GEBCO-NF Alumni Team Technology Solution for Shell Ocean Discovery XPRIZE Final Round

Yulia Zarayskaya
Geological Institute
Russian Academy of Science
Moscow, Russia
geozar@yandex.ru

Craig Wallace
Kongsberg Maritime AS
Subsea Division
Horten, Norway
craig.wallace@km.kongsberg.com

Rochelle Wigley
Center for Coastal & Ocean Mapping
University of New Hampshire
Durham, USA
rochelle@ccom.unh.edu

Karolina Zwolak
Institute of Navigation and Marine Hydrography / Faculty of Navigation and Naval Weapon
Polish Naval Academy
Gdynia, Poland
k.zwolak@amw.gdynia.pl

Evgenia Bazhenova
Saint Petersburg State University
Saint Petersburg, Russia
evgenia.bazhenova@gmail.com

Aileen Bohan
Geological Survey of Ireland
Dublin, Ireland
aileenbohan@gmail.com

Mohamed Elsaied
Petroleum Geology Department
Faculty of Petroleum and Mining Science
Matrouh University
Matrouh, Egypt
mmgeologist@gmail.com

Jaya Roperez
Center for Coastal & Ocean Mapping
University of New Hampshire
Durham, USA
jroperez@ccom.unh.edu

Masanao Sumiyoshi
Japan Coast Guard
Tokyo, Japan
sumi44masa@gmail.com

Seeboruth Sattiabaruth
Ministry of Housing and Land
Ebene, Mauritius
shailesh_chem@yahoo.com

Wetherbee Dorshow
Earth Analitic, Inc.
Santa Fe, USA
wdorshow@earthanalytic.com

Tomer Ketter
Center for Coastal & Ocean Mapping
University of New Hampshire
Durham, USA
tketter@ccom.unh.edu

Hadar Sade
Yam-Yafo Ltd.
Rishon Lezion, Israel
hadarsade@me.com

Alison Proctor
Ocean Floor Geophysics
Vancouver, Canada
alison.proctor@oceanfloorgeophysics.com

Ivan Ryzhov
Arctic and Antarctic Research Institute
St. Petersburg, Russia
ryzhov@aari.ru

Neil Tinmouth
University of Stellenbosch
Stellenbosch, South Africa
neiltinmouth@gmail.com

Ben Simpson
Hushcraft Ltd.
Tollesbury, United Kingdom
ben@hushcraft.com

Stian Michael Kristoffersen
Kongsberg Maritime AS
Subsea Division
Horten, Norway
stain.michael.kristoffersen@km.kongsberg.com

Abstract—**The GEBCO-NF Alumni Team is one of the five teams who completed the final round of the Shell Ocean Discovery XPRIZE challenge. This international team is made up of industry experts, advisors from within the GEBCO community and broader ocean community and is led by alumni from the Nippon Foundation / GEBCO Graduate Certificate Ocean Mapping Training Program at the Centre for Coastal and Ocean Mapping / Joint Hydrographic Center (CCOM/JHC) of the University of New Hampshire. The Team is distinguished by its extraordinary diversity with a global distribution of representatives from academic institutions, offshore survey and technology industries, academia as well as national hydrographic offices. The alumni worked closely with partners such as Hushcraft Ltd., Ocean Floor Geophysics Inc., Earth Analytic and Teledyne CARIS as well as equipment supplier Kongsberg Maritime AS to develop and advance the Team concept created for the Shell Ocean Discovery XPRIZE. The project was established and supervised at the University of New Hampshire.**

The Shell Ocean Discovery XPRIZE competition aimed to push the boundaries of ocean technologies by creating solutions to the grand challenge of mapping our ocean floor. The competition requirements had to be met within a short timeline of approximately one year per round. The Round 2 final field test was to demonstrate a complete system that could map 250 km^2 in 24 hours to produce a grid with 5 m cell size and at least 10 images of the sea floor. 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 has been to leverage existing technology, wherever possible, and to integrate them to achieve the competition requirements. The strategic approach is 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 Unmanned Surface Vehicle (USV), concept to autonomously

XXX-X-XXXX-XXXX-X/XX/$XX.00 ©20XX IEEE

map the seafloor in a wide variety of ocean environments. 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 during Round 1.

SEA-KIT, the Team's USV, is an innovative new vessel that allows for autonomous management of AUV deployment and retrieval. In addition, the capability of being a stand-alone mapping platform was demonstrated during the competition using Kongsberg Maritime's deep-water multibeam sonar EM304 mounted on the gondola below SEA-KIT.

The Kongsberg Maritime HUGIN AUV was used for this competition to execute the underwater operations. The Team was confident that competition criteria could be met by overcoming the surface challenges of delivering an AUV to a deep-water location for mapping, coupled to the proven abilities of the HUGIN.

During Round 2 Field Test, the team demonstrated automated and remote processing using a cloud-based hosting environment. End users (judges) were able to consume the GEBCO-NF Alumni Team information rapidly and efficiently.

The technology, processes and procedures developed for this project are a big step towards larger scale implementation of these concepts. This development of new and innovative technologies that increase the efficiency of seafloor mapping is the Team's contribution towards helping meet the ambitious goals of the Nippon Foundation—GEBCO Seabed 2030 Project.

Keywords—USV, AUV, sea floor mapping, GEBCO-NF Alumni team, Shell Ocean Discovery XPRIZE, HUGIN, SEA-KIT, EM304, EM2040, HISAS

I. Introduction

The GEBCO-NF Alumni Team has developed a two-component solution for the Shell Ocean Discovery XPRIZE competition [1, 2]. The team's concept aims to solve one of the limiting factors in utilizing existing underwater robotic technology for high-resolution deep-water mapping - the cost of transportation to the open seas. Traditional methods are not only expensive and high-risk, but are also bound by availability, schedules, maintenance and weather variability.

Hushcraft Ltd. developed an innovative Unmanned Surface Vessel (USV) for the GEBCO-NF Alumni Team that acted as the multi-purpose surface support vehicle for the Autonomous Underwater Vehicle (AUV). SEA-KIT, the Team's USV, is a mothership, data repeater station and USBL acoustic positioning source.

The Kongsberg Maritime HUGIN AUV was used for this competition to execute the underwater operations. The HUGIN is a configurable platform that can have multiple sensors integrated into it for a wider range of applications. The vehicle is a deep-water rated, long-range solution utilizing reliable, consistent technology that has a track record of deep-water bathymetric mapping from dozens of HUGIN distributed around the globe.

The mapping solution consisted of the HISAS interferometric synthetic aperture sonar system, along with the EM2040 multibeam echosounder acting as a gap filler, mounted on the HUGIN AUV, with both working concurrently. An EM304 deep-water multibeam system mounted on the USV SEA-KIT worked in parallel to produce data that was merged with AUV data, and subsequently processed into bathymetric maps and acoustic images of the sea floor. The team philosophy was to be as inclusive as possible and demonstrate the variability in quality of data that can be collected depending on user requirements.

