Unlocking the power of combined autonomous operations with underwater and surface vehicles: success with a deep-water survey AUV and USV mothership

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***Abstract*— The GEBCO-NF Alumni Team is an international team working on solution towards autonomous Ocean Mapping operations. The Team was initiated and led by alumni of the Nippon Foundation / GEBCO training program at the University of New Hampshire. The alumni worked closely with international partners and suppliers to develop and advance their concept created for the Shell Ocean Discovery XPRIZE.**

The Shell Ocean Discovery XPRIZE competition aimed to push the boundaries of ocean technologies by creating solutions to the grand challenge of mapping our oceans. The Shell Ocean Discovery XPRIZE challenge was to develop a complete system that could map 100 km^2 in 16 hours at 5 m horizontal resolution grid and produce images the elicited excitement in the general public. The designated survey area for the XPRIZE challenge could be up to 50 nautical miles offshore and operations had to be remotely coordinated from a land-based operation center. The entire mapping system had to fit into a standard 40-foot shipping container.

The aim of the GEBCO-NF Alumni Team was to leverage existing technology, wherever possible, and to integrate them to achieve the competition requirements. Their strategic approach was to develop strong partnerships with technology and services providers to augment the hardware, integration and software needs of the Team. The GEBCO-NF Alumni Team conceived a two-system, Autonomous Underwater Vehicle (AUV) and Remote-controlled or Uncrewed Surface Vehicle (USV), concept to autonomously map the seafloor in a wide variety of ocean environments. The AUV-USV idea will lead to more efficient, safer and cost-effective seafloor mapping operations.

Autonomous seafloor surveys, with remote AUV launch and recovery (human-in-the-loop) and with the USV autonomously tracking the AUV for a complete survey mission while being monitored from a remote shore station, were demonstrated to be a viable option for future offshore survey and inspection projects. The technology, processes and procedures developed for this project are a big step towards larger scale implementation of these concepts.

Keywords—Autonomous Underwater Vehicle, HUGIN, AUV, Unmanned Surface Vessel, bathymetry, multibeam, synthetic aperture sonar, SAS.

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I. The GEBCO-NF Alumni Team

GEBCO-NF Alumni Team is led by alumni of the Nippon Foundation / GEBCO Training Program in Ocean Mapping at the Center for Coastal and Ocean Mapping of University of New Hampshire and is being advised by selected GEBCO and industry partners. The Team is characterized by its diversity, from its global distribution, to diverse backgrounds ranging from ocean mapping, hydrography, geology, engineering, boat design, software development, physics and computer science that includes representatives of academic institutions, industry and national hydrographic offices.

The idea to participate the Shell Ocean Discovery XPRIZE competition was first conceived at the Nippon Foundation/GEBCO Forum for the Future of Ocean Floor Mapping held in Monaco in June of 2016. In February 2017, the Team learned that their concept had made it through to the first round of field tests. From that point they had 9 months to take their concept from a conceptual paper design and make it a reality.

II. Overview of Shell Ocean Discovery XPRIZE Competition

The XPRIZE mission is to bring about "radical breakthroughs for the benefit of humanity" through incentivized competition. XPRIZE fosters high-profile competitions that motivate individuals, companies and organizations across all disciplines to develop innovative ideas and technologies that help solve the grand challenges that restrict humanity's progress.

Ocean exploration technologies today—from human divers to satellites, and relatively simple buoys to the most sophisticated Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs)—currently cannot scale to gather the detailed data and information necessary to understand and leverage our ocean resources in sustainable ways. Moreover, it is a significant challenge to inspire new innovation, investment, and discovery with only a limited understanding of the ocean's potential.

The Shell Ocean Discovery XPRIZE will address these challenges by incentivizing platforms for ocean exploration that can demonstrate the combination of capabilities critical to expanding discovery of the world's oceans: improved autonomy, faster speeds, and the ability to explore at significant depths. To demonstrate these capabilities, teams will have a limited period of time for exploring an area of the ocean and producing: (1) a high-resolution, accurate map of the ocean floor, which is essential for establishing a baseline understanding of the oceans; and (2) images of biological, archaeological, and geological features of the ocean environment, which are critical to understanding the oceans and will help inspire the next generation of educators, students, policymakers, and investors to care about ocean discovery, resource development, and protection.

The objectives of the Shell Ocean Discovery XPRIZE competition are described in TABLE I.

TABLE I. Shell Ocean Discovery XPRIZE Competition Objectives

Criterion	Round 1 Min Requirements	Round 2 Min Requirements
Area Mapped	100 km^2	250 km^2
Resolution	5.0 m horizontal, 0.5m vertical	
Bathymetric Map Accuracy	Pass/Fail vs Statistical Accuracy relative to Baseline Map	
Depth Requirements	2,000 m	4,000 m
Additional Features	5	10
Survey Time	16 hours	24 hours
Data Processing Time	48 hours	
Equipment Size	All components must fit into a single 40ft container	
Potential distance to survey site	Operate up to 50 nm offshore	

III. Proposed Solution

A two-system concept, with an AUV and an Uninhabited or Uncrewed Surface Vehicle (USV), was conceived to autonomously map the seafloor for longer time periods and in a wide variety of ocean environments [1,2]. The AUV/USV concept will lead to more efficient, safer and cost-effective seafloor mapping operations.

