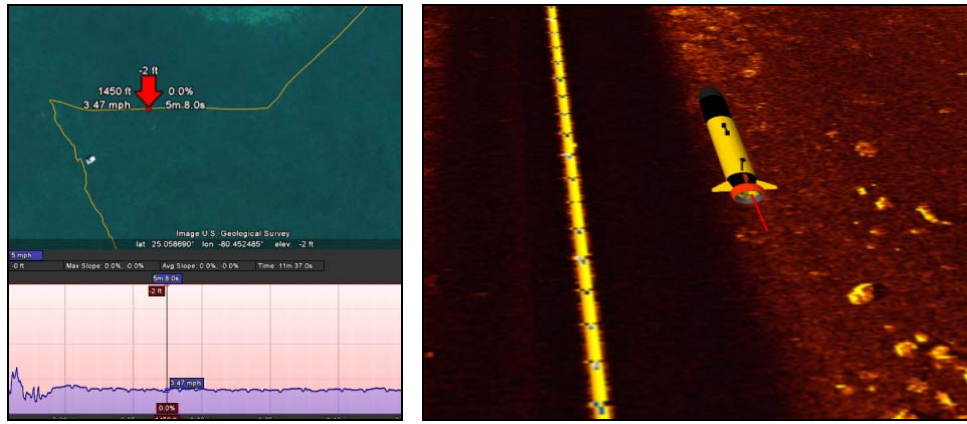


Fig 6 (a-b) The .kmz files can be used with various layered analysis and animation tools to support fly-through data viewing and multi-dimensional evaluations .

IV. CONCLUSIONS

Economical, man-portable AUVs can be used effectively to meet mission requirements for Rapid Environmental Assessment (REA) by forward deployed tactical units. The benefits of this class of AUV are significant, and the CONOPS finally brings to reality the objective of a single operator managing multi-vehicle operations to allow timely surveys with fidelity suited to tactical decision making by NSW, NECC, and other communities. REP 10A demonstrated that half a dozen AUVs could be shore- or ship-launched under operational conditions by a single operator with a PDA, independent of special teams, equipment, or other logistical support. The straightforward field servicing and module replacement further promotes acceptance of this CONOPS. The on-scene data production capability using accepted software applications meets the objectives for REA set by NSWG 4 leadership and establishes a new benchmark for this capability in forward deployed units not dedicated to AUV operations. As this class of AUVs sees increased application, the demand for component integration (e.g., IR sensors and cameras) and enhanced C2 behaviors (e.g., specialized search, avoidance, or communication responses to through-the-sensor data) will almost certainly occur. The open APIs and Back-Seat Driver supported by the second CPU with MOOS and IvP guarantee an economical and rapid pathway to introduce this capability independent of the vendor.

REP 10A provided an effective operational venue to promote the evaluation, tuning, and final test design for the lightweight Iver 2 AUVs targeted for delivery in September to NSWG 4 under ONR TechSolutions program office sponsorship.

ACKNOWLEDGMENTS

Thanks are extended to Marinha Portuguesa for the hosting of the exercise REP 10A and the opportunity to participate in operational events. The NRP Bacamarte officers and crew provided outstanding support, as did the dive and AUV squadrons deployed with NRP Bacamarte during the exercise. Gratitude is also extended to personnel at Faculdade de Engenharia - Universidade do Porto for their support in the planning and execution of exercise events, and the NATO Undersea Research Center, Naval Research Laboratory – Stennis, and U MASS Dartmouth Advanced Technology and Manufacturing Center for their support and participation in planning, data processing, and product generation.