Communication between the AUV-USV/Data management was paramount and provided the pathways for connectivity, system health, operational parameters, potential for human intervention, spatial constraints and direction, data harvesting, communications relay and information flow. The Team leveraged a range of commercially-available technologies, including satellite, cellular, wireless internet, acoustic and other radio communication channels.

The team were committed to using automated functions wherever possible. There are existing and emerging technologies that provide an end-to-end capability for the automated processing of the data. Human intervention was utilised for metadata entry, quality control (QC), aesthetic finishing, image selection for post-processing, cartographic tuning and other Geographic Information System (GIS) server-based functions. The team solution processed bathymetric, vessel attitude, water temperature/salinity and depth measurements onshore upon the docking of the USV. Mapping products were delivered to end users using ArcGIS Online platform which made it possible to consume the GEBCO-NF Alumni Team information rapidly and efficiently on a variety of platforms including desktop, mobile apps and inside other applications as nested knowledge.

II. Shell Ocean Discovery XPRIZE requirements overview

The team was required to demonstrate that their entry could meet the Round 2 operational endurance requirements: to reach the competition area, complete the 24-hour mapping mission and return to shore. The team then needed to demonstrate that the data collected could be accurately acquired, subsequently processed and delivered as a final product to XPRIZE within 48 hours of the completion of the Field Test [3].

To fairly evaluate all the entries, the submissions were assessed based on following four criteria:

1. Area - the area of coverage acquired, as a percentage of the overall area
2. Resolution - horizontal and vertical resolution of the final bathymetric surfaces
3. Accuracy - a statistical comparison of the bathymetric map produced by the team, compared with a baseline map of the area.
4. Additional Features - Imagery of features in the ocean environment

Additionally, NOAA offered a bonus prize for an Entry to detect and trace a chemical or biological signal to the source.

III. GEBCO-NF Alumni team's vehicles

A. SEA-KIT USV

1) Vehicle Architecture

The newly developed USV, SEA-KIT (fig. 1), is a promising design for the launch and recovery, positioning, and communication with various AUV types. SEA-KIT had a Kongsberg HiPAP System mounted for this competition, which was used for positioning and as a command and data link to the AUV. SEA-KIT, not only a multi-purpose AUV launch and recovery system, but also a platform for a surface bathymetric surveying operations. It was designed to exceed competition goals with un-manned, long-range, trans-ocean capabilities (Table. 1). The capability of being a stand-alone mapping platform was demonstrated during the competition using Kongsberg Maritime's deep-water multibeam sonar EM304 mounted on a gondola.

Figure 1. SEA-KIT in unmanned operation during sea trials (Horten, Norway, 2018). Photo: T. Ketter.

The USV is capable of carrying a deployable and retrievable payload of up to 2.5 tons through an impact-safe, low-density foam and low-friction entrance to the internal slipway. The rugged aluminium hull, with passive motion damping, is single compartment flooding stable and has a self-deploying and stowing sea anchor.

Commercially available systems for unmanned vessel operation and collision avoidance were integrated into SEA-KIT to manage operations during the Shell Ocean Discovery XPRIZE competition. The vehicle for the competition had the Kongsberg Topside Unit (computers and other hardware installed on SEA-KIT) located in the forward electronics hold, where this allows SEA-KIT to act as the traditional "AUV host vessel" to allow remote access to manage AUV operations.

SEA-KIT is container transportable with removable propulsion pods, skegs and communications tower to allow all the parts of SEA-KIT, including the AUV, to be neatly stored inside a 40' (12.19 m) container.

TABLE 1: FABRICATED SEA-KIT SPECIFICATIONS

SEA-KIT "Maxlimer" Dimensions	I.	Length: 11.75 m (38.55 ft)
	II.	Beam: 2.2 m (7.22 ft)
	III.	Transport Height: 2.0 m (6.56 ft) - Operational Height: 8.5 m (27.89 ft)
	IV.	Weight: 12,000 kg (estimated)
Propulsion and communication systems	I.	Propulsion: 2 X 10 kW / 1200 rpm electric directional thrust motors
	II.	Communication: Wi-Fi, Radio, Satellite (Iridium and Inmarsat) and Kongsberg Maritime Broadband Radio (<45 km offshore)
	III.	CCTV: 2 interior and 6 fore and aft cameras, 360 degree FLIR camera
Power supplies	IV.	Generator 2 X 18 kW 48V DC
	V.	Fuel 2,000 l
	VI.	56 Gel and Absorbent Glass Mat (AGM) types of valve-regulated lead-acid battery (VRLA) Marine Batteries, 12V – 214Ah capacity
	VII.	4 dry cell Absorbed Glass Matt (AGM) VRLA 12V 100Ah Marine Dual Purpose Batteries for the engine and propulsion

2) SEA-KIT EM304

In order to meet the coverage requirements, as set by XPRIZE, it was decided to utilise SEA-KIT as a mapping platform by installing an EM304 on a gondola. The EM304 is a deep-water multibeam system from Kongsberg Maritime that is an evolution of the EM302 and EM300 series sonars. New signal processing cards, with improved noise channels, allow the system to achieve greater depths than previous systems whilst maintaining high range resolution through improved sampling rates.

Previous generation EM302/300 systems had considerable topside electronics that precluded their use in vessels of this nature i.e <12 m autonomous vessel of opportunity, as substantial space was required to mount transmit and receive electronics. The new configuration provides a smaller footprint for the topside components that is roughly 50% of the previous generation.

In order to fit within size constraints for different vessels, the EM304 transducers have a modular nature allowing the user to reduce or increase transmitter and receiver for the application. The gondola had a 2 by 4 degree transmit/receive configuration mounted for XPRIZE.

The EM304 mounted aboard SEA-KIT was a first of its kind, a deep-water solution on board an unmanned vessel.

B. HUGIN AUV

1) Vehicle Architecture

The GEBCO-NF Alumni Team has aligned with Kongsberg Maritime AS and rented a free-swimming HUGIN AUV (fig. 2) designed for long-duration deep-water surveying with the vehicle capable of descending to 4500 metres for Round 2. After completing final acceptance trials in September 2018, the team worked with Kongsberg Maritime HUGIN operators and engineers to prepare the vehicle for Round 2 of the competition. HUGIN operators from Ocean Floor Geophysics, who had previously worked with the team during Round 1, continued the collaboration during 2018.

Figure 2. Kongsberg Maritime HUGIN AUV "Rental 1" during Round 2 in Kalamata, Greece. Photo: M. Elsaied.