A. *Hushcraft SEA-KIT USV*

The GEBCO-NF Alumni team concept of USV/AUV operations required the development of a new USV capability. They required a vessel which could operate independently of a mother-ship and perform complex AUV operations over-the-horizon. Since no such vehicle existed, the design and development of the SEA-KIT USV was undertaken by Hushcraft Ltd.

The USV SEA-KIT *Maxlimer* was designed to act as a surface support vessel for the AUV, including the capacity to launch and recover the AUV and to provide subsea communications and positioning [2]. SEA-KIT is capable of sustained long range operations exceeding the capabilities required for the XPRIZE competition, offering up to 12,000nm range and 9 months endurance. The vessel can be operated in significant sea-states and can carry a deployable and retrievable payload of up to 2.5 tons. The SEA-KIT USV was designed to DNV-GL ST0342 Craft standards for operations in any waters not requiring ice-class vessels. SEA-KIT International Ltd. has been simultaneously working on the development of safe operational practices for this new type of offshore USV and is working to have them included as part of the developing rule sets for commercial autonomous maritime operations.

B. *Kongsberg HUGIN AUV*

The Team choose the industry leading HUGIN AUV developed by Kongsberg Maritime for this project, specifically Ocean Floor Geophysics' HUGIN AUV Chercheur [3]. This vehicle is equipped with the Kongsberg EM2040 and HISAS 1032. The HISAS is a deep-water interferometric synthetic aperture sonar used to collect high resolution bathymetric and imagery data. The Team wanted to utilize HISAS as this exciting innovative technology answered the competition requirements by providing ultra-high-resolution imagery and rapid bathymetry coverage.

TABLE II. TECHNOLOGY READINESS CRITERIA

	Shell Ocean Discovery XPRIZE Criteria	Team actions
1	Autonomy	Team needs to demonstrate that their Entry can conduct autonomous and untethered operations
2	Collision Avoidance	Team needs to demonstrate that their Entry shall operate safely in water and avoid contact with other obstacles using passive or active avoidance measures.
3	Data Retrieval	Team needs to demonstrate that data collected by the Entry can be retrieved completely and accurately and delivered to XPRIZE.
4	Depth Capability	Teams need to demonstrate that their Entry is capable ofachieving the original Round 1 depth rating (2,000 m).
5	Endurance	Team needs to demonstrate that their Entry can meet the original Round 1 operational endurance.
6	Imagery	Team needs to demonstrate that their Entry can collect underwater images. There are no specific restrictions on the format of eligible image types.
7	Mapping Resolution	Team needs to demonstrate that their Entry can meet the original Round 1 horizontal mapping resolution (5 m horizontal).
8	Navigation	Team needs to demonstrate that their Entry can meet the original Round 1 navigational requirements (i.e. navigate from shore to specified location and return to shore).
9	Seaworthiness	Team needs to demonstrate that their Entry is capable of operating and surviving at sea.
10	Size and Weight	Team needs to demonstrate that their Entry is capable of operating and surviving at sea.
11	Speed	Team needs to demonstrate that their Entry can meet the original Round 1 requirements to map at least 100 km2 in 16 hours.

C. *Data Processing Workflow*

A complete data processing workflow using Teledyne CARIS and ESRI software was developed to allow all the data products to be delivered within 48 hours. The workflow developed was highly automated and resulted in the delivery of a complete ArcGIS database of the entire survey area, including HISAS imagery at 4 cm resolution, multibeam bathymetry, interferometric HISAS bathymetry, and reprocessed 50 m x 50 m spots of HISAS imagery and bathymetry at 2 cm resolution.

IV. TECHNOLOGY READINESS TEST

The site chosen by the Shell Ocean Discovery XPRIZE organizers for the Fall 2017 Round 1 competition was deep sea off the southern coast of Puerto Rico. In September 2017, shortly before the start of the Round 1 competition, Puerto Rico was dealt a glancing blow by category 5 hurricane Irma followed a few days later by a direct hit from category 4

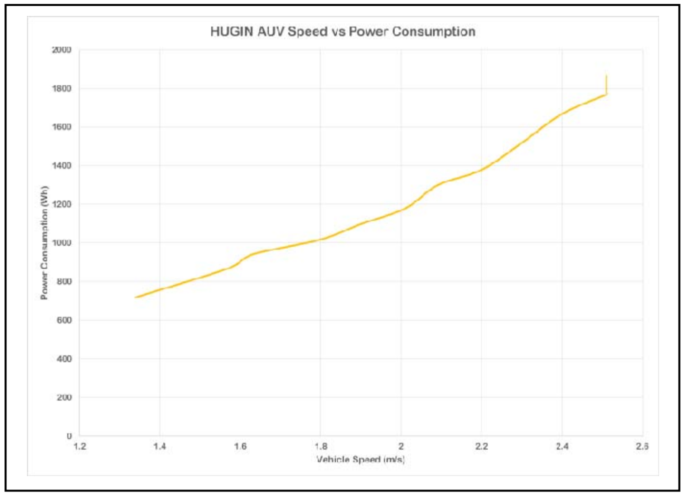


Fig. 1. Power consumption curve showing power consumption as a function of vehicle speed for the OFG HUGIN Chercheur.

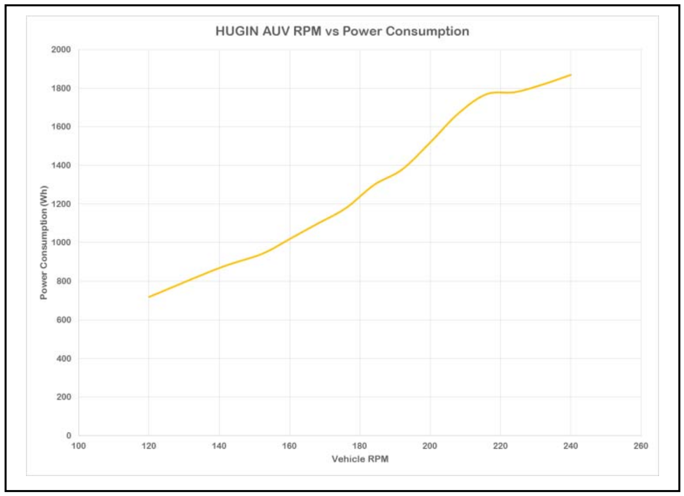


Fig. 2. Power consumption curve showing power consumption as a function of thruster RPM for the OFG HUGIN Chercheur.

hurricane Maria. Maria left the island in a state of emergency where all local resources were required for the recovery effort.

In November 2017, the Shell Ocean Discovery XPRIZE Committee released an update to the competition guidelines, replacing the original Round 1 competition with a Technology Readiness Test comprised of site visits to each team. The teams would be judged against 11 key measurement criteria that were designed such that the teams could show that their existing technologies meet the operational requirements necessary for rapid, unmanned, and high-resolution ocean exploration and discovery [4]. The measurement criteria for the Technology Readiness Test are listed in TABLE II.

V. PREPARATION TO MEET THE READINESS CRITERIA

Preparatory sea trials were conducted at the Kongsberg Maritime AS facilities in Horten, Norway during the second half of 2017. This allowed the Team to fully research the capabilities and limitations of the concept system to maximize sonar coverage and performance, and to understand the integra-

TABLE III. OFG HUGIN CHERCHEUR TOTAL POWER CONSUMPTION AT DIFFERENT RPM, BASED ON EXPERIMENTS PERFORMED BY GEBCO-NF ALUMNI TEAM AND OCEAN FLOOR GEOPHYSICS IN HORTEN, NORWAY (GREYED OUT COLUMNS DESCIBED IN TEXT)

	Commanded RPM													
	120	**140**	**152**	**160**	**168**	**176**	**184**	**192**	**200**	**208**	**216**	**224**	**232**	**240**
Measured RPM	120	140	152	160	168	176	184	192	200	208	215	222	231	239
Measured AUV Speed (m/s)	1.34	1.57	1.63	1.8	1.9	2.01	2.09	2.2	2.3	2.4	2.51	2.51	2.51	2.51
Measured AUV Speed (kts)	2.60	3.05	3.17	3.50	3.69	3.91	4.06	4.28	4.47	4.67	4.88	4.88	4.88	4.88
Measured Voltage (V)	44.1	44.1	43.7	43.7	43.37	43.3	43.3	43.2	43	42.9	42.7	42.5	42.5	42.5
Measured Thruster Current (A)	4.5	9	10	11	13.1	15	18	20	22	26	30	31	30	31
Measured Thruster Power (W)	200	350	422	500	580	660	780	860	1000	1150	1250	1260	1300	1350
Power incl. hotel & sensors (W)	719	869	941	1019	1099	1179	1299	1379	1519	1669	1769	1779	1819	1869

TABLE IV. OFG HUGIN CHERCHEUR HOTEL AND PAYLOAD POWER CONSUMPTION (NOT INCLUDING THRUSTER)

Component	(Wh)
All Hotel[a] (incl FLS + NAS)	219
Payload (HISAS+EM2040)	300
Total	**519**

a. Hotel includes all software and equipment to operate AUV

tion and management of the AUV and USV systems to ensure reliable operations at sea without physical intervention.