The HUGIN is remotely programmed by the Topside Unit that is used for configuration, control, monitoring and maintenance of the AUV. The HUGIN Operator Station (HOS) comes with a collection of programs, that interface to the AUV through specific modules used for mission planning, AUV configuration, and real-time control. The payload software controls and displays data from sensors in real time, allowing assessment of functionality at a global remote desktop location via satellite link through the Topside Unit and subsequently to the vehicle through the subsea modem using HiPAP and Acoustic Data Link (ADL). The HUGIN can operate in either autonomous or supervised mode and can seamlessly switch between depending on operator preference.

HUGIN AUVs are fitted with sensors for the detection of critical operational conditions and error handling systems. In the unlikely event of equipment failure, the HUGIN has redundant onboard safety checks and most issues can be resolved onboard, while underwater. For example, in the event of a forward-looking sonar dropping out, an automatic restart of the unit through a hard reset will attempt to bring the unit back on-line. If an obstacle has been detected that cannot be overcome, the vehicle then recursively retraces it path through known safe passage to mission start. The system would only abort the mission and come to the surface if it is a critical situation threatening the integrity and safety of the AUV (e.g. critically low altitude, extreme battery situation etc.). The likelihood of this happening is extremely rare (much less than 1% of all sea-time to date for HUGIN). In the event of emergency situation requiring an ascent, certain protocols are implemented through semiconscious decision making. Timeouts are in place to establish topside communication through regular channels, if these fall through, satellite modems are activated relaying current positioning to a mail server that can be collected by the Topside Unit. In addition, direct modem communication can be established over satellite, taking control of the HUGIN from any location and allowing safe retrieval to be conducted, either through attempting a new dive or starting a transit back to shore.

2) HUGIN HISAS 1032

The Kongsberg HUGIN AUV was mounted with the proprietary HISAS 1032 Interferometric Synthetic Aperture Sonar (SAS), a new high-technology hydrographic sonar system, that was used to collect bathymetric and imagery data. HISAS is a wideband interferometric SAS sonar with frequency range of 60-120 kHz, and is capable of producing ultra-high resolution acoustic images as well as co-registered bathymetry. SAS systems combine a number of acoustic pings, effectively enlarging the sonar array, to form an acoustic image with much higher resolution at equivalent swath widths to interferometric side-scan data (at 300 m range this corresponds to an improvement from 5 m to 5 cm in along-track resolution). The sonar is tightly integrated with the Aided Inertial Navigation of the HUGIN AUV and 4D Kalman Filtering to process the raw data into bathymetry and images of the sea floor. The SAS system mode was utilised to collect images of the sea floor as well as a subset of higher-resolution bathymetric data.

The system can operate in a number of modes, however, for the XPRIZE competition only 2 primary solutions were implemented, wide area and standard HISAS mode. Note that wide area mode negates SAS processing, but allows a much larger swath width to be realised with decimated resolution. Regardless the system outputs essentially four main data types:

- Side Scan Sonar Data

This Dataset is produced by default where one of the receiver arrays acts as a normal side scan sonar and along-track resolution is governed by centre frequency and array length.

- Side Scan Bathymetry

Dual receivers are used for a phase discrimination interferometer to generate bathymetry. As per side scan, the along-track resolution is a function of frequency and array length while the across-track resolution is a function of range resolution. This mode was used predominantly during the XPRIZE competition in order to meet lower resolution, but high coverage rates.

- Synthetic Aperture Side Scan Sonar

This synthesised side scan dataset has range independent along-track resolution better than 5x5cm. This mode requires certain controls on speed and range settings. This mode was used for a subsection of the XPRIZE area, in order to demonstrate this solution.

- Synthetic Aperture Bathymetry

A synthetic aperture bathymetric dataset is produced that has a resolution several orders of magnitudes higher than that of the side scan bathymetry. This was at late stages of development for the wide area mode during the XPRIZE Round 2 challenge, and although collected and tested internally by Kongsberg, this was not released.

3) HUGIN EM2040

The EM2040 multibeam, with a transducer depth rating of 6,000 m, is capable of operating between 200 and 400 kHz with 0.7 x 0.7 degree angular resolution, producing a maximum coverage sector of 140 degrees. The wide bandwidth of the transducer gives an operational window from 0.5 metres to more than 500 metres range which when equipped on this HUGIN gives an operational survey window down to more than 5,000 metres (with reduced resolution). This is the first shallow water system to bring all the advanced features of deep-water multibeam to the near-bottom sounding environment, hence it is capable of complete roll, pitch and yaw stabilization, dual swath, FM transmit pulses for deeper water depth ranges, and near field focusing on both transmit and receive. Normal operations at 400 kHz, give an optimum balance between high resolution, depth capability and tolerance of detrimental factors. During the Round 2 Field Test, the data was collected at 400 kHz and a beam width of 120°, producing 400 soundings per swath using high density equidistant beam spacing.

For the XPRIZE data, the EM2040 acts predominantly as a gap filler to the wide area HISAS mode, but also acts as a ground truth for data checking given that the closer to nadir the more quantifiable the data.

IV. DATA PROCESSING WORKFLOW

XPRIZE requirements stated that the final product had to be ready 48 hours after the end of data acquisition. Improvements in standard data processing techniques had to be made, such as selective prioritisation on data transfer, the utilization of CARIS Process Models and cloud-based data processing in order to meet such tight time constraints.

The Team data processing workflow (fig. 3) consists of four main parts. The times reported below represent the total time taken to carry out the task, with some stages being run concurrently.

- Navigation and HISAS processing using Navlab and FOCUS machines (16 hours total).
    - Navlab processing: The primary function is to rerun the navigation algorithm from priori to empirically known data and can be broken into two main components. Depth calculations and position updates. Depth is calculated based on conductivity, temperature and latitude (CTD) information which is extracted from the ascent and descent of the mission. Any logged vehicle positions during data collection, where the vehicle ran autonomously with interrogations from the USBL (but not sent real time)

  - are injected to a newly computed navigational solution to establish the optimal flight path
  - Once the navigation solution has been generated by Navlab, the FOCUS processor can process the raw HISAS stave data to generate bathymetric and side-scan data using the optimal navigation solution
- CARIS processing to create bathymetric surfaces and side scan mosaics (31 hours).
  - CARIS Process Designer tool was used to reduce processing times. At this stage CARIS also was used to merge the NAVLAB Navigation and Depth strings into EM2040 Data.
- Qimera and Fledermaus 3D visualization
- ArcGIS visualization of final products (bathymetric maps and side-scan imagery) for import to the ArcGIS Online account (24 hours).

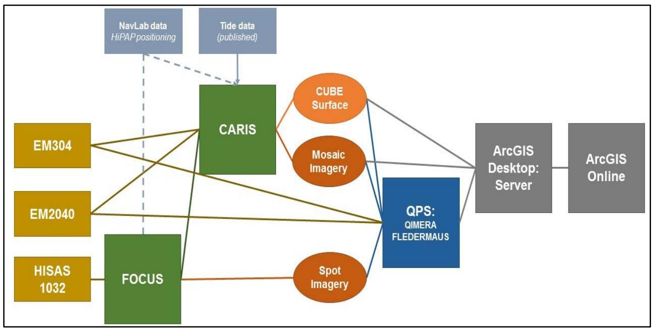

Figure 3. Data workflow diagram used by the GEBCO-NF Alumni Team.