A. Evaluation of AUV Performance

The AUV was evaluated to determine the most efficient survey speed and to verify how much area coverage is possible during the allotted time with this system. The power consumption of the vehicle at different surveys speeds was measured. Fig. 1 shows the total power consumption for the AUV including thruster and all hotel loads as a function of survey speed and Fig. 2shows the same thing as a function of RPM. TABLE III. shows a breakdown of the measurements taken during the power experiments. Running the thruster at RPMs of 200 or greater (grey columns) resulted in elevated temperatures in the motor controller, and was therefore considered unsustainable. TABLE IV. shows a breakdown of the hotel load and the power consumption for the payload.

B. Evaluation of Sensor Performance

The AUV is equipped with an EM2040 multibeam and a HISAS 1032 bathymetric synthetic aperture sonar. The HISAS has a wide swath that extends out several hundred meters to each side, but cannot collect data in the nadir region below the AUV. Data from the EM2040 multibeam can be used to fill the nadir gap as shown in Fig. 3.

The sea trials allowed the GEBCO-NF Alumni Team, working closely with Kongsberg Maritime engineers, to develop a methodology for a new wide-area mode of operations that dramatically increased swath width and coverage of the HISAS 1032 while maintaining data integrity

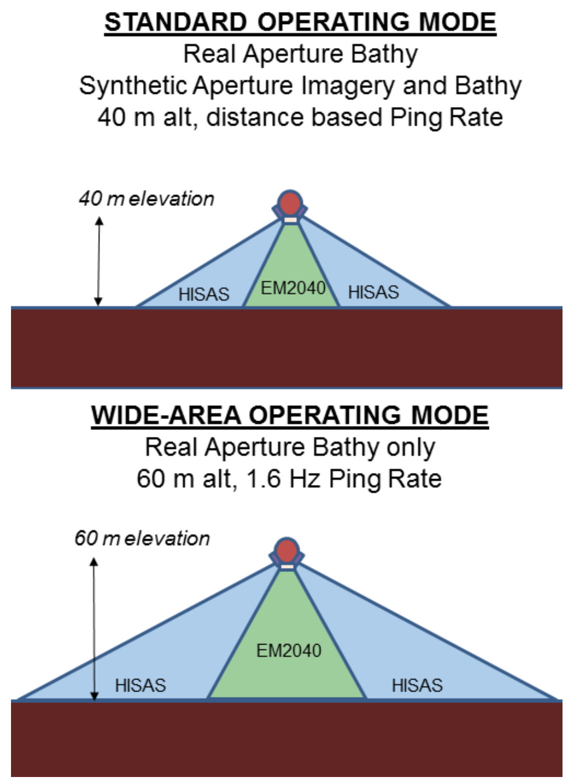


Fig. 3. Bathymetric coverage with the AUV using the EM2040 and HISAS sensors. HISAS can be configured for standard (Top) or wide-area (Bottom) operating mode, swath width for the two configurations is 340 m and 780 m respectively.

and resolution. In wide-area mode, the HISAS operates like a standard bathymetric side scan sonar and the SAS timing requirements are ignored. In this mode, it is not possible to construct synthetic aperture imagery or bathymetry, but it gives the operator flexibility in the ping rate allowing them to slow the rate down to get a wider real aperture bathymetry swath.

The standard operating mode for the HISAS uses a trigger based on distance travelled by the AUV. The HISAS transducer is comprised of 32 elements. The distance for the

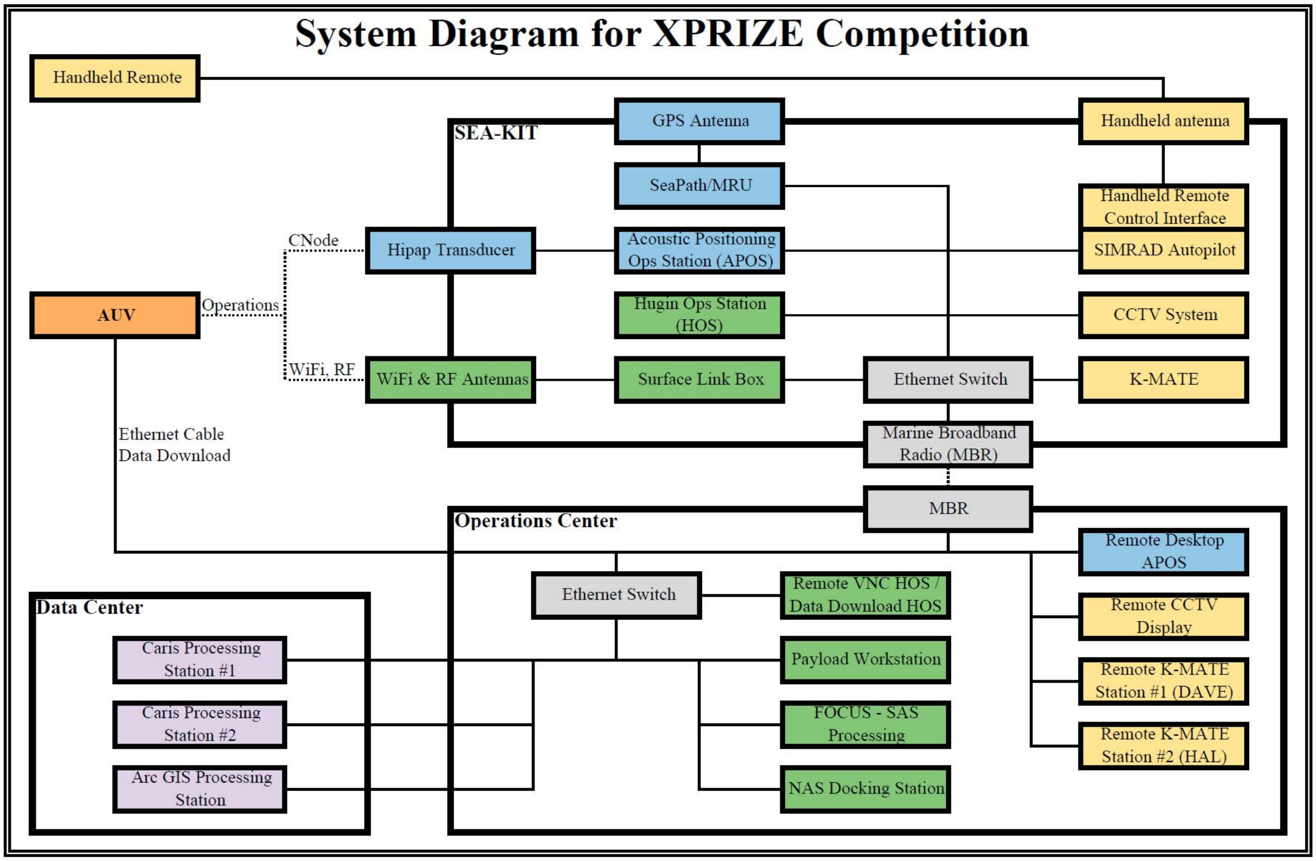


Fig. 4. System Diagram showing the different components for communication and remote management of the AUV, USV and the data processing. Remote and autonomous control of SEA-KIT is managed through handheld remote (remote control), the remote K-MATE station DAVE (autonomous remote), and the remote K-MATE station HAL (fully autonomous).

standard trigger is based on an integral number of element lengths. This ensures that the pings can be coherently assembled using the synthetic aperture algorithm.

In standard operating mode, the Team chose to run the AUV at 40 m altitude and 2 m/s with the ping distance set to 28 elements. For wide-area mode, the AUV was flown at 60 m altitude and 2.2 m/s with a ping rate of 1.6 Hz. With these settings the Team achieved a swath width of 780 m for wide-area operating mode and 340 m for standard operating mode. In these two modes, the across-track sounding density for the HISAS is 1 m and the along track sounding density is 0.5 m for standard mode and 1.5 m for wide-area mode. The HISAS data density was the limiting factor in creating grids, as the density of EM2040 soundings was much higher in both modes.

The Team could switch between the standard HISAS and wide-area modes on the fly to capture both ultra-high-resolution imagery of the sea-floor in standard mode and conduct high-speed bathymetry collection in wide-area mode during the same mission. The use of wide-area mode with a slight increase in AUV survey speed allowed the Team to closely approach the minimum 100 km^2 coverage criterion stipulated for Round 1.

C. Autonomous and remote capabilities of the vessels

1) USV Capabilities

The SEA-KIT USV *Maxlimer* can be operated in 4 modes:

- Manual – where a pilot operates the USV from the physical helm of the vessel.
- Remote control – where a pilot remotely operates the vessel using the ship controller handset.
- Autonomous remote – an operator commands a speed and heading through the K-MATE interface.
- Fully Autonomous – waypoint or AUV following modes with the vessel fully controlled by K-MATE.

The USV *Maxlimer* was certified through UK Maritime and Coastguard Agency as a Small Commercial Vessel Category 3. This allows her to carry up to two people onboard within 20 nm of shore. This capability was added to allow people to be on-board during sea-trials and technology development. The USV also has a physical helm, allowing human crew members to pilot her like any other vessel.

The autonomous functionality of the SEA-KIT USV is provide by the Kongsberg Maritime K-MATE Autonomy Controller. The Team is the first client for the new software, which was developed through collaboration between FFI and Kongsberg Maritime [5]. K-MATE is an autonomous system for executing mission plans in globally supervised operations or, for complex tasks, under direct operator control. K-MATE also provides adaptive waypoint following, which allows the vessel to track an AUV during a survey without a priori knowledge of the mission plan.

Fig. 4 is a system diagram showing the interconnection of all the components in the system and the means for controlling the SEA-KIT USV in the remote and autonomous modes.