Results were presented to the Shell Ocean Discovery XPRIZE representatives using the team's ArcGIS Online Portal. Prior to publishing in the online account, all of the processed data was integrated within an ArcGIS Desktop (ArcMap) map document (.mxd). Vector datasets were published to an ArcGIS Feature Service and raster products (bathymetric maps and imagery) were published to ArcGIS Image Services using Earth Analytic's SmartOcean ArcGIS Enterprise Server Cluster (SmartOcean). The raster data handling workflow, graphically depicted in Fig. 4, began with several ArcGIS "Mosaic Datasets" and the application of a series of "raster functions" to enable dynamic manipulation of dataset pixels for various display and information settings. These functions include: hillshade, slope, slope-aspect, aspect, and elevation with a preconfigured stretch. Subsequently, the ArcGIS team published these mosaic datasets as ArcGIS Image Services: a web services that enable dynamic access to raster pixel values, thereby allowing on-the-fly changes to display parameters and numeric cell values.

Finally, these Image Services were registered with the team's ArcGIS Online Organizational account, shared with specific user groups, and added to the final ArcGIS WebMap. This WebMap was in turn, embedded in a customised web application developed with ArcGIS Web AppBuilder. The team made a variety of configurations to the application including "Pop-ups" showing imagery linked to specific geographic locations.

V. Concept Adjustments and Sea Trials After Round 1

Final sea trials were conducted in Horten, Norway at Kongsberg Maritime facilities in June-October 2018 and in Kalamata, Greece the week before the team's competition attempt in November 2018. The purpose of the trials was to develop integration of the vehicles and optimization of the survey methods in accordance with the capabilities and limitations of the acoustic equipment. With respect to risk mitigation, management procedures of the AUV and USV systems were documented to ensure reliable operations at sea without physical intervention. Finally, extensive "failure" testing ensured the robustness of the system as whole, both with respect to the package as an XPRIZE solution, but also towards the ultimate goal of being an ocean-mapping tool for the real world.

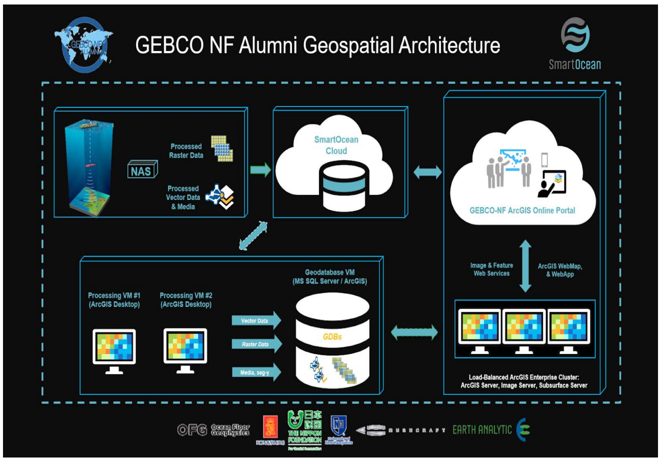

Figure 4. GEBCO-NF Alumni Team Geospatial Architecture & Workflow.

A. *HISAS wide area mode development*

Crucial to the innovative nature of this competition, the team collaborated to develop a new operational mode of the HISAS sonar. This new survey mode, called "wide area mode", allows greatly increased area coverage rates exceeding 2 - 3 times the coverage of the default operation. Bathymetric data is then obtained by the side scan seafloor depth estimation method, although running with reduced resolution, the output meets the specifications as outlined by the competition requirements.

Bottom coverage for the HISAS system is determined by swath width multiplied by speed (Table. 2). During Round 1, the Team operated Standard HISAS at 2 m/s (3.9 kts) and wide area mode at 2.2 m/s (4.3 kts). In preparation for Round 2, several HISAS sonar parameters were changed to achieve wider coverage with the wide area mode. It was established that optimal survey speed for both the AUV and USV considering battery dissipation, control et cetera, was 1.8 m/s (3.5 kts).

TABLE 2. THE DIFFERENT COVERAGE RATES DEPENDING ON SURVEY MODE

Survey Mode	Coverage Rate
Standard HISAS mode[a]	2.3 km^2/hour
Wide Area HISAS mode[a]	6.48 km^2/hour

[a] This includes EM2040 nadir gap data

B. *Gondola design and EM 304 installation*

The EM304 multibeam sonar was mounted on the SEA-KIT gondola, that was designed by Hushcraft Ltd. based on Kongsberg set dimensions. The gondola was built to be easily installed/removed and to be fitted into a 40' container with the other equipment. During preparations for Round 2, the gondola was fitted to the hull of the *USV Maxlimer*. The gondola is a wet floodable unit open to seawater and therefore everything installed within it must be watertight. The gondola has several roles, housing the EM304 transducers, the HiPAP 502 High Precision Acoustic Positioning System, the Kongsberg Seatex MGC-R3-SB50 gyro compassing motion unit and the sound velocity probe (fig. 5). In addition, it positions the transducers about 1.7 m below the waterline, thus minimizing the acoustic effects of bubble sweep down from the hull or surface wave activity. The motion sensor with gyro compassing functionality establishes its own North, from which all rotations in dimensional control are based. Consequently, it is the origin of the vessels' reference frame and is the navigation reference point; hence all other components (transducers, GNSS antenna) are referenced to it. By having the MGC mounted within the gondola and tightly coupled to the sonars eliminates the need for repeating the dimensional control survey/calibration after mobilisation / demobilisation, essentially making for a calibration-free gondola. A confidence check is, however, performed on site to verify no gross errors.

Figure 5. The new gondola installed on SEA-KIT MSV Maxlimer with the HiPAP and multibeam transducers installed. Photo: T. Ketter.

The approach to combine AUV mounted sonars with the data acquired by the sonar mounted on the USV, all of which were geographically controlled by the surface GPS solution, allowed the team to increase the coverage and leverage the GEBCO philosophy of combining all available data types to produce one final product.

C. EM304 tuning to meet the team's requirements

In order to satisfy the 0.5 m vertical resolution criterion, set by XPRIZE on the final data submission, the pulse mode of the EM304 was internally modified to generate a short FM pulse, thus improving range resolution and signal to noise ratio. On the receiving end, beam number was doubled to 512. This allowed an increase in data density to satisfy the 5 m gridding requirement set by XPRIZE. Runtime parameters included a maximal swath width that would not hinder horizontal spacing in the across-track dimension as well as vessel speed control for ping spacing in the along-track dimension.