2) AUV Capabilities

The HUGIN AUV *Chercheur* can perform a pre-programmed survey mission without any outside intervention. The AUV generates a navigation estimate (an estimate of where the AUV thinks it is) in real-time using an extended Kalman filter developed by Kongsberg called NavP. NavP takes in all the available sensor information (INS, DVL, depth, etc.) and calculates the most probable position and attitude of the vehicle given the measurements available and their statistical accuracies. All the sensor measurements have different update rates; NavP uses a dynamic model of the AUV to smoothly update the position and attitude estimate between sensor measurements. The AUV uses the estimate of where it thinks it is to move from waypoint to waypoint and complete the mission.

When operating purely autonomously, NavP will continually estimate the position of the AUV, but the estimate will drift and the uncertainty for the estimate will slowly increase. The drift in the horizontal position estimate for the HUGIN with only the Honeywell HG9900 and DVL is less than 0.1% of distance travelled. This drift can be bounded by sending tracking information to the AUV from an acoustic positioning system, such as a surface based Ultra Short BaseLine (USBL) system. In this work, a Kongsberg HiPAP 351P-MGC USBL was mounted to *Maxlimer* to provide positioning updates and an acoustic communication link to the AUV during the mission. The USBL tracking information bounds the navigation error. The communication capability allows the operators to remotely monitor the mission and *Maxlimer* to autonomously follow the AUV during the mission in AUV following mode.

D. Uncertainty Analysis

The total propagated uncertainty in the bathymetry is a function of the uncertainty in the AUV positioning, relative uncertainty in the sensor measurements, and the uncertainty in the post-processing analysis.

During normal operations, NavP receives a position update from the HiPAP once every thirty seconds and the uncertainty in the position estimate remains bounded and relatively constant throughout the survey. The AUV operator can visually track the AUVs position estimate, the uncertainty associated with that estimate and the HIPAP measurements using the HuginOS software.

The navigation is post-processed after the survey using NavLab. NavLab re-processes the navigation in two stages:

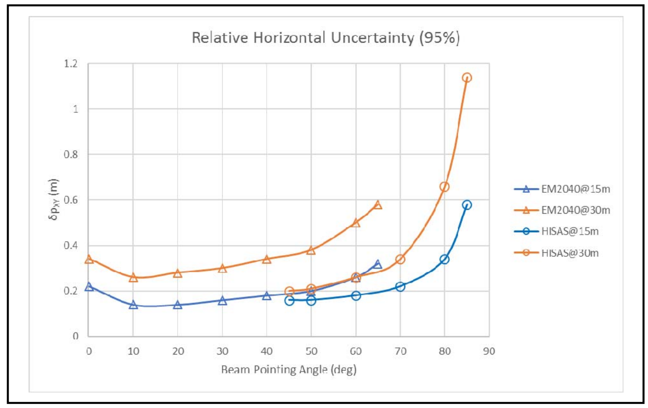


Fig. 5. Relative Horizontal Uncertainty of soundings for the EM2040 and HISAS at two survey altitudes

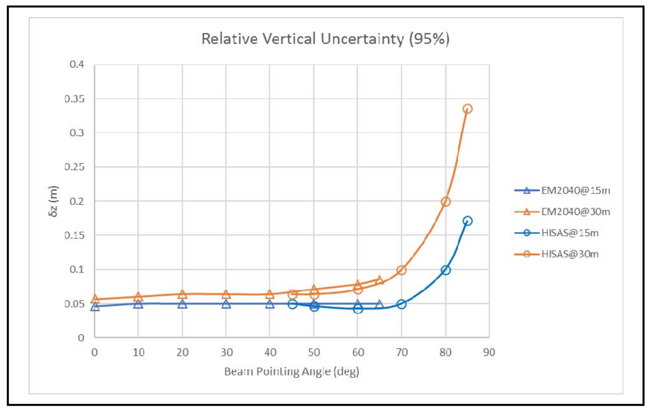


Fig. 6. Relative Vertical Uncertainty of soundings for the EM2040 and HISAS at two survey altitudes

(1) forward estimation and (2) backwards smoothing. During the first stage NavLab uses the same Kalman filter as NavP to estimate the most probably position and orientation of the vehicle. However, NavLab has access to all the HiPAP measurements, not just the ones that were received by the AUV, and the operator can remove wild-points from the measured data to improve the estimation. In supervised mode, the 1-σ horizontal positioning accuracy of the post-processed navigation is 0.3 m - 4 m depending on survey depth.

The estimated relative uncertainty of the EM2040 and HISAS are shown in Fig. 5 and Fig. 6. This uncertainty is intrinsic to the sensors and would be there even if the AUV had perfect positioning.

Finally, after the data is collected and the post-processed navigation is applied, the bathymetry is post-processed to correct for tides and sound velocity errors.

VI. The Shell Ocean Discovery XPRIZE Technlogy Readiness Test

The Technology Readiness Tests were conducted in Horten, Norway near the offices of Kongsberg Maritime AS from November 20, 2017 to November 23, 2017. On Day 2 of the Technology Readiness Tests, a data collection dive was performed.

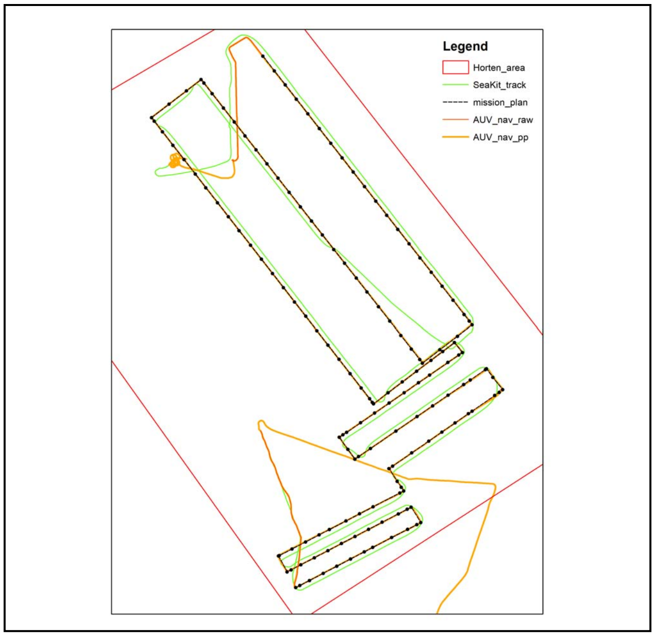


Fig. 7. Summary of the Shell Ocean Discovery XPRIZE GEBCO-NF Alumni Team AUV mission.

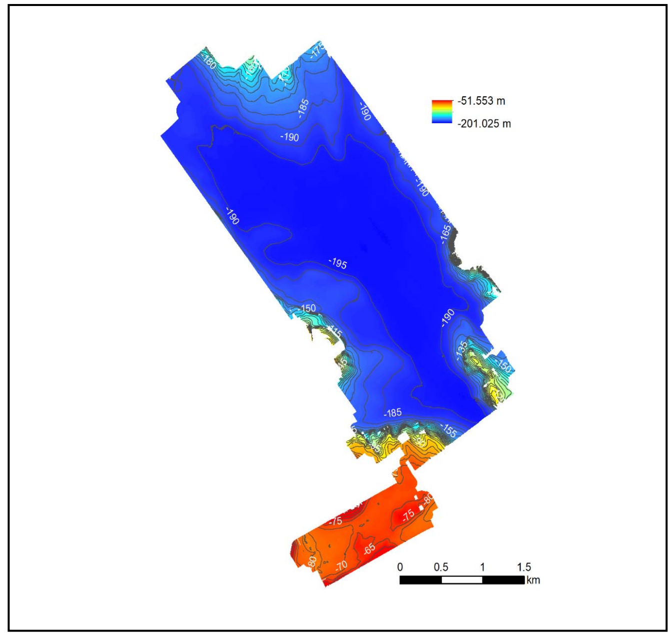


Fig. 8. Final 2 m-resolution bathymetric grid of the area surveyed on day 2 of the Technology Readiness Tests in Norway.

The joint AUV/USV operations were managed from the remote Operation Center. The operations team included an operations manager, an AUV pilot, a USV remote operations pilot, a USV autonomous operations pilot, and a situational awareness observer. Communication between the operation center and USV occurred via Kongsberg Maritime Marine Broadband Radio.

The launch of the AUV was initiated once the USV started waypoint following and obtained a steady course. After tracking the AUV underwater, the USV went into AUV following mode and attempted to maintain a range and bearing of 75 m and 225° from where the AUV was predicted to be.

The AUV dive lasted 4 hours and 11 km^2 of seafloor data (bathymetry and imagery) was collected (Readiness Criteria). The USV was actively under remote control or autonomous control for more than 9 hours while underway.

At the end of the AUV mission plan, the AUV surfaced and the USV and AUV were put on parallel courses in waypoint following mode with matching speed. Once the AUV was aligned with the USV and the approach was good, the retrieval process was initiated and the conveyor was turned on ready for retrieval of the AUV. The AUV then drove into the back of the USV and the mission came to an end. The USV then resumed normal operations and continued to the next waypoint, heading back towards the dock with the AUV on board.