Since SEA-KIT is an unmanned vessel and since electronics are not infallible, there is a requirement to provide hard resets. Powering the EM304 relays, controllable over satellite link, offered a simple and effective solution allowing installed operators to be able to restart the Transceiver Unit should it be required in real time. This option was efficiently demonstrated during sea trials, however, during the final round 2 mission the system operated continuously without the need to reboot. The EM304 was, as outlined, a new to market product and the rate of development was shown by the system changes between the Norwegian and Greek sea trials.

Data acquisition was done using the new Seafloor Information Software SIS 5. This allows users normal data storage as per conventional surface operation, but for the first time, the new SIS 5 Remote software was implemented. This remote module enables a secure data link for telemetry to the processing unit allowing users to control the system parameters remotely without requiring a large bandwidth as per traditional remote desktop applications. Dependent on available bandwidth, the user can request a decimated dataset providing real-time mapping onshore with a grid engine for real time quality control (QC). During the trials, this was typically consuming 5-10 Kbytes/s which had no detrimental effect on vehicle and vessel controls and worked seamlessly for the duration of the mission.

D. Interference

As with any operation where multiple sonars are used, frequency management and bandwidth control remains a constant concern to ensure the best dataset is realised. With the HUGIN alone containing 7 or more sonars, which when coupled to the surface mount EM304 and HiPAP, the control of sonar system transmission is paramount and subsequently exhaustive interference testing was conducted. In the course of the sea trials, it was established that three major forms of interference existed and would need to be mitigated. The HiPAP in the 20 -35 kHz region is using the entire bandwidth of the EM304 and produced direct interference. The HiPAP, in addition to EM304 interference has a second harmonic which affects the HISAS wide area mode. Lastly, the EM304 has a harmonic which in unusual situations causes bad tracking on a 500 kHz Nortek Doppler Velocity Log DVL.

1) EM304 and HiPAP

This can be characterised by the distinct "smiles" in EM304 swaths and visualised clearly in the water column data. There are several considerations in the method of HiPAP utilization in AUV operations. With AUV methods aside, under normal use a HiPAP USBL system uses an interrogation whereby it will transmit a channel ID for a transponder, in this case aboard the HUGIN, which is dutifully listening. By knowing turnaround times, range through phase azimuth and angle is established. This is a simple interrogation mode and can be set to defined periods and the EM304 will see the transmit pulse of both the HiPAP transmission and the transponder transmission. Whilst the interrogation interval can be defined to reduce interference, there is no modem functionality. Normal operations with AUV are, however, considerably different and generally defined as "Beacon" mode. In this scenario, the HiPAP and AUV are synchronised on, for example, a 30 second interval. The AUV will transmit long data packets up to 5 seconds containing both mission and sensor information. The header of this data packet contains vehicle depth. The HiPAP listens for this 30 seconds to each packet arriving determining arrival azimuth and angle and decoding depth information that allows intersection to establish relative location. Each 30 seconds, the HiPAP then gets the opportunity to transmit a packet down to the vehicle containing control information or indeed positional updates to the AUV inertial system. The HiPAP and AUV CNode are effectively in constant transmission, meaning that interference mitigation is virtually impossible with default operations in respect to EM304 and HiPAP.

As a result, it was necessary to reduce the modem telemetry between AUV and the Topside Unit and this was therefore a consideration in the mission planning. This can be achieved by allowing the AUV to run on its own, with the ADL set to off, configured to only send a data packets when requested. This allows intervals of autonomous running with occasional handshakes between vehicles at predefined rendezvous points.

2) HiPAP and wide area Mode HISAS

Somewhat in parallel to the EM304 experienced interference, the HiPAP beacon mode functionality can be exemplified in the HISAS wide area mode (fig. 6).

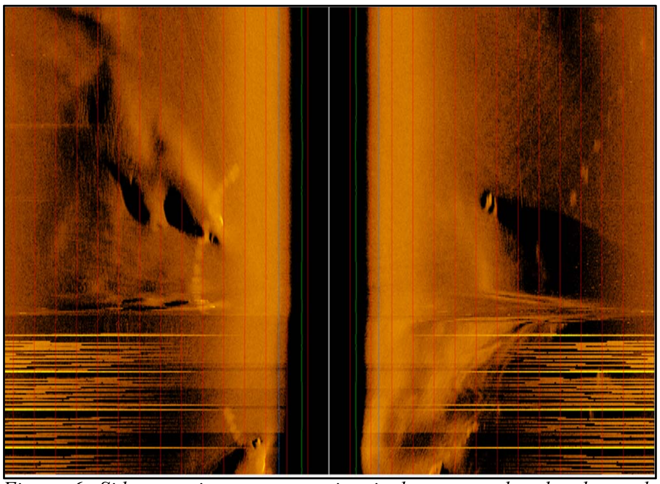

Figure 6. Side scan imagery operating in beacon mode whereby each telemetry packet from the AUV is shown and the stronger signal from the HiPAP downward packet on a 30 second interval is clearly defined.

The source level on AUV with 180 Degree transducer is typically 173 db versus the HiPAP 188 dB, both in low power mode, and hence the apparent "striping". As soon as the ADL on the AUV is switch to Off, the side scan data is clean out to 600 metres. When the HISAS is operating in normal mode, the time varying gain (TVG) does not increase the HiPAP interference enough to cause problems, only when extending range > 250 metres does this become a problem.

As per the EM304 interference, mitigation through traditional means such as synchronised transmission is not really applicable, requiring the ADL to be switched off.

3) EM304 and Nortek DVL

Through testing, it was established that in unusual scenarios, it is possible for the Nortek DVL to track Harmonics of the EM304 surface sonar. This was achieved once and could not be repeated or recreated. Analysis into the timing showed that upon starting the EM304 in close proximity to the AUV, and in shallow water, it was possible for the DVL to track a harmonic. In this scenario, the DVL locked on and maintained lock for a set period during which the AUV navigation would drift excessively quickly. Given that in all likelihood the AUV would be required to run silently, effectively leaving the topside with no information on the AUV location, establishing that there was a problem with DVL tracking would only be realised after the vehicle had been either lost or by excessive drift upon a rendezvous. As such, when putting the AUV silent, the HiPAP would be switched to interrogation mode to allow several pings tracking the AUV after leaving the rendezvous to verify the vehicle path corresponds to any set mission plan.

E. Permissible methods of operation

Prior to attendance in Greece, and given the information presented in sections D(1) – D(3), operational methods were restricted to a more defined solution. At this stage, an optimal approach was estimated to use the AUV in a true autonomous fashion, whereby she would run with occasional handshakes. An interval for handshakes can be established through priori knowledge of expected inertial drift, for example estimating drift at 0.05% of distance travelled we can expect 3 metres drift per hour and when coupled to knowledge that Navlab processing will effectively halve the drift we can expect to run autonomously for 2-3 hours before an inertial update is required to constrain the drift below 5 metres. This allows for mitigated risk commercially, as assets are never left unattended for excessive durations and through careful mission planning with AUV and SEA-KIT, maintaining good temporal and spatial control, the mission can be conducted in an efficient and optimal manner.

F. Over-the-horizon Capabilities

Kongsberg Maritime K-MATE Autonomy Controller provided the autonomous functionality of SEA-KIT [2,4]. This system allows SEA-KIT a "Follow Sub" mode, whereby the vessel will automatically follow the HUGIN. In this state, the collective survey solution from both AUV and SEA-KIT enter a feedback loop. The HUGIN AUV will follow its predefined mission plan, using its inertial navigation system that is receiving occasional navigational updates from the HiPAP acoustic data link from SEA-KIT, which are in turn based on the navigational solution on board SEA-KIT. The K-MATE autonomy solution will navigate SEA-KIT to maintain separation to the HUGIN as found position. As a result, the solution is fully self-reliant, allowing SEA-KIT operators the ability to focus on more complex tasks such as vessel management or indeed mapping control. In essence, the potential is present for an operator to run fully hands off for more than 24 hours whilst the mapping solution runs in accordance with the pre-defined mission plans.

A new "Virtual Anchor" functionality was added during 2018 sea trials that allows K-MATE to maintain SEA-KIT on a location without deployment of physical anchor by using vessel positioning system and thrusters. This capability was used on number of occasions for testing purposes as well as for problem solving in the water.

Hushcraft Ltd. have developed the Global Situation Awareness via Internet (G-SAVI) system to ensure the safety of over-the-horizon operations. The system allows CCTV, radar, thermal images, and sound data etc. to be sent through Internet / Satellite links from the USV to the remote land station.

VI. GEBCO-NF ALUMNI TEAM ATTEMPT FOR SHELL OCEAN DISCOVERY XPRIZE ROUND 2

A. Round 2 Field Test mission planning

Geographical coordinates of the mapping area were provided to the team on the day of official registration at XPRIZE Mission Control in Kalamata, Greece on November 5th, 2018 (Fig. 7). The mission planning was done by GEBCO-NF Alumni Data Team along with Kongsberg Maritime and OFG HUGIN operators. The plan was done according to the sea trials results described in Section V, although some changes were made that were dictated through final testing experiences.

The survey lines for both survey platforms were designed considering optimal combination of speed, interference mitigation and maximum achievable swaths during data acquisition. The values are presented in Table 3.

Considerations included the allocated 48 hour processing time following equipment departure from the survey area. As such, mapping equipment was scheduled to leave the survey area at the closest possible point from the harbour to reduce transit time on the return. Given this requirement, all survey lines were planned 'backwards', to choose the launching point in a location which covered the whole survey in 24 hours using the maximum presence of equipment in the survey area.

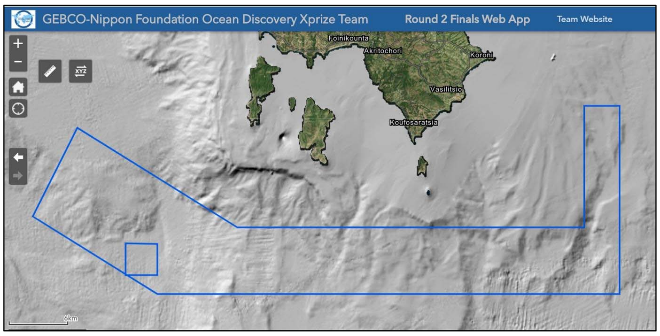

Figure 7. The shape and location of the survey area. Blue square represents the portion of the survey area to be mapped obligatory

TABLE 3. MAIN PARAMETERS AFFECTING THE SURVEY PERFORMANCE AND MISSION PLANNING.

Mapping equipment	Survey speed [kn]	Height above the seafloor [m]	Max. swath (approximate) [m]
Hugin – HISAS wide area mode	3.5	70	1000
Hugin – HISAS standard mode	3.5	40	350
SEA-KIT EM 304 multibeam echosounder	3.5-4.2	surface vessel	2000

The Team realised that the longest east-west leg can be almost completely mapped (excluding unavoidable gaps on the steep topography caused by side-scan ensonification geometry) in two parallel runs of the HUGIN – SEA-KIT pair. It also minimised the number of turns, increasing the overall data coverage rate, and avoiding loss of data due to suboptimal routines. SEA-KIT was to map the large portion of the longest east-west leg with EM 304 deep-water system, running parallel to the HUGIN AUV.

At this point, the navigation should be considered given the time and geometric relationship between AUV and SEA-KIT; they would run with a Port/Starboard offset to allow a tandem survey that increases navigational uncertainties. At an approximate 45 degree from vertical the HiPAP rotational accuracy remains constant, but any sound velocity (SV) error plays a role. Upon initial inspection, the lack of handshakes would be a problem. By using extended interrogation intervals of 2-3 minutes in transponder mode, however, the Topside unit of SEA-KIT could log the HUGIN position real time for post processing in Navlab. This low rate interrogations would only marginally increase dataset noise through interference but gives the added benefit of real time confidence to the operator, the AUV location can be checked manually correlating it to mission plan as a real time QC. Running for extended periods without inertial update means that drift incurred over periods greater than 3-4 hours the dataset exceeds navigational requirements set by the project and the dataset would at this stage in effect be relative. Navlab post processing allows these real time interrogations to be used by the navigation engine during re-estimation from all raw logged sensor data, creating a true absolute dataset.

Some concern could be extended initially to potentially induced SV error or indeed any calibration errors exaggerated by extended Port/Starboard relationship between AUV and SEA-KIT on these East to West passages and vice versa. This can be controlled by careful evaluation of navigation uncertainties during post processing through use of dead reckoning at set points. For example, at the start of the East to West leg, the geometric relationship is favourable with no appreciable horizontal separation. The time taken to establish a parallel running relationship is relatively short and the inertial drift is minimal hence the navigation algorithm runs in dead reckoning during this separation phase. This confidence in inertial drift or rather lack of it is then used to cross check the HiPAP calculated position against the estimated inertial uncertainty during this phase i.e. once parallel running is established. This is done both at start and end of the East West legs when the vehicle once again converges horizontally.

The deep-water testing prior the competition showed that below 2,500 m, the EM304 performance does not achieve data density sufficient for required gridding. Thus, it was decided to use SEA-KIT as a positioning platform in deeper areas an operating in "Beacon" or AUV following mode. In the deepest west part of the survey area, the lines were planned to completely cover the obligatory 10 km² box with the HISAS data acquired by HUGIN AUV. Two lines were extended to map the portion of the seafloor at 4,000 m depth to prove the system capabilities of working at the maximum depth required by the competition.