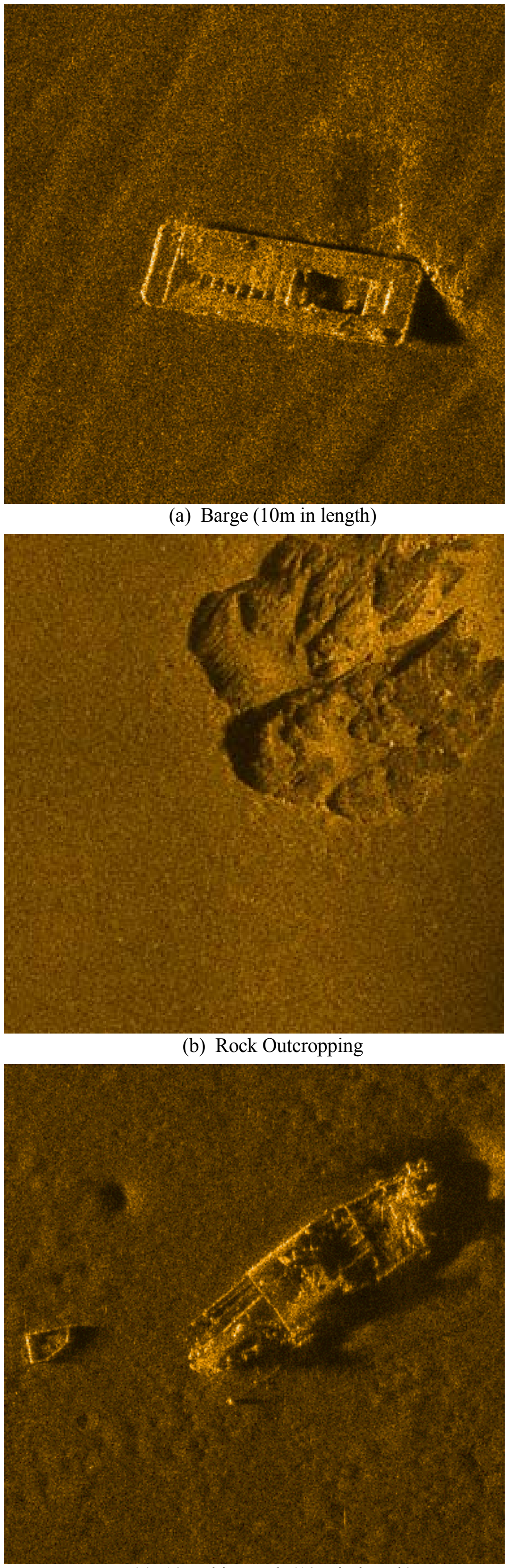
Once the HUGIN AUV was back at the dock, a network cable was attached. This cable is used to download navigation and vehicle health from the Control Processor (CP) and payload data from the Payload Processor (PP) (approximately ½ hour for planned mission). The removable NAS (Network Attached Storage) was physically removed from the AUV and plugged in the NAS dock in the operations center. Once the download was complete, the data processing was initiated.

TABLE V. SUMMARY OF GEBCO-NF ALUMNI TEAM TECHNOLOGY READINESS TESTS

	Shell Ocean Discovery XPRIZE Criteria	Team actions
1	Autonomy	Remote AUV launch & recovery from USV, autonomous waypoint following, and autonomous AUV following
2	Collision Avoidance	Situational awareness and remote control piloting of USV to & from the dock. Bottom following and collision avoidance capabilities on the AUV.
3	Data Retrieval	Data from AUV downloaded via NAS/Ethernet and USV data downloaded via USB drive
4	Depth Capability	Proven AUV technology from Kongsberg Maritime, OFG *Chercheur* (3,000 m rated)
5	Endurance	AUV Mission with 9 hours of continuous autonomous or remote operations
6	Imagery	Spot-focused acoustic images at 2 cm resolution using Kongsberg Reflection software
7	Mapping Resolution	Datasets from multiple sensors fused into a 2 m data grid with Teledyne CARIS software
8	Navigation	Autonomous waypoint following by USV and AUV, and AUV following by USV
9	Seaworthiness	Proven through Sea Trials
10	Size and Weight	System meets the criteria, as proven during shipping from the United Kingdom
11	Speed	Theoretical coverage of the area is ~90% of the Round 1 requirement.

A. Outcome of Technlogy Readiness Test

The Teams competing in the Shell Ocean Discovery Technology Readiness Tests were assessed against the 11 criteria in TABLE II. The mission plan for the GEBCO-NF Alumni Team's Technology Readiness Tests, shown in Fig. 7, was designed to maximize collection of data over different surfaces and to allow for collection of the best imagery.



(a) Barge (10m in length)

(b) Rock Outcropping

(c) 10m shipwreck (10m in length)

Fig. 9. Spot processed synthetic aperture imagery (2 cm x 2 cm resolution) from the HISAS 1032 collected by the GEBCO-NF Alumni Team.

The Data Group processed and submitted all data in 16 hours. Grids were created using Teledyne CARIS software and all of the data products were uploaded to a GIS project in ArcGIS Online. The final data products included navigation data for both vehicles, a 2 m grid (Fig. 8), and imagery (Fig. 9).

VII. Conclusion

Autonomous seafloor surveys, with a semi-autonomous AUV launch and recovery (human-in-the-loop) and with the USV autonomously tracking the AUV for a complete survey mission while being monitored from a remote shore station, were demonstrated to be a viable option for future offshore survey and inspection projects. The technology, processes and procedures developed for this project are a big step towards larger scale implementation of these concepts.

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