Whilst mapping coverage rates was focused by the XPRIZE guidelines, the GEBCO-NF Alumni Team plan was to operate two modes for data collections to highlight the capabilities of the system (the HUGIN AUV with a default configured HISAS 1032 as payload). As such, in the shallow East part of the survey area (North-South oriented leg) additional lines were planned to present high-resolution HUGIN HISAS standard mode with SEA-KIT operating in the AUV following mode to provide the best positioning solution for ultra high-resolution data.

B. Round 2 Field Test Mapping mission

No personnel were on-board SEA-KIT during the duration of Round 2 Field Test. The team were allowed to have one team member on-board a chase vessel in case of an emergency situation both with SEA-KIT and/or AUV. The USV was equipped with a tow line. The towing operation was tested and procedures were established earlier during the sea trials in Horten, Norway all of which remain valid.

The GEBCO-NF Alumni Team demonstrated 24 hour long remotely operated mapping capability by carrying out the survey in the Kalamata region. The AUV entered the box at 6:48 UTC on the morning of November 9th. The mapping equipment was turned off at 6:48 UTC on the November 10th, while AUV was still underwater with sufficient battery charge for the ascent, retrieval and transit to shore allowing the data download (Table 4).

TABLE 4. BATTERY PACK STATUS DURING ROUND 2 FIELD TEST DIVE.

		On Dock before Mission		After retrieval	
Battery N	**Storage capacity**	**Volts**	**Percent Charge**	**Volts**	**Percent Charge**
1	8.5 kW/h	50.0	100%	42.5	16 %
2	8.5 kW/h	50.0	100%	42.5	16 %
3	8.5 kW/h	50.0	100%	42.5	16 %

The maximum depth reached by HUGIN AUV "Rental 1" during the Round 2 Field Test was 3,997.7 m. The deepest area of 4,134 m was mapped during the survey.

Statistics that demonstrate the data coverage achieved in Round 2 Field Tests are included in Table 5.

TABLE 5. DATA COVERAGE FOR AREA MAPPED DURING ROUND 2 FIELD TEST

Survey mode	V, m/sec	AUV altitude, m	Half Swath, m	Survey time, hrs	Coverage, km²
HISAS Wide area	1.8	75	500	22	142.56
HISAS Standard	1.8	40	175	2	4.54
EM304	1.8	var	1000	12.6	163.30
Total					**310.39**

The final coverage produced in the bathymetric products has an area of 278.9 km² as the overlap between HUGIN HISAS data and EM304 data is ~ 28 km² and some data was excluded, such as transits and turns, to produce a better product.

The launch and recovery was all managed from the land-based Operation Center (fig. 8) – with AUV pilots from Kongsberg Maritime and OFG. Operators from Hushcraft Ltd managed control of SEA-KIT, and oversaw a situational awareness during the mission.

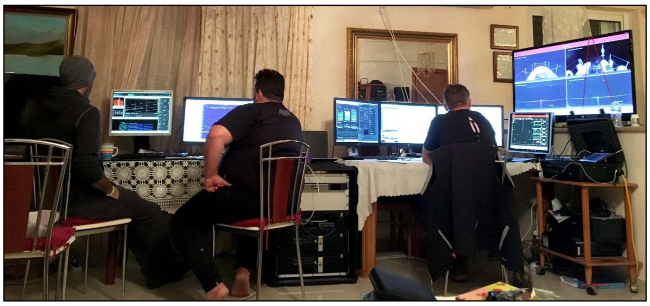

Figure 8. The GEBCO-NF Alumni Operation Center located in a rented apartment in Kalamata, Greece. Photo: E. Bazhenova

During the Round 2 Field Test, both launch and recovery was performed successfully. The AUV was launched outside the competition area according to the established procedures and both vessels entered the box following their mission plans. The HUGIN AUV was on its operational altitude above the see floor.

Two attempts were made to recover HUGIN AUV onboard SEA-KIT after the completion of the 24-hour mapping mission. No human intervention was required. The recovery procedure established during the testing and training period required the AUV to surface 100-400 m away from SEA-KIT to exclude any potential for collision and to give pilots a sufficient amount of time to properly set the AUV on course for the recovery. However, during the final sea trials prior the competition, it was established that AUV pilots could not locate HUGIN on surface outside the SEA-KIT CCTV observation coverage due to technical issues. Thus, the HiPAP acoustic link was used to operate and position AUV while under water.

The pilots positioned the AUV at 40 m below water level and commanded an ascent that should locate the vehicle within the CCTV visibility range. During the first attempt, the AUV surfaced 30 m behind SEA-KIT, but was lost because of the sun glare. The AUV was then brought back to a safe depth of 40 metres and acoustically commanded to navigate to a more comfortable position relative to SEA-KIT.

It was decided to bring the AUV as close as possible to the SEA-KIT port side for the second attempt. This required high level of confidence in HiPAP positioning accuracy closer to the surface. The AUV was brought to surface 10 m to the SEA-KIT's port side (Fig. 9). Once on the surface, good visual was established for the recovery, manually controlled over satellite link.

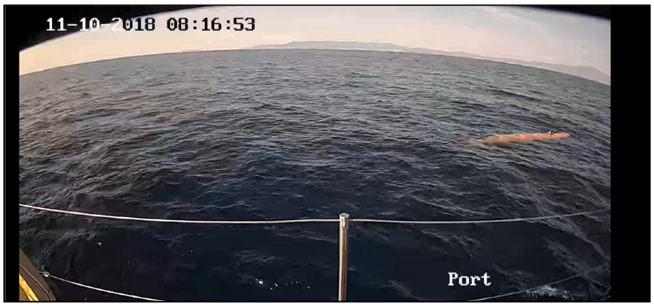

Figure 9. SEA-KIT port side CCTV screen capture showing AUV surfacing

C. Data processing

The data team had 43 hours for data retrieval, processing and delivery once SEA-KIT with HUGIN AUV onboard docked alongside the Kalamata Port pier.

All data collected (see below), with correct navigation, was uploaded to the Cloud on Team's closed ArcGIS online account to demonstrate Team's workflow capabilities.

1. **MAPS:**
   - Overall combined bathymetric dataset at 5 m resolution grid
   - 2 m resolution grid of HISAS1032 wide area mode data
   - 1 m resolution grid of standard HISAS1032 mode data
   - 1 m resolution grid of EM2040 data
   - 5 m resolution grid of EM304 data
2. **IMAGERY:**
   - 10 cm resolution mosaic of standard HISAS1032 mode
   - 1 m resolution mosaic of HISAS1032 wide area mode
   - 1 m resolution mosaic of EM2040 backscatter
   - 2 cm resolution Spot processed side-scan images of objects (produced using KM FOCUS software)
   - 3D images: bathymetry drapes (produced using Fledermaus), remotely produced at UNH point cloud images (using Qimera)

Data processing was set up at the XPRIZE Mission Control in Kalamata, Greece and at the HUGIN 10 ft. container.

Given the fairly large data volumes, it is important to understand the data structure and as a result the data download process. The following download procedure was used for the competition.

SEA-KIT HUGIN Mission and navigation data were downloaded using USB transfer from the HOS and EM304 data from the Hydrographic Working Station onboard SEA-KIT.

HUGIN data was downloaded using a 1 Gigbit network cable directly connected. This link was used to download navigation, vehicle health and payload data from the Payload Processor (PP) (approximately 2 hours for planned mission), however HISAS Stave data was not downloaded over this link. Once the main dataset was downloaded the removable NAS (Network Attached Storage) was physically removed from the AUV and plugged in the NAS dock in the FOCUS rack to conduct HISAS processing.

The resulting map is shown in Fig. 10, and is built on four bathymetric datasets: EM2040 (1 m grid resolution), wide area HISAS (2 m), HISAS standard (1 m), and EM304 (5 m).

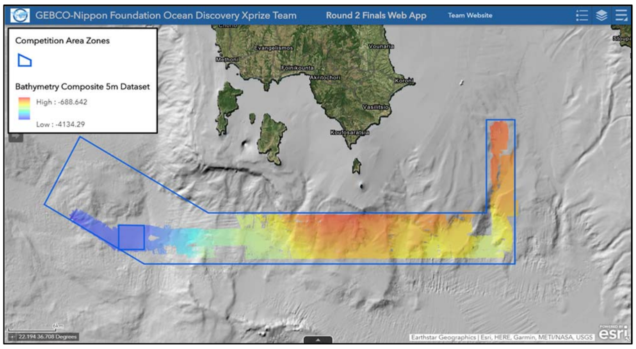

Figure 10. Final bathymetric map (5m grid) of the area surveyed during Round 2 Field Test Kalamata, Greece (9-12 November 2018).

Data Team processed all the data and produced surfaces and images at the Mission Control in Kalamata, Greece. Simultaneously team members were processing EM304 data at the UNH in Durham, USA using Earth Analytic and QPS cloud-based solution to produce additional 3D point cloud images. As a result, three types of images were submitted to the judges (fig. 11): high-resolution spot images, surfaces, and 3D point cloud images.

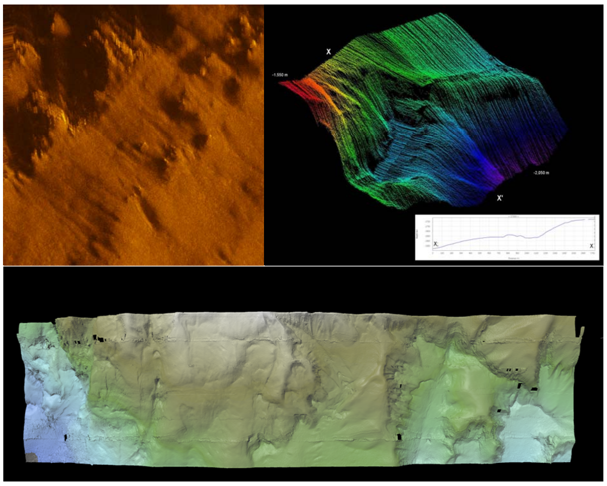

Figure. 11. Examples of images submitted to judges: top left – spot image of an 50x50 m area, top right – 3D point cloud, bottom – 3D surface rendered using Fledermaus

VIII. Conclusion

This project encompasses three years of work from an international team to accomplish what was previously not possible. This paper outlines integration across a broad spectrum of fields and shows what in essence proves to be a commercially viable solution for broad scale ocean mapping. By combining the latest technology from surface mapping solutions with high resolution AUV based surveying methods and through the manipulation of existing marine robotic technologies the team delivered on physical requirements. Combining this hardware based data collection technology to flow based processing techniques the result is a data set delivered for analysis faster and to a wider potential audience.

Whilst focus has been on delivering specifications meeting with XPRIZE stringent guidelines, traditionally the end product would be high risk with a low technological readiness level. The GEBCO-NF Alumni solution has pushed past research level solutions by leveraging risk quantified products that meet requirements beyond any current scope and deliver to a level accepted by commercial industry.

With such a complicated operation it is easy to over simplify what has been achieved.

- Successful AUV launch and recovery without human interaction
- Over-the-horizon operation for 35 hours, all done remotely
- Data processing and delivery to an online cloud base solution
- Successful collaboration around the world by bringing together specialists from different sectors

Here, within the GEBCO-NF Alumni team, we see collaboration within Industry, in Academia, in Research all striving together in unity for the same goal and have delivered unequivocally.

Acknowledgment

This work was done in partnership with the Nippon Foundation and would not have been possible without the support of the Sasakawa Peace Foundation, University of New Hampshire, Ocean Floor Geophysics, Kongsberg Maritime, Hushcraft Ltd., Teledyne CARIS and Earth Analytic. The authors would also like to thank the 77 individuals from 22 countries who all dedicated themselves to ensuring the success of this project.

References

[1] K. Zwolak, B. Anderson, E. Bazhenova, R. Falconer, T. Kearns, H. Minami, J. Roperez, A. Rosedee, H. Sade, N. Tinmouth, R. Wigley and Y. Zarayskaya, "An unmanned seafloor mapping system: The concept of an AUV integrated with the newly designed USV SEA-KIT," in OCEANS, Aberdeen, 2017.

[2] Proctor, Y. Zarayskaya, E. Bazhenova, M. Sumiyoshi, R. Wigley, J. Roperez, K. Zwolak, S. Sattiabaruth, H. Sade, N. Tinmouth, B. Simpson, S.M. Kristoffersen, "Unlocking the Power of Combined Autonomous Operations with Underwater and Surface Vehicles: Success with a Deep-Water Survey AUV and USV Mothership," 2018 OCEANS - MTS/IEEE Kobe Techno-Oceans (OTO), Kobe, 2018, pp. 1-8. DOI: 10.1109/OCEANSKOBE.2018.8558784

[3] Shell Ocean Discovery XPRIZE Committee "Shell Ocean Discovery XPRIZE Competition Guidelines," 25 April 2016. [Online]. Available: https://assets-us-01.kc-usercontent.com/5cb25086-82d2-4c89-94f0-8450813a0fd3/8a5ecfeb-2f19-44f4-a96f-c27ec459e087/shell_ocean_discovery_xprize_final_guidelines.pdf [Accessed 30 April 2019].

[4] Kongsberg Maritime AS, "K-MATE Autonomy Controller Technology Put to Test for Shell Ocean Discovery," 27 November 2017. [Online]. Available: https://www.kongsberg.com/maritime/about-us/news-and-media/news-archive/2017/k-mate-autonomy-controller-technology-put-to-test-for-shell-ocean-discovery/ [Accessed 30 April 2